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(54) **HEAT PUMP WATER FLOW CONTROL**

(57) An electronic controller for controlling a heat pump water heater is configured to receive a first signal from a first sensor and receive a second signal from a second sensor. The first signal is indicative of a first variable the second signal is indicative of a second variable. The electronic controller is configured to determine a target flow rate based on the first variable and the second variable and control a water flow rate of the heat pump water heater based on the target flow rate.

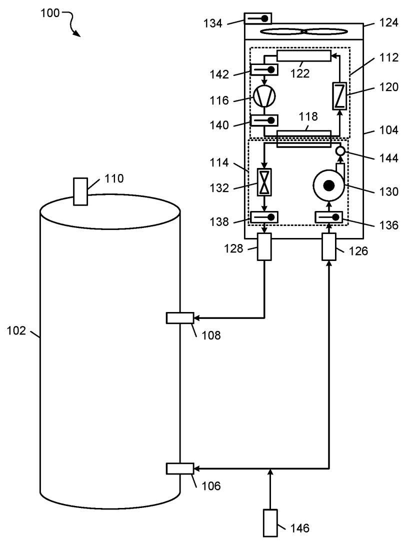

FIG. 1

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Description

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 63/610,105 filed December 14, 2023, the entire disclosure of which is incorporated by reference.

FIELD

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

SUMMARY

[0003] Heat pump water heating 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 water heating systems include heat pump heater units, which use a refrigeration cycle to extract heat from external environment (such as ambient air, the ground, and/or an external water source) and transfer the extracted heat into water in the system. Because heat pump heater units move heat, they may be more efficient than heater units that generate heat directly (such as electric resistance heater units). This is because moving heat generally requires less energy than generating heat. For example, heat pump water heater units transfer existing heat from the external environment into water in the system, rather than creating the heat. Because it generally requires less energy to move heat than to create it, heat pump water heating systems can be significantly more energy efficient compared to systems that generate heat.

[0004] Heat pump water heating systems may be configured as single-pass systems or multi-pass systems. In multi-pass systems, the water to be heated circulates through the heat pump heater unit multiple times, and the heat pump heater unit gradually transfers heat from the external environment to the water in the system in each pass until the water reaches the desired set-point temperature. Thus, in a multi-pass system, the temperature of the water exiting the heat pump heater unit may increase with each subsequent pass until the temperature eventually reaches the set-point temperature. By contrast, in single-pass systems, the flow rate of the water moving through the heat pump heater unit may be regulated so that the water exiting heat pump heater unit is maintained at the set-point temperature. Generally, single-pass systems may be more efficient than multi-pass systems.

[0005] For example, in a multi-pass system, the temperature gradient between the heated refrigerant of the heat pump heater unit and the water may decrease in each subsequent pass. Because a larger temperature gradient provides a stronger thermal driving force, the efficiency of the heat transfer may diminish with each subsequent pass. By contrast, in a single-pass system, the water may be brought to the set-point temperature in a single pass. Thus, the temperature gradient does not diminish, and the heat transfer efficiency remains relatively high. Furthermore, heat may be lost to the external environment as water within the system is cycled between a tank and the heat pump heater unit. In a multi-pass system, the water continues to cycle between the tank and the heat pump heater unit during the multiple passes. Thus, as the water may cycle for a longer duration, more heat may be lost to the external environment than in a single-pass system.

[0006] While single-pass systems tend to be more efficient than multi-pass systems, implementing control systems for single-pass systems tends to be more technically challenging compared to multi-pass systems. For example, in a multi-pass system, the flow rate of the water through the heat pump heater unit may be maintained at a fixed rate until the water in the system eventually reaches the set-point temperature. By contrast, in a single-pass system, the flow rate of the water through the heat pump heater unit may need to be quickly and/or continuously adjusted so that the temperature of the water exiting the heat pump heater unit remains at the set-point temperature.

[0007] Some examples of control systems for single-pass systems operate according to a simple feedback control loop. In such examples, the temperature of water output from the heat pump heater unit may be measured and compared to the set-point temperature. When the temperature of the output water is below the set-point temperature, the flow rate through the heat pump heater unit may be decreased, which increases the temperature of the output water. Conversely, when the temperature of the output water is above the set-point temperature, the flow rate through the heat pump heater unit may be increased, which decreases the temperature of the output water. However, such examples of feedback loops may be unstable due to the time lag that may be present between changes to the flow rate and resultant changes in the temperature of the output water. Furthermore, heat pump water heating systems using air-source heat pump heater units (which transfer heat from the ambient air to water in the system) may further need to account for changes to the heating capacity of the system as ambient conditions change (for example, the heating capacity of the system may vary by a factor of 3:1 or more over the typical range of ambient operating temperatures).

[0008] To address these and other technical problems, systems, apparatuses, and methods described in this specification implement techniques that may include a first feedback loop (for example, a fast feedback loop) and a second feedback loop (for example, a slow feedback loop). In various implementations, the fast feedback loop quickly determines an available heating rate based on various sensor readings, determines an available heating rate of the system, and sets a target water flow rate. The slow feedback loop adjusts the target water flow rate (for example, based on actual operating conditions) to fine-tune the system and precisely maintain the temperature of water output from the heat pump heater unit at the set-point temperature. These technical solutions allow the system to respond to changes (such as changes to the demand draw of the system and/or changes in ambient conditions) in a quick and stable manner, ensuring that water output from the heat pump heater unit steadily remains at the set-point temperature.

[0009] An electronic controller for controlling a heat pump water heater is configured to receive a first signal from a first sensor and receive a second signal from a second sensor. The first signal is indicative of a first variable the second signal is indicative of a second variable. The electronic controller is configured to determine a target flow rate based on the first variable and the second variable and control a water flow rate of the heat pump water heater based on the target flow rate.

[0010] In other features, the first variable is a water inlet temperature and the second variable is an ambient temperature. In other features, determining the target flow rate based on the first variable and the second variable comprises determining a first estimated refrigerant pressure based on the first variable, determining a second estimated refrigerant pressure based on the second variable, determining an available heating rate based on the first estimated refrigerant pressure and the second estimated refrigerant pressure, and determining the target flow rate based on the available heating rate and an adjustment factor.

[0011] In other features, the first variable is a first refrigerant pressure and the second variable is a second refrigerant pressure. In other features, determining the target flow rate based on the first variable and the second variable comprises determining an available heating rate based on the first refrigerant pressure and the second refrigerant pressure and determining the target flow rate based on the available heating rate, a water inlet temperature, and an adjustment factor.

[0012] In other electronic controller for controlling a heat pump features, the water inlet temperature is determined from the first signal. In other features, the water inlet temperature is determined from the second signal. In other features, the electronic controller is further configured to receive a third signal from a third sensor, the third signal indicative of a third variable, update the adjustment factor based on the third variable, determine an updated target flow rate based on the available heating rate and the updated adjustment factor, and control the water flow rate of the heat pump water heater based on the updated target flow rate.

[0013] In other features, the water inlet temperature is determined from the third signal. In other features, the third variable is a water outlet temperature. Updating the adjustment factor based on the third variable comprises increasing the adjustment factor in response to the water outlet temperature being above a set-point temperature and decreasing the adjustment factor in response to the water outlet temperature being below the set-point temperature. In other features, the first sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from a compressor to an expansion device.

[0014] In other features, the second sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from an expansion device to a compressor. In other features, controlling the water flow rate of the heat pump water heater based on the target flow rate comprises controlling a flow control valve to operate at a fixed valve position and adjusting an operating speed of a water pump.

[0015] A method for controlling a heat pump water heater includes receiving a first signal from a first sensor and receiving a second signal from a second sensor. The first signal is indicative of a first variable and the second signal is indicative of a second variable. The method includes determining a target flow rate based on the first variable and the second variable and controlling a water flow rate of the heat pump water heater based on the target flow rate.

[0016] In other features, the first variable is a water inlet temperature and the second variable is an ambient temperature. In other features, determining the target flow rate based on the first variable and the second variable comprises determining a first estimated refrigerant pressure based on the first variable, determining a second estimated refrigerant pressure based on the second variable, determining an available heating rate based on the first estimated refrigerant pressure and the second estimated refrigerant pressure, and determining the target flow rate based on the available heating rate and an adjustment factor.

[0017] In other features, the first variable is a first refrigerant pressure and the second variable is a second refrigerant pressure. In other features, determining the target flow rate based on the first variable and the second variable comprises determining an available heating rate based on the first refrigerant pressure and the second refrigerant pressure and determining the target flow rate based on the available heating rate, a water inlet temperature, and an adjustment factor. In other features, the water inlet temperature is determined from the first signal. In other features, the water inlet temperature is determined from the second signal.

[0018] In other features, the method includes receiving a third signal from a third sensor, the third signal indicative of a third variable, updating the adjustment factor based on the third variable, determining an updated target flow rate based on the available heating rate and the updated adjustment factor, and controlling the water flow rate of the heat pump water heater based on the updated target flow rate. In other features, the water inlet temperature is determined from the third signal.

[0019] In other features, the third variable is a water outlet temperature and updating the adjustment factor based on the third variable comprises increasing the adjustment factor in response to the water outlet temperature being above a set-point temperature and decreasing the adjustment factor in response to the water outlet temperature being below the set-point temperature. In other features, the first sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from a compressor to an expansion device.

[0020] In other features, the second sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from an expansion device to a compressor. In other features, controlling the water flow rate of the heat pump water heater based on the target flow rate comprises controlling a flow control valve to operate at a fixed valve position and adjusting an operating speed of a water pump.

[0021] Other examples, embodiments, features, and aspects will become apparent by consideration of the detailed description and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0022]

FIG. 1 is a schematic illustration of an example heat pump water heating system.

FIG. 2 shows a graph illustrating a relationship between an enthalpy and a pressure of refrigerant as it progresses through a refrigerant circuit of a heat pump water heater unit according to some embodiments.

FIG. 3 is a block diagram showing an interconnected hardware control system of a heat pump water heater unit according to some embodiments.

FIG. 4 is a flowchart of an example process for controlling a heat pump water heater unit.

FIG. 5 is a flowchart of an example process for implementing a fast control loop for controlling a heat pump water heater unit.

FIG. 6 is a flowchart of an example process for implementing a slow control loop for controlling a heat pump water heater unit.

FIG. 7 shows a graph illustrating relationships between valve positions of a flow control valve and pump speeds of a pump for a range of water flow rates in a water circuit of a heat pump water heater unit according to some embodiments.

[0023] In the drawings, reference numbers may be reused to identify similar and/or identical elements.

DETAILED DESCRIPTION

[0024] FIG. 1 is a schematic illustration of an example heat pump water heating system 100. As illustrated in FIG. 1, some examples of the system 100 include one or more hot water storage tanks, such as tank 102, and one or more heat pump heater units, such as heater unit 104. Although a single tank 102 and a single heater unit 104 is shown in FIG. 1, various implementations of the system 100 may include any number of tanks 102 and any number of heater units 104. In some examples, the heater unit 104 may include an air-source heat pump heater unit (for example, as illustrated in FIG. 1), a water-source heat pump heater unit, or a ground-source heat pump heater unit. In various implementations, the 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 material such as steel. The inner lining may include a corrosion-resistant material such as glass or a polymer coating and be configured to contain a fluid (such as water). The insulation material may include a material that minimizes and/or reduces heat transfer from the contents of the interior of the tank 102 to an external ambient environment (for example, fiberglass or a polyurethane foam).

[0025] The tank 102 may include one or more ports for fluid such as water to enter and/or exit the tank 102. For example, the tank 102 may include a recirculation supply port 106, a return port 108, and a hot water supply port 110. In various implementations, the recirculation supply port 106 is positioned near the bottom of the tank 102 (for example, within the bottom half, third, quarter, fifth, or tenth of the tank 102) so that cooler, less buoyant water within the tank 102 can be supplied to the heater unit 104 via the recirculation supply port 106. In some examples, the return port 108 is located near the top of the tank 102 (for example, within the top half, third, quarter, fifth, or tenth of the tank 102) so that water heated by the heater unit 104 can be returned via the return port 108 near the top of the tank 102. The heated water returned from the heater unit 104 may be near the hot water supply port 110 and supplied via the hot water supply port 110 in response to a hot water demand draw.

[0026] The heater unit 104 may include a refrigerant circuit 112 and a water circuit 114. The refrigerant circuit 112 may include a compressor 116, a heat exchanger such as a condenser 118, an expansion device 120 (for example, an expansion valve), and an evaporator 122. In various implementations, the compressor 116, condenser 118, expansion device 120, and evaporator 122 may be fluidly coupled by one or more refrigerant lines (for example, as illustrated in FIG. 1). The refrigerant may include hydrofluorocarbon (HFC) refrigerants (such as R-134a, R404A, R-407C, R-410A, R-32, etc.), hydrofluoroolefin (HFO) refrigerants (such as R-1234yf, R-1234ze, R-1233zd, etc.), or natural refrigerants (such as carbon dioxide, propane, etc.).

[0027] FIG. 2 shows a graph 200 illustrating a relationship between an enthalpy and a pressure of refrigerant as it progresses through the refrigerant circuit 112. The enthalpy axis 202 represents the enthalpy of the refrigerant at a given point in the cycle while the pressure axis 204 represents the pressure of the refrigerant at that given point. The liquid-vapor dome 206 represents a transition between different phases of the refrigerant. At points to the left of the dome 206, the refrigerant exists in a purely liquid state. At points to the right of the dome 206, the refrigerant exists in a purely vapor state. At points below the dome 206, the refrigerant exists in a mixed two-phase state (the refrigerant exists as a mixture of liquid and vapor states).

[0028] Points 208, 210, 212, and 214 represent states of the refrigerant as it progresses through the refrigerant circuit 112. Referring collectively to FIGS. 1 and 2, point 208 represents the refrigerant after it exits the compressor 116 and is delivered to the condenser 118. At point 208, the refrigerant is in a vapor state at a first pressure. At the condenser 118, the refrigerant transitions from point 208 to point 210. Within the condenser 118, the refrigerant rejects heat energy to water passing through the condenser 118 (for example, to water in the water circuit 114). As the refrigerant transfers heat energy to water passing through the condenser 118, the enthalpy of the refrigerant decreases and the refrigerant is condensed from a vapor state to a liquid state and exits the condenser 118 in a subcooled liquid state at the first pressure (indicated by point 210). The refrigerant is then expanded at the expansion device 120 to a second pressure (lower than the first pressure) at point 212. The expansion of the refrigerant at the expansion device 120 may be substantially adiabatic, such that the enthalpy of the refrigerant remains substantially unchanged between points 210 and 212. As a result, the refrigerant at point 212 is within the liquid-vapor dome 206, and therefore exists in a two-phase state at a substantially lower temperature than it had at point 210.

[0029] The refrigerant exits the expansion device 120 (at point 212) and is heated to a superheated vapor state in the evaporator 122. In various implementations, the evaporator 122 is an air-to-refrigerant heat exchanger, with ambient air directed through the heat exchanger by way of a blower or fan 124 while the refrigerant flows through tubes of the heat exchanger of the evaporator 122. In some examples, the evaporator 122 is a liquid-to-refrigerant heat exchanger (similar to condenser 118). Due to the lower pressure of the refrigerant at and between points 212 and 214 (as the refrigerant exits the expansion device 120, flows to the evaporator 122, flows through the heat exchanger of the evaporator 122, and exits the evaporator 122), heat can be transferred into the refrigerant from even a relatively low-temperature heat source (such as the ambient air). After exiting the evaporator 122 at point 214, the refrigerant (which may be a slightly superheated low-pressure vapor) flows to the compressor 116. The compressor 116 compresses the refrigerant (which is a vapor) back to the higher first pressure, moving the refrigerant's state from point 214 back to point 208. This compression does not occur adiabatically, resulting in an increase in the enthalpy of the refrigerant between point 214 and point 208. Thus, as shown by the graph 200, the heat energy available to be transferred into the water of the water circuit 114 via the condenser 118 (represented by the enthalpy change from point 208 to point 210) is substantially greater than the work put into the system by the compressor 116 (represented by the enthalpy change from point 214 to point 208). Accordingly, the water heating process of the heater unit 104 is very energy efficient.

[0030] Returning to FIG. 1, in various implementations, water enters the water circuit 114 via an inlet port 126 and exits the water circuit 114 via an outlet port 128. The inlet port 126 may be fluidly coupled to the recirculation supply port 106 via one or more manifolds, lines, and/or pipes, and the outlet port 128 may be fluidly coupled to the return port 108 via one or more manifolds, lines, and/or pipes. In some examples, the water circuit 114 includes a pump 130, the condenser 118, and a flow control valve 132. The inlet port 126 and the outlet port 128 may be fluidly coupled to the pump 130, condenser 118, and the flow control valve 132 via one or more manifolds, lines, and/or pipes. In various implementations, the pump 130 draws water (such as cold water) in from the tank 102 via the recirculation supply port 106 and the inlet port 126 and pumps the water to the condenser 118. At the condenser 118, the water enters the heat exchanger of the condenser 118 and heat from the refrigerant is transferred to the water (between points 208 and 210 of graph 200), heating the water. The water exits the condenser 118, flows through the flow control valve 132, and exits the heater unit 104 via the outlet port 128.

[0031] The heated water may return to the tank 102 via the return port 108. In various implementations, the order of the components in the water circuit 114 may be varied from that illustrated in FIG. 1. For example, the pump 130 and/or the flow control valve 132 may be placed before or after the condenser 118. Heated water supplied from the heater unit 104 to the tank 102 may be delivered to the tank via the hot water supply port 110. Cold water may be resupplied to the tank 102 or provided to the inlet port 126 via a cold water port 146. In various implementations, the cold water port 146 may be fluidly coupled to the recirculation supply port 106 and/or the inlet port 126 via one or more manifolds, lines, and/or pipes. In some examples, the cold water port 146 may be directly coupled to the tank.

[0032] The heater unit 104 may also include a variety of sensors that measure one or more variables such as temperature, pressure, flow rate, etc. In various implementations, the heater unit 104 includes one or more temperature sensors. For example, the heater unit 104 may include a temperature sensor 134 positioned on an exterior of the heater unit 104 to measure an ambient temperature T_{amb} of the external ambient air, a temperature sensor 136 positioned between the inlet port 126 and the condenser 118 (for example, between the inlet port 126 and the pump 130) to measure a water inlet temperature T_{w_in}, and a temperature sensor 138 positioned between the condenser 118 and the outlet port 128 (for example, between the flow control valve 132 and the outlet port 128) to measure a water outlet temperature T_{w_out}. In various implementations, the heater unit 104 includes one or more pressure sensors, such as a pressure sensor 140 (positioned between the compressor 116 and the condenser 118 to measure a high-side refrigerant pressure P_{high}) and a pressure sensor 142 (positioned between the evaporator 122 and the compressor 116 to measure a low-side refrigerant pressure P_{low}). In some examples, the heater unit 104 includes a flow meter 144 to measure a water flow rate V_w within the water circuit 114. In various implementations, the flow meter 144 may be positioned at any point in the water circuit 114, such as between the inlet port 126 and the pump 130, between the pump 130 and the condenser 118, between the condenser 118 and the flow control valve 132, or between the flow control valve 132 and the outlet port 128.

[0033] FIG. 3 is a block diagram showing an interconnected hardware control system of the heater unit 104 according to some embodiments. As illustrated in FIG. 3, the heater unit 104 may include a heater unit controller 302. In various implementations, the controller 302 includes one or more electronic processors and non-transitory computer-readable storage media containing instructions executable by the one or more electronic processors. The controller 302 may be operatively coupled to and communicate with the compressor 116, the fan 124, the pump 130, the flow control valve 132, the temperature sensor 134, the temperature sensor 136, the temperature sensor 138, the pressure sensor 140, the pressure sensor 142, and/or the flow meter 144. In various implementations, the controller 302 controls operation of the compressor 116, the fan 124, the pump 130, and/or the flow control valve 132. In some examples, the controller 302 receives signals indicative of temperature readings from the temperature sensor 134, the temperature sensor 136, and/or the temperature sensor 138. In various implementations, the controller 302 receives signals indicative of pressure readings from the pressure sensor 140 and the pressure sensor 142. In some examples, the controller 302 receives signals indicative of water flow rates from the flow meter 144.

[0034] FIG. 4 is a flowchart of an example process 400 for controlling the water heater unit 104. At block 402, the controller 302 detects a change in the system 100. For example, the controller 302 detects a demand draw of heated water. In response to the demand draw, the controller 302 initiates a first control loop (for example, a fast control loop) to regulate the water circuit 114 so that water flows through the water circuit 114 at a target flow rate V_{target} at block 404. For example, the controller 302 computes the target flow rate V_{target} based on readings from one or more sensors of the heater unit 104 and controls the pump 130 and/or flow control valve 132 so that water flows through the water circuit 114 at the computed flow rate V_{target}. The computed target flow rate V_{target} may correspond to a flow rate at which water is calculated to exit the heater unit 104 (for example, via outlet port 128) at a set-point temperature T_{set}.

[0035] The set-point temperature T_{set} may be a specific temperature that a user of the system 100 sets for the system 100 to maintain. For example, the set-point temperature T_{set} may correspond to the desired temperature of water inside tank 102. In various implementations, the set-point temperature T_{set} may correspond to a desired temperature of hot water drawn from the tank 102 via the hot water supply port 110. Additional details associated with the first control loop will be described with reference to FIG. 5. At block 406, the controller 302 initiates a second control loop (for example, a slow control loop) to regulate the water circuit 114 so that water flows through the water circuit at an updated target water flow rate V_{target}. In the slow control loop, the controller may adjust the target flow rate V_{target} based on the actual performance of the system 100 and/or changes in the operating conditions. Additional details associated with the slow control loop will be described with reference to FIG. 6.

[0036] In various implementations, the controller 302 first initiates the first control loop at block 404 to determine an initial target flow rate V_{target}. After determining the initial target flow rate V_{target}, the controller 302 may continue executing the first control loop and the second control loop in parallel. For example, the controller 302 may continue computing the target flow rate V_{target} according to the first control loop and continue adjusting the target flow rate V_{target} according to the second control loop in parallel with the first control loop.

[0037] FIG. 5 is a flowchart of an example process 500 for implementing a first control loop (for example, a fast control loop). At block 502, the controller 302 determines whether the compressor 116 is operating. In response to determining that the controller 302 is not operating ("N" at decision block 504), the controller 302 starts the pump 130 at block 506. For example, the controller 302 operates the pump 130 at a low flow rate. In various implementations, the low flow rate may be in a range of between about 0 and 1 gallons per minute or in a range of between about 1 and 2 gallons per minute. At block 508, the controller 302 measures the inlet water temperature T_{w_in} by processing signals received from the temperature sensor 136. At block 510, the controller 302 measures the ambient temperature T_{amb} by processing signals received from the temperature sensor 134. At block 512, the controller 302 determines an available heating rate Q of the heater unit 104 based on the inlet water temperature T_{w_in} and the ambient temperature T_{amb}. In various implementations, the controller 302 may include a two-dimensional lookup table correlating combinations of high-side pressure P_{high} and low-side pressure P_{low} to available heating rates Q. The controller 302 may compute an estimated high-side pressure P_{high} and an estimated low-side pressure P_{low} based on the inlet water temperature T_{w_in} and the ambient temperature T_{amb} and use the lookup table to determine an available heating rate Q corresponding to the estimated high-side pressure P_{high} and the estimated low-side pressure P_{low}.

[0038] In order to drive heat from the ambient air into the low-pressure refrigerant in the evaporator 122, the saturation temperature of the refrigerant on the low-pressure side of the refrigerant circuit 112 (e.g., between the expansion device 120 and the compressor 116) must be at least slightly below the ambient temperature T_{amb}. The controller 302 may apply a small offset (for example, about 2° F, 3° F, 4° F, 5° F, etc.) to the ambient temperature T_{amb} to determine an estimated evaporator saturation temperature. The controller 302 may be programmed with pressures corresponding to saturation temperatures for the refrigerant of the refrigerant circuit 112 and determine an estimated low-side pressure P_{low} corresponding to the estimated evaporator saturation temperature.

[0039] Similarly, in order to drive heat from the high-pressure refrigerant on the high-pressure side of the refrigerant circuit 112 (e.g., between the compressor 116 and the expansion device 120), the saturation temperature of the refrigerant must be above the temperature of the water in the water circuit 114. Since the controller 302 operates the pump 130 at the low flow rate, the controller 302 is able to accurately measure the inlet water temperature T_{w_in}. The controller 302 may apply an offset (for example, about 5° F, 6° F, 7° F, 8° F, etc.) to determine an estimated condenser saturation temperature. The controller 302 may determine an estimated high-side pressure P_{high} corresponding to the estimated condenser saturation temperature. After determining an estimated high-side pressure P_{high} and an estimated low-side pressure P_{low}, the controller may use the lookup table to determine an available heating rate Q corresponding to the estimated high-side pressure P_{high} and the estimated low-side pressure P_{low}.

[0040] At block 514, the controller 302 measures an updated water inlet temperature T_{w_in}, by processing signals from the temperature sensor 136. Alternatively, the controller may continue to use the water inlet temperature T_{w_in} that was measured at block 508. At block 516, the controller 302 computes a target water flow rate V_{target} based on the available heating rate Q and the water inlet temperature T_{w_in}. In various implementations, the controller 302 may be programmed with the density ρ of water for a range of temperatures (for example, including the water inlet temperature T_{w_in}) and the specific heat of water c_p. The controller 302 may compute the target water flow rate V_{target} for any given set-point temperature T_{set} according to equation (1) below:

$$V_{target} = K \cdot \left(\frac{Q}{\rho \cdot c_p \cdot (T_{set} - T_{w\_in})} \right) \quad (1)$$

[0041] In the fast control loop (e.g., the process 500), the controller 302 may set the adjustment factor K to a value of 1. In various implementations, the controller 302 refines the adjustment factor K during the slow control loop (described further on with reference to FIG. 6) based on operating conditions of the system 100. At block 518, the controller 302 controls heater unit 104 to operate the water circuit 114 at the target flow rate V_{target}. For example, the controller 302 adjust settings of the pump 130 and/or the flow control valve 132 until signals from the flow meter 144 indicate the target flow rate V_{target}. At block 519, the controller 302 starts the compressor to circulate refrigerant through the refrigerant circuit 112. Additional details associated with operating the water circuit 114 at the target flow rate V_{target} will be described further on in this specification with reference to FIG. 7.

[0042] From block 519, the process 500 proceeds to block 520. The process 500 also proceeds to block 520 in response to the controller 302 determining that the compressor 116 is operating ("Y") at decision block 504. At block 520, the controller 302 measures the high-side refrigerant pressure P_{high} by processing signals from the pressure sensor 140. At block 522, the controller 302 measures the low-side refrigerant pressure P_{low} by processing signals from the pressure sensor 142. At block 524, the controller 302 determines an available heating rate Q based on the measured high-side refrigerant pressure P_{high} and the measured low-side refrigerant pressure P_{low}. For example, the controller 302 determines the available heating rate Q corresponding to the measured high-side refrigerant pressure P_{high} and the measured low-side refrigerant pressure P_{low} from the lookup table. The available heating rate that is determined at block 524 will, generally speaking, be more accurate than the available heating rate that is determined at block 512.

[0043] At block 526, the controller 302 measures the water inlet temperature T_{w_in}, by processing signals from the temperature sensor 136. At block 528, the controller 302 computes the target water flow rate V_{target} based on the available heating rate Q and the water inlet temperature T_{w_in} (for example, according to techniques previously described with reference to block 516). At block 530, the controller 302 controls heater unit 104 to operate the water circuit 114 at the target flow rate V_{target}. For example, the controller 302 adjust settings of the pump 130 and/or the flow control valve 132 until signals from the flow meter 144 indicate the target flow rate V_{target}. Additional details associated with operating the water circuit 114 at the target flow rate V_{target} will be described further on in this specification with reference to FIG. 7.

[0044] The process 500 will run repeatedly, from block 520 to block 530, in order to rapidly adjust the target water flow rate (and, consequently, the delivered water flow rate) in response to changes in the refrigerant pressures and/or the water inlet temperature. By way of example, a change in the rate of hot water draw can result in a sudden change to the temperature of water that is received into the heater unit 104 by way of port 126, due to a variation in the ratio of cold water from cold water port 146 to warmer water from recirculation supply port 106. The fast control loop (e.g., the process 500) is capable of rapidly responding to such a change by updating the target water flow rate.

[0045] FIG. 6 is a flowchart of an example process 600 for implementing a second control loop (for example, a slow control loop). In various implementations, the process 600 begins after the controller 302 first executes the fast control loop of process 500. In some examples, after the controller 302 executes the first iteration of the fast control loop, the controller 302 may execute the slow control loop in parallel with the fast control loop. For example, process 600 may begin after the controller 302 controls heater unit 104 to operate the water circuit 114 at the target flow rate V_{target} at block 530 of process 500. At block 602, the controller 302 monitors the water outlet temperature T_{w_out} (for example, by monitoring signals from the temperature sensor 138). At decision block 604, the controller 302 determines whether the water outlet temperature T_{w_out} has stabilized. For example, the controller 302 may determine that the water outlet temperature T_{w_out} has stabilized when it deviates less than a threshold value over a set period of time. In response to determining that the water outlet temperature T_{w_out} has not stabilized ("N" at decision block 604), the process 600 continues monitoring the water outlet temperature T_{w_out} at block 602. In response to determining that the water outlet temperature T_{w_out} has stabilized ("Y" at decision block 604), the controller 302 determines whether the water outlet temperature T_{w_out} is less than the set-point temperature T_{set} at decision block 606.

[0046] In response to determining that the water outlet temperature T_{w_out} is less than the set-point temperature T_{set} ("Y" at decision block 606), the controller 302 reduces the adjustment factor K at block 608. The updated adjustment factor is then used in subsequent calculations of the target flow rate V_{target} according to equation (1) above at block 528, and, in some implementations, the process 600 returns to block 602. In response to determining that the water outlet temperature T_{w_out} is not less than the set-point temperature T_{set} ("N" at decision block 606), the controller 302 determines whether the water outlet temperature T_{w_out} is greater than the set-point temperature T_{set} at decision block 612. In response to determining that the water outlet temperature T_{w_out} is greater than the set-point temperature T_{set} at decision block 612 ("Y" at decision block 612), the controller 302 increases the adjustment factor K at block 614. The updated adjustment factor is then used in subsequent calculations of the target flow rate V_{target} according to equation (1) above at block 528, and, in some implementations, the process 600 returns to block 602. In response to determining that the water outlet temperature T_{w_out} is not greater than the set-point temperature T_{set} at decision block 612 ("N" at decision block 612), the process 600 returns to block 602.

[0047] In various implementations, the controller 302 saves current values of the adjustment value K for use in subsequent heating cycles. For example, the controller 302 may save values of the adjustment value K along with corresponding high-side pressures P_{high} and low-side pressures P_{low} to a lookup table. During subsequent heating cycles, the controller 302 may initiate the adjustment value *K* (for example, during the fast control loop at blocks 516 and/or 528 of process 500) according to the adjustment value *K* in the lookup table corresponding to the estimated/measured high-side pressure P_{high} and low-side pressure P_{low} (instead of initiating *K* to a value of 1).

[0048] FIG. 7 shows a graph 700 illustrating relationships between valve positions of the flow control valve 132 and pump speeds of the pump 130 for a range of water flow rates in the water circuit 114. In various implementations, the full range of available water flow rates for the water circuit 114 may be divided into discrete sub-ranges, and the controller 302 may be programmed with a fixed valve position (for example, a percentage of a fully open position of the flow control valve 132) and a range of available pump speeds for the sub-range (for example, the low end of the range may correspond to the pump speed necessary to maintain the water flow at the low end of the sub-range and the high end of the range may correspond to the pump speed necessary to maintain the water flow at the high end of the sub-range at the fixed valve position). The controller 302 may interpolate the range of available pump speeds to determine an initial pump speed corresponding to the target flow rate V_{target}. In some embodiments, the percentage of a fully open position of the flow control valve 132 may correspond to a duration of time that the valve is driven towards a fully open or a fully closed position from an initial position. The initial position can, for example, be a hard stop position when the valve is fully closed or when the valve is fully open.

[0049] In order to maintain a target flow rate V_{target}, the controller 302 determines the sub-range that the target flow rate V_{target} falls within and operates the flow control valve 132 at the fixed valve position for the sub-range and initially operates the pump 130 at an initial pump speed. For example, a maximum flow rate and a maximum pump speed may be known for the sub-range, along with a minimum flow rate and a minimum pump speed. The initial pump speed may be linearly interpolated over the known range of minimum and maximum pump speeds for the sub-range to determine the initial pump speed corresponding to the target flow rate V_{target}. In various implementations, the flow control valve 132 may be a ball valve that can travel between a fully closed position and a fully open position. The controller 302 may control the flow control valve 132 and stop the valve at any position between the fully closed position and the fully open position (between

0% and 100% open, inclusive). After setting the flow control valve 132 to the fixed valve position for the sub-range and setting the pump 130 to the initial pump speed, the controller 302 monitors signals from the flow meter 144 to determine the actual water flow rate within the water circuit 114. Based on the actual water flow rate, the controller 302 adjusts the pump speed (for example, within the range of available pump speeds) while operating the flow control valve 132 at the fixed valve position to maintain the target flow rate V_{target}.

[0050] Graph 700 illustrates an example of discrete sub-ranges for a water circuit 114 having a maximum flow rate of 6 gallons per minute (GPM). In the example illustrated by graph 700, the discrete sub-ranges may be 0-1 GPM, 1-2 GPM, 2-3 GPM, 3-4 GPM, 4-5 GPM, and 5-6 GPM. Within each sub-range, a fixed valve position is indicated by the triangle, an initial pump speed (for example, at the mid-point of each sub-range) is indicated by the square, and a range of available pump speeds is indicated by the vertical bars. In various implementations, the initial pump speed may be pre-programmed (e.g., a single pre-programmed initial pump speed for the sub-range) or linearly interpolated between the minimum and maximum available pump speed for the sub-range based on the target flow rate V_{target}. For example, in a scenario where the controller 302 maintains a target flow rate V_{target} of about 2.75 GPM, the controller 302 sets the position of the flow control valve 132 to about 40% open, and interpolates the initial pump speed as the point between the low end of range of available pump speeds and the high end of the range of available pump speeds corresponding to the target flow rate V_{target}.

[0051] For example, in the example of FIG. 7, operation of the pump 130 at about 27% of full speed will maintain a 2 GPM flow rate and operation of the pump 130 at about 67% of the full speed will maintain a 3 GPM flow rate of the water within the water circuit 114 (at the fixed valve position of about 40%). The controller 302 may interpolate the pump speed corresponding to the 2.75 GPM target flow rate V_{target} (in this example, about a 57% initial pump speed). The controller 302 sets the flow control valve 132 to the fixed valve position of about 47%, operates the pump 130 at the initial pump speed of about 57%, monitors the actual flow rate within the water circuit 114 based on signals received from the flow meter 144, and adjusts the pump speed as necessary to maintain the target flow rate V_{target} of 2.75 GPM. For example, in response to determining that the actual flow rate is above the target flow rate V_{target}, the controller 302 reduces the pump speed while maintaining the fixed valve position. In response to determining that the actual flow rate is below the target flow rate V_{target}, the controller 302 increases the pump speed while maintaining the fixed valve position.

[0052] Water flow rate control techniques described with reference to FIG. 7 offer a variety of technical benefits over other techniques. For example, once the controller 302 sets the flow control valve 132 to the fixed valve position and the pump 130 to the initial pump speed, the controller 302 then adjusts the pump speed based on the actual flow rate of the water in the water loop as measured at the flow meter 144. Since the response signal from the water flow meter updates quickly, this allows for a quick feedback control loop for the controller 302 to rapidly manage the water flow rate in the water circuit 114 to deliver a water flow that is close to the desired temperature. The slower response loop then operates to fine-tune the delivered water temperature with smaller adjustments to the water flow rate. By contrast, techniques that regulate flow rate in the water circuit 114 solely based on the water outlet temperature T_{w_out} will be significantly slower, since the water outlet temperature T_{w_out} takes much longer to adjust to changes in the flow rate. Furthermore, by throttling the water flow in the water circuit 114 using the flow control valve 132, the pump 130 is able to operate over a wider portion of its operating range, allowing for more precise control of water flow rates (especially at lower target flow rates, where it may be otherwise difficult to precisely control the pump 130 at slow pump speeds).

[0053] 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 processes within any given method may be executed in a different order - or processes may be executed concurrently or in combination with each other - 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.

[0054] 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.

[0055] 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.

[0056] In the figures, the directions of arrows generally demonstrate the flow of information - such as data or instructions. 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.

[0057] 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. 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.

[0058] 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.

[0059] 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. An electronic controller for controlling a heat pump water heater, the electronic controller configured to:

receive a first signal from a first sensor, the first signal indicative of a first variable;
receive a second signal from a second sensor, the second signal indicative of a second variable;
determine a target flow rate based on the first variable and the second variable; and
control a water flow rate of the heat pump water heater based on the target flow rate.

2. The electronic controller of claim 1, wherein the first variable is a water inlet temperature and the second variable is an ambient temperature; optionally wherein determining the target flow rate based on the first variable and the second variable comprises:

determining a first estimated refrigerant pressure based on the first variable;
determining a second estimated refrigerant pressure based on the second variable;
determining an available heating rate based on the first estimated refrigerant pressure and the second estimated refrigerant pressure; and
determining the target flow rate based on the available heating rate and an adjustment factor.

3. The electronic controller of claim 1, wherein the first variable is a first refrigerant pressure and the second variable is a second refrigerant pressure.

4. The electronic controller of claim 3, wherein determining the target flow rate based on the first variable and the second variable comprises:

determining an available heating rate based on the first refrigerant pressure and the second refrigerant pressure; and
determining the target flow rate based on the available heating rate, a water inlet temperature, and an adjustment factor.

5. The electronic controller of claim 4, wherein the water inlet temperature is determined from the first signal or the second signal.

6. The electronic controller of claim 4, wherein the electronic controller is further configured to:

receive a third signal from a third sensor, the third signal indicative of a third variable;
update the adjustment factor based on the third variable;
determine an updated target flow rate based on the available heating rate and the updated adjustment factor; and
control the water flow rate of the heat pump water heater based on the updated target flow rate;
optionally wherein:

(i) the water inlet temperature is determined from the third signal; or
(ii) the third variable is a water outlet temperature; and
updating the adjustment factor based on the third variable comprises:

increasing the adjustment factor in response to the water outlet temperature being above a set-point temperature, and
decreasing the adjustment factor in response to the water outlet temperature being below the set-point temperature.

7. The electronic controller of claim 3, wherein: (i) the first sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from a compressor to an expansion device; or (ii) the second sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from an expansion device to a compressor.

8. The electronic controller of claim 1, wherein controlling the water flow rate of the heat pump water heater based on the target flow rate comprises:

controlling a flow control valve to operate at a fixed valve position; and
adjusting an operating speed of a water pump.

9. A method for controlling a heat pump water heater, comprising:

receiving a first signal from a first sensor, the first signal indicative of a first variable;
receiving a second signal from a second sensor, the second signal indicative of a second variable;
determining a target flow rate based on the first variable and the second variable; and
controlling a water flow rate of the heat pump water heater based on the target flow rate.

10. The method of claim 9, wherein the first variable is a water inlet temperature and the second variable is an ambient temperature; optionally wherein determining the target flow rate based on the first variable and the second variable comprises:

determining a first estimated refrigerant pressure based on the first variable;
determining a second estimated refrigerant pressure based on the second variable;
determining an available heating rate based on the first estimated refrigerant pressure and the second estimated refrigerant pressure; and
determining the target flow rate based on the available heating rate and an adjustment factor.

11. The method of claim 9, wherein the first variable is a first refrigerant pressure and the second variable is a second refrigerant pressure.

12. The method of claim 11, wherein determining the target flow rate based on the first variable and the second variable comprises:

determining an available heating rate based on the first refrigerant pressure and the second refrigerant pressure; and
determining the target flow rate based on the available heating rate, a water inlet temperature, and an adjustment factor.

13. The method of claim 12, wherein:

(i) the water inlet temperature is determined from the first signal; or
(ii) the water inlet temperature is determined from the second signal; or
(iii) the method further comprises:

receiving a third signal from a third sensor, the third signal indicative of a third variable;
updating the adjustment factor based on the third variable;
determining an updated target flow rate based on the available heating rate and the updated adjustment factor; and
controlling the water flow rate of the heat pump water heater based on the updated target flow rate;
optionally wherein:

(a) the water inlet temperature is determined from the third signal; or
(b) the third variable is a water outlet temperature; and
updating the adjustment factor based on the third variable comprises:

increasing the adjustment factor in response to the water outlet temperature being above a set-point temperature, and
decreasing the adjustment factor in response to the water outlet temperature being below the set-point temperature.

14. The method of claim 11, wherein: (i) the first sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from a compressor to an expansion device; or (ii) the second sensor is a pressure sensor positioned to measure a pressure of a refrigerant as the refrigerant flows from an expansion device to a compressor.

15. The method of claim 9, wherein controlling the water flow rate of the heat pump water heater based on the target flow rate comprises:

controlling a flow control valve to operate at a fixed valve position; and
adjusting an operating speed of a water pump.

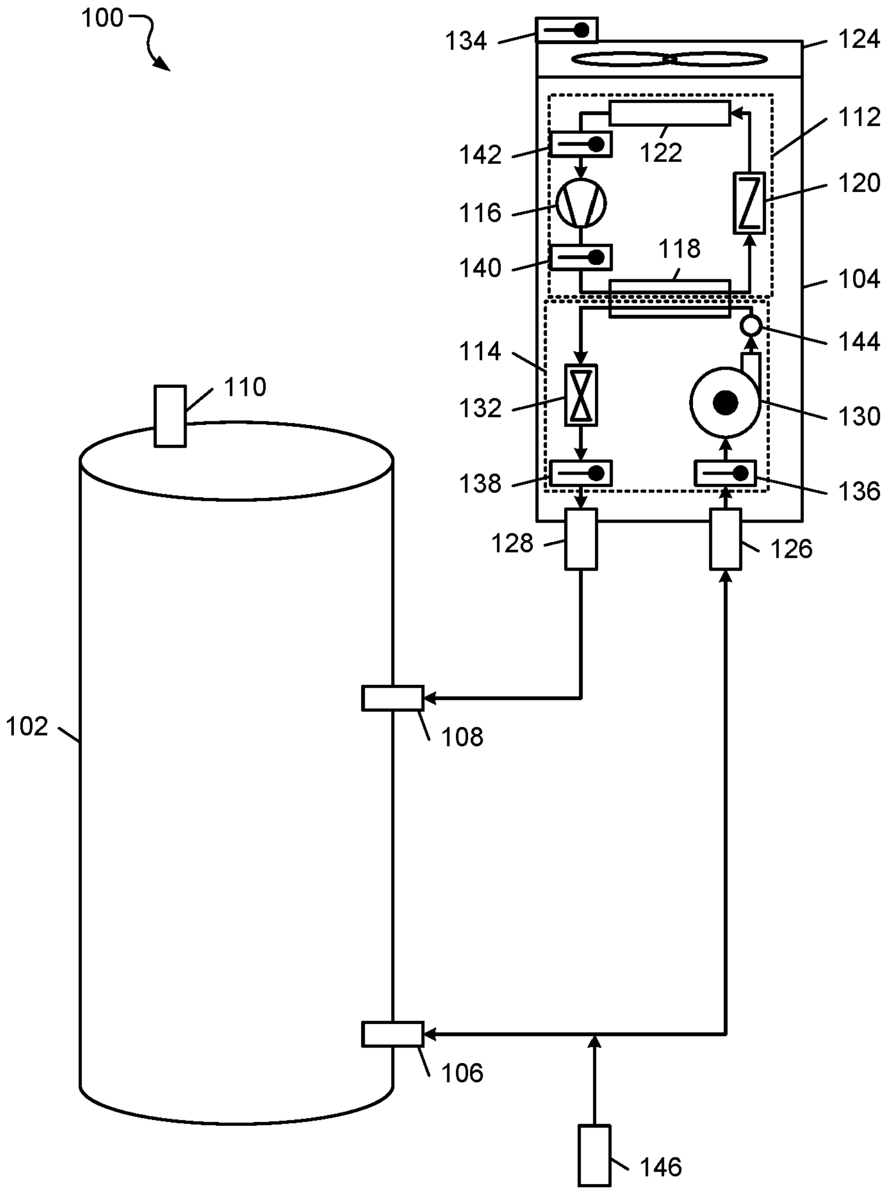
100
134
124
112
142
122
120
116
118
140
104
144
114
110
132
130
138
136
128
126
102
108
106
146

FIG. 1

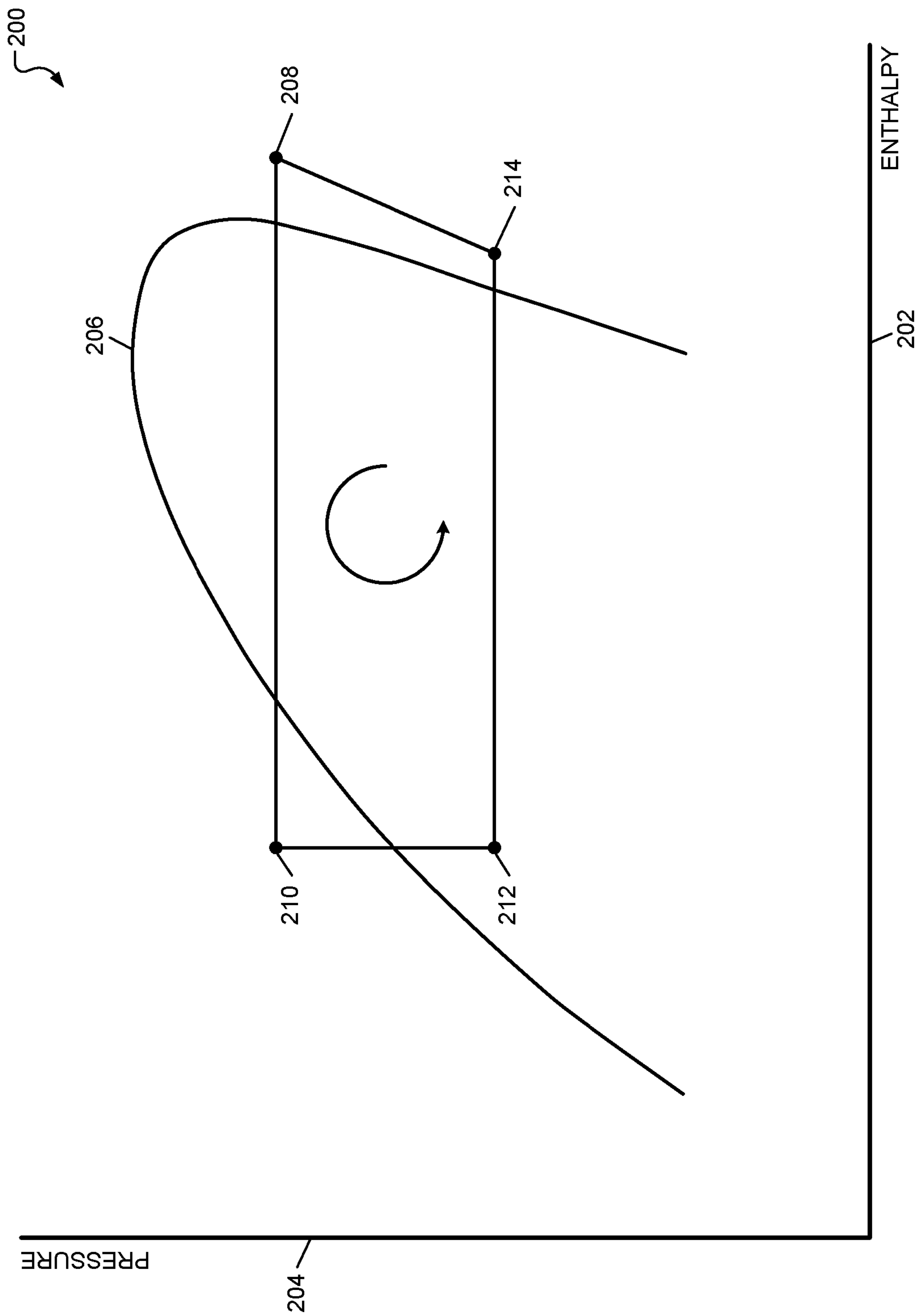

FIG. 2

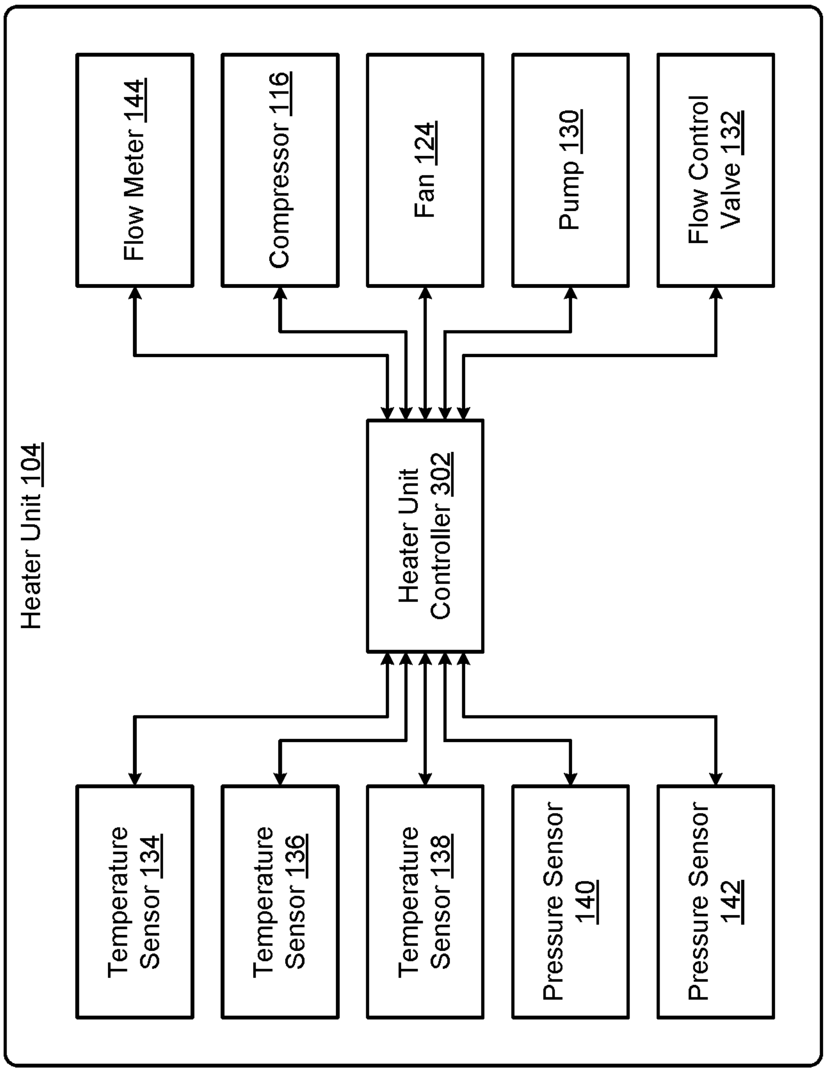
Heater Unit 104
Flow Meter 144
Compressor 116
Fan 124
Pump 130
Flow Control Valve 132
Heater Unit Controller 302
Temperature Sensor 134
Temperature Sensor 136
Temperature Sensor 138
Pressure Sensor 140
Pressure Sensor 142

FIG. 3

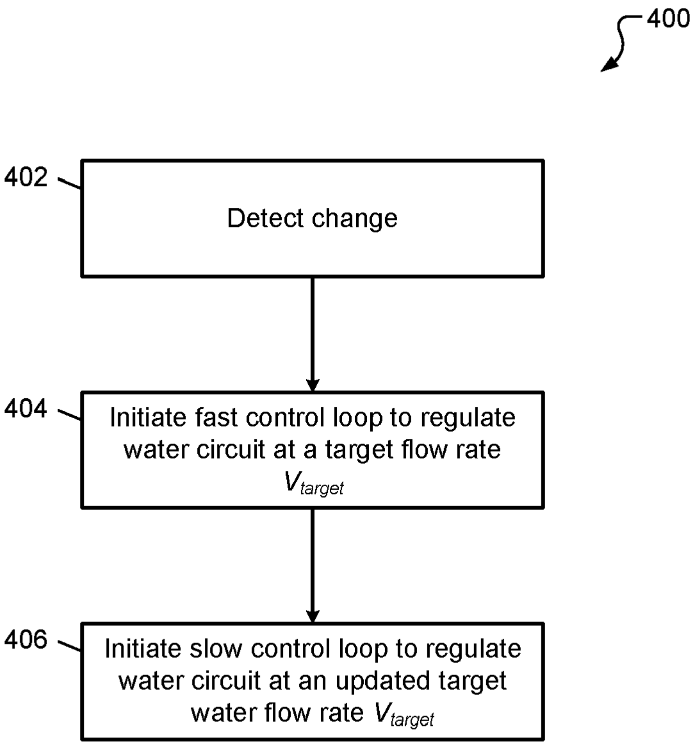
400
402
Detect change
404
Initiate fast control loop to regulate water circuit at a target flow rate V_{target}
406
Initiate slow control loop to regulate water circuit at an updated target water flow rate V_{target}

FIG. 4

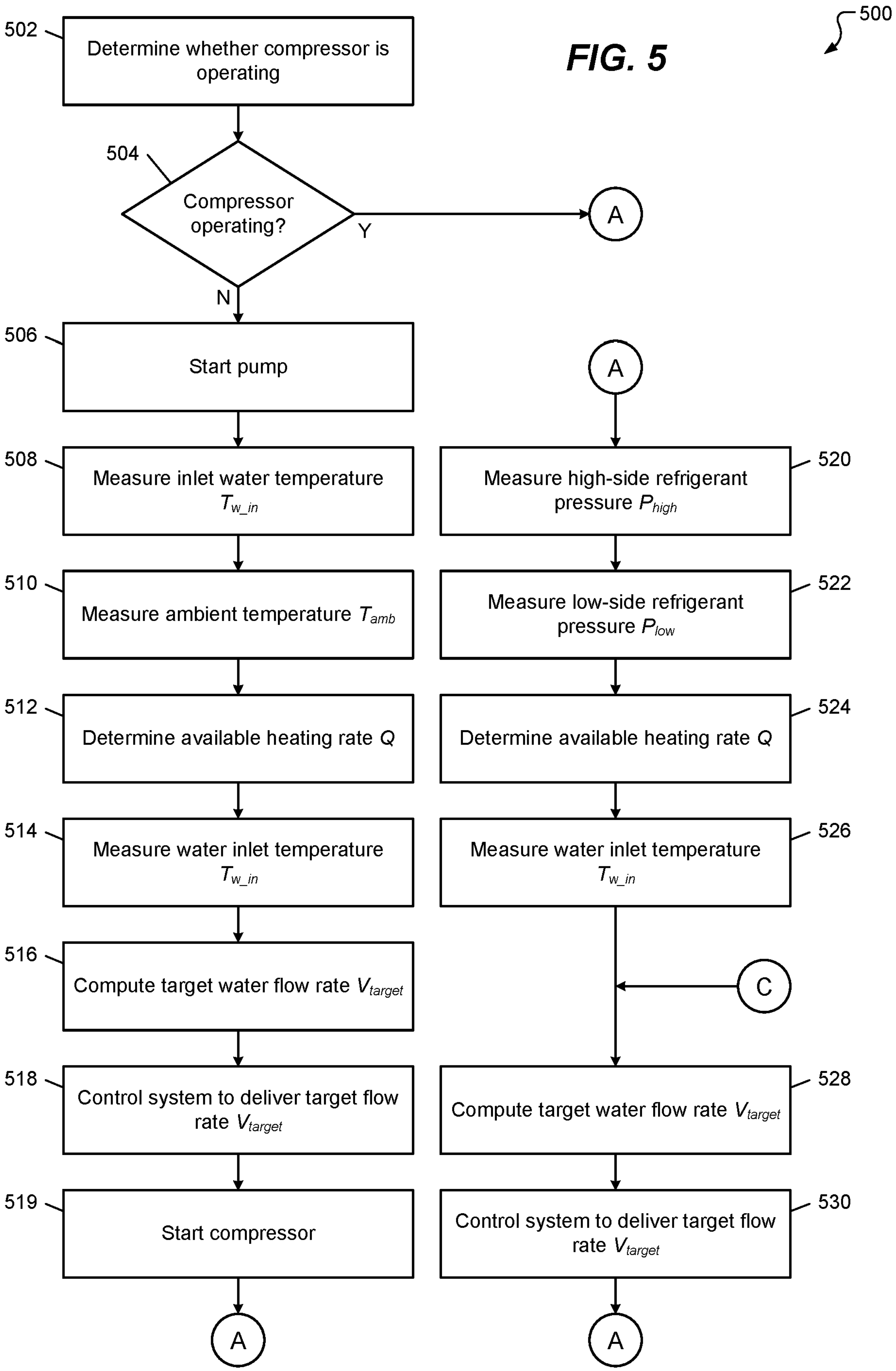
500
502
Determine whether compressor is operating
504
Compressor operating?
Y
A
N
506
Start pump
508
Measure inlet water temperature T_{w_in}
510
Measure ambient temperature T_{amb}
512
Determine available heating rate Q
514
Measure water inlet temperature T_{w_in}
516
Compute target water flow rate V_{target}
518
Control system to deliver target flow rate V_{target}
519
Start compressor
A
A
520
Measure high-side refrigerant pressure P_{high}
522
Measure low-side refrigerant pressure P_{low}
524
Determine available heating rate Q
526
Measure water inlet temperature T_{w_in}
C
528
Compute target water flow rate V_{target}
530
Control system to deliver target flow rate V_{target}
A

FIG. 5

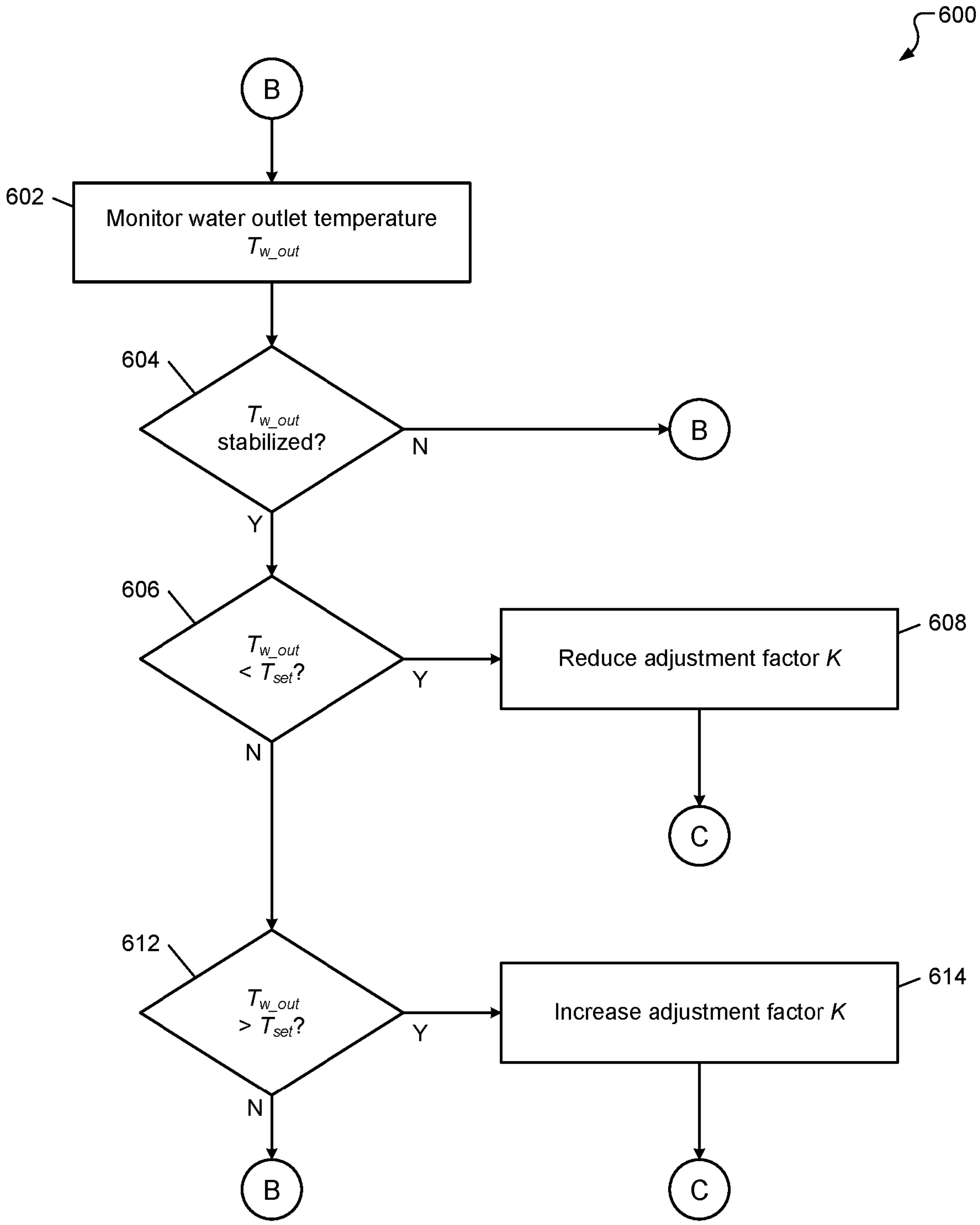
600
B
602
Monitor water outlet temperature
T_{w_out}
604
T_{w_out}
stabilized?
N
B
Y
606
T_{w_out}
< T_{set}?
Y
Reduce adjustment factor K
608
N
C
612
T_{w_out}
> T_{set}?
Y
Increase adjustment factor K
614
N
B
C

FIG. 6

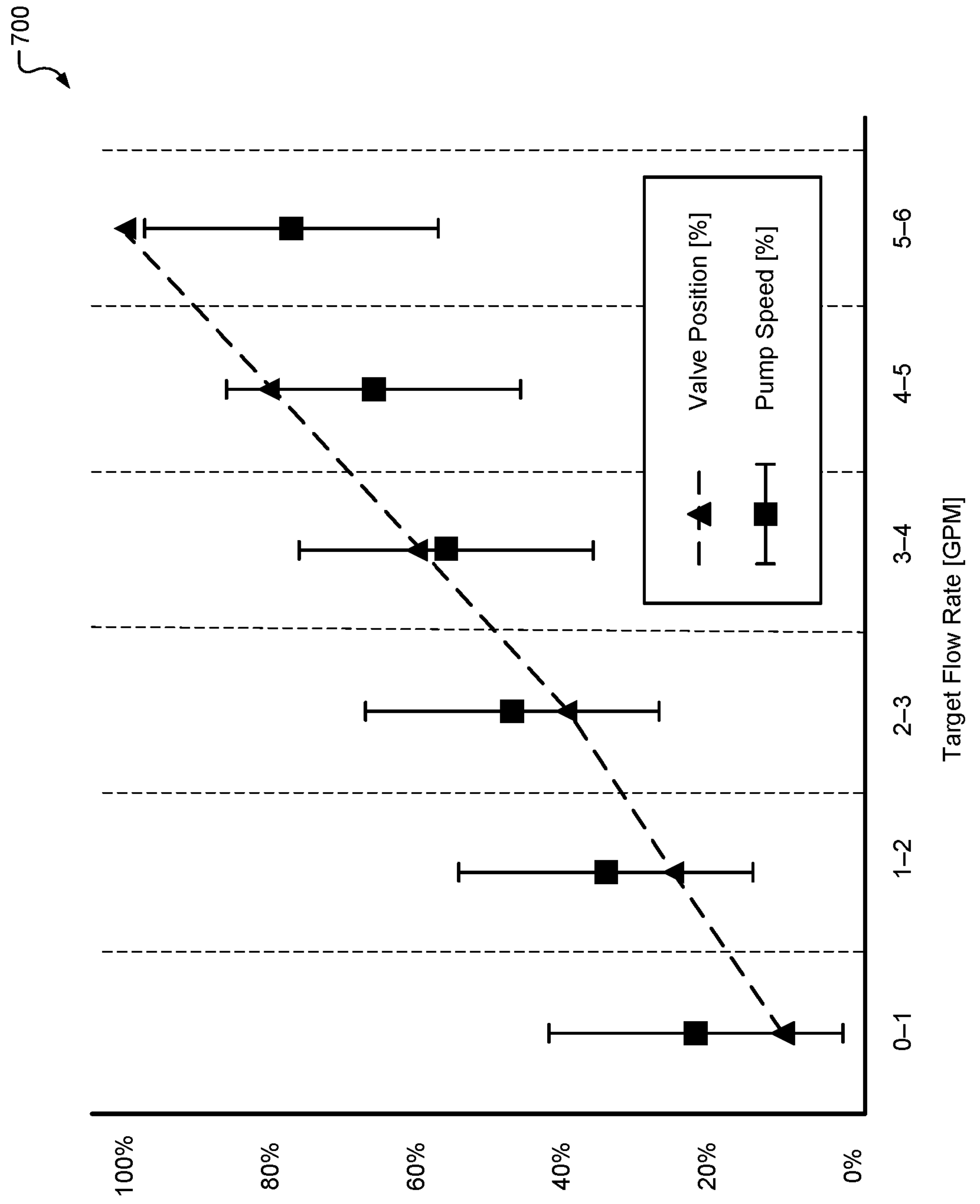
700
100%
80%
60%
40%
20%
0%
0–1
1–2
2–3
3–4
4–5
5–6
Target Flow Rate [GPM]
Valve Position [%]
Pump Speed [%]

FIG. 7

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EUROPEAN SEARCH REPORT

Application Number
EP 24 21 9962

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 2 615 384 B1 (PANASONIC IP MAN CO LTD [JP]) 12 June 2019 (2019-06-12) * paragraphs [0020] - [0039], [0042], [0045], [0049], [0062]; claims 1-9; figures 1,4 *	1,2, 8-10,15	INV. F24D19/10 F24H15/215 F24H15/219 F24H15/242 F24H15/281 F24H15/31 F25B30/02 F24H4/04 F24H15/174 F24H15/175 F24H15/238 F24H15/254 F24H15/34 F24H15/38
X	EP 3 115 699 B1 (PANASONIC IP MAN CO LTD [JP]) 1 May 2019 (2019-05-01) * paragraphs [0023], [0041], [0051] - [0056]; claim 1; figures 1-4 *	1,2,9,10	
X	EP 2 261 574 A1 (HITACHI APPLIANCES INC [JP]) 15 December 2010 (2010-12-15) * paragraphs [0002], [0003], [0008], [0015], [0023] - [0025]; claim 1; figures 1-3 *	1,2,9,10	
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The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	6 May 2025	García Moncayo, O

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
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A : technological background
O : non-written disclosure
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E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
& : member of the same patent family, corresponding document

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 24 21 9962

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06-05-2025

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JP 2007327725	A	20-12-2007	NONE			
AU 2009101129	A4	03-12-2009	NONE			
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For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

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