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(54) **ENERGY EFFICIENT DEHUMIDIFYING REFRIGERATION SYSTEM**

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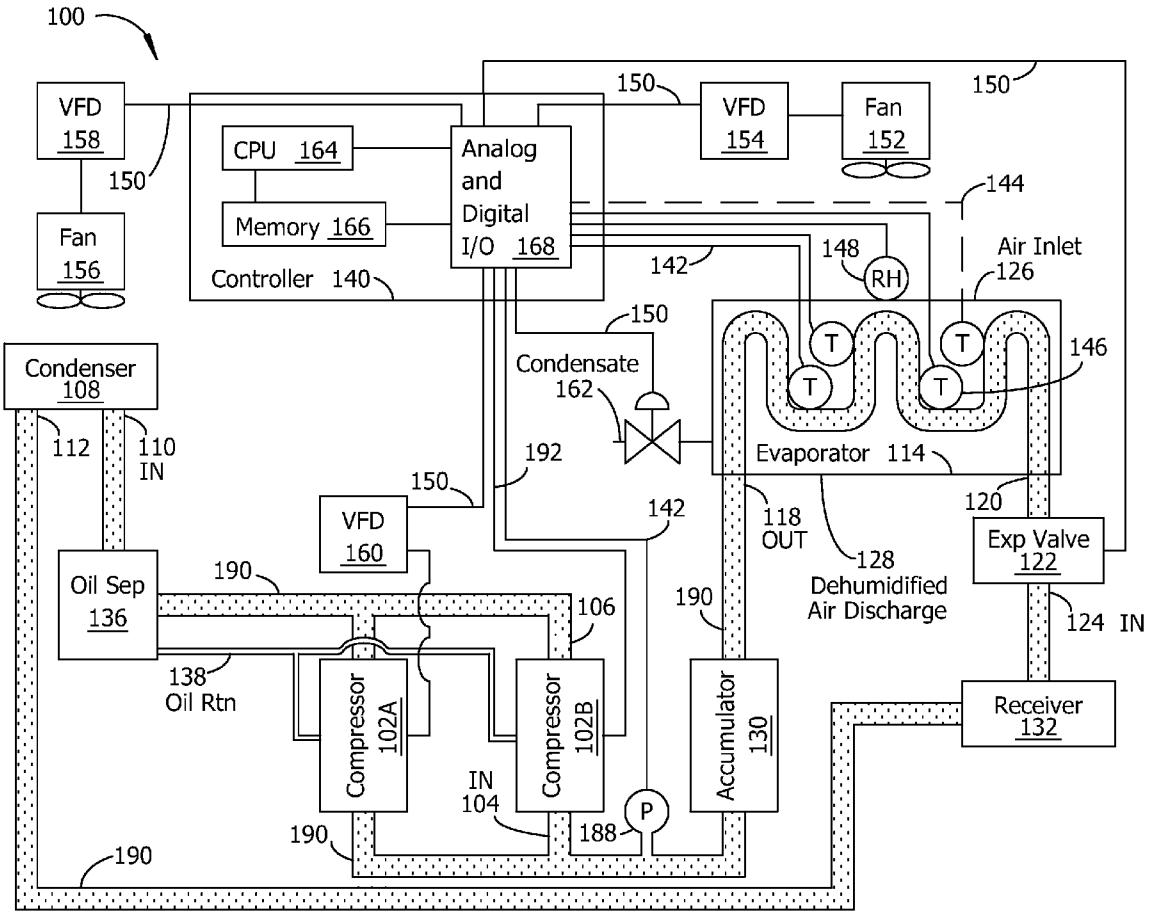
(57) **ABSTRACT**

An evaporator setpoint temperature for a refrigeration system is adjusted by an electronic control module to maximize a ratio of volume of condensate produced per unit of electricity consumed. When the control module detects a change in the relative humidity of air entering an evaporator in the refrigeration system, the module determines the new dew point for the air, compensates the dew point value by a predetermined offset value, and changes the setpoint for refrigerant temperature in the evaporator to the compensated dew point value. The control module operates the refrigeration system to drive the evaporator temperature to the compensated dew point value. Refrigeration system parameters measured and modified by the control module include operating speed of compressors, number of operating compressors, refrigerant flow through an expansion valve, compressor suction pressure, and fan speeds for the condenser and evaporator.



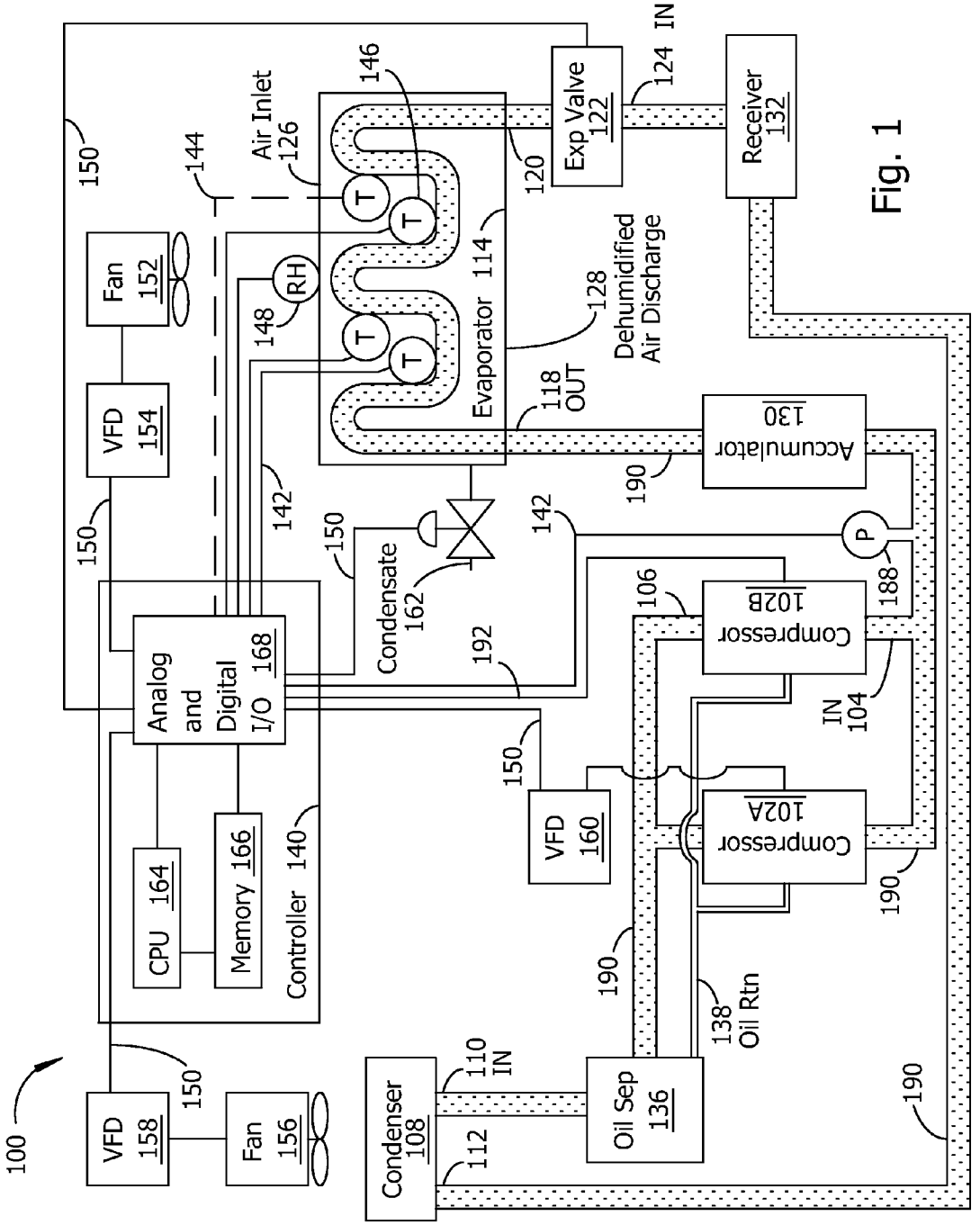

100
150
VFD 158
Fan 156
VFD 154
Fan 152
Analog and Digital I/O 168
CPU 164
Memory 166
Controller 140
Air Inlet 126
144
146
148
RH
T
Evaporator 114
128 Dehumidified Air Discharge
118 OUT
120
Exp Valve 122
124 IN
Receiver 132
Accumulator 130
190
142
Condensate 162
192
P
188
106
Compressor 102B
IN 104
Compressor 102A
VFD 160
Condenser 108
110 IN
112
Oil Sep 136
138 Oil Rtn

Fig. 1

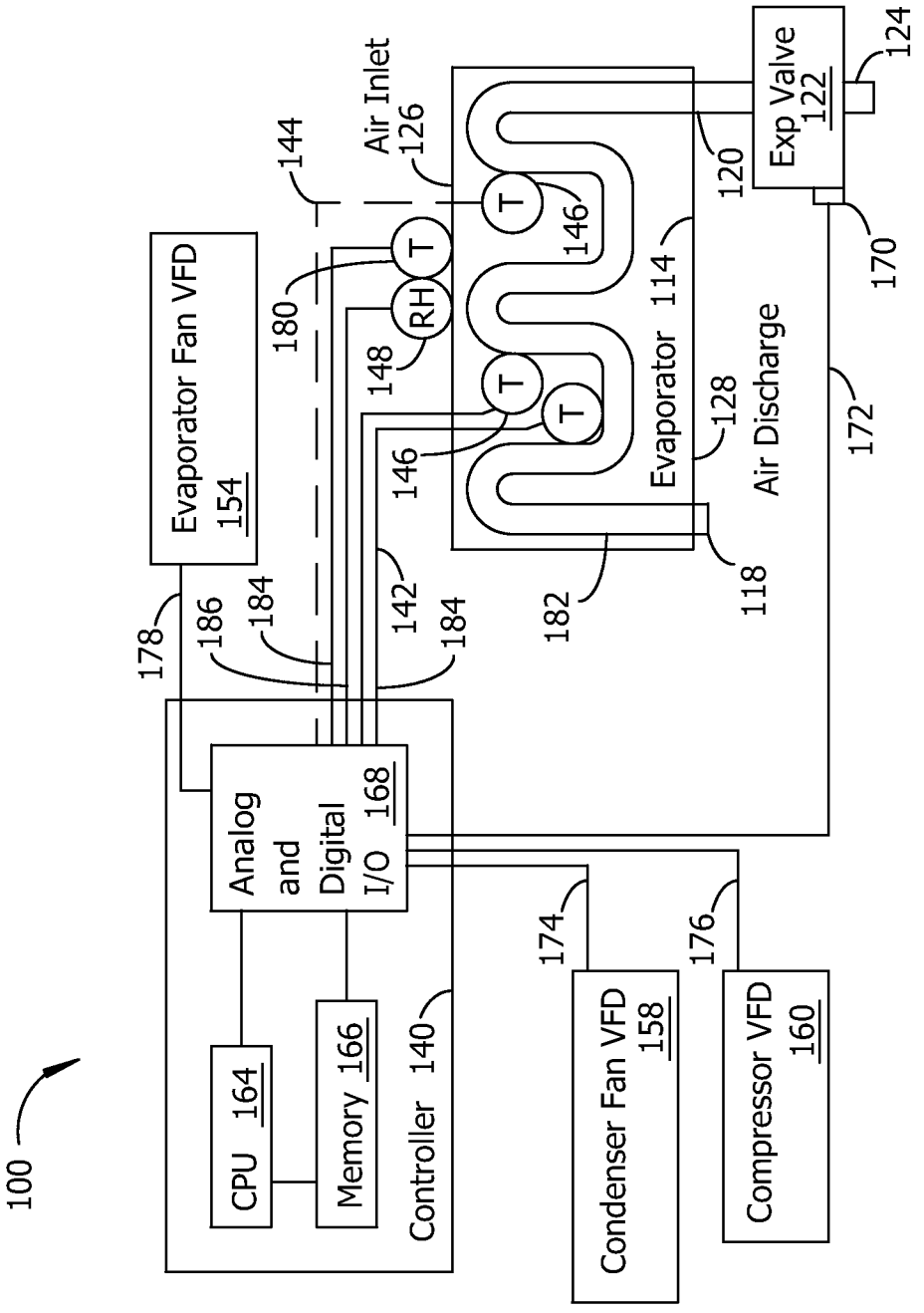

100
Controller 140
CPU 164
Memory 166
Analog and Digital I/O 168
Evaporator Fan VFD 154
Condenser Fan VFD 158
Compressor VFD 160
Exp Valve 122
Evaporator 114
Air Inlet
Air Discharge
T
RH
120
124
126
128
142
144
146
148
170
172
174
176
178
180
182
184
186
118

Fig. 2

ENERGY EFFICIENT DEHUMIDIFYING REFRIGERATION SYSTEM

FIELD OF THE INVENTION

[0001] Embodiments of the invention are related generally to refrigeration systems using closed-loop refrigeration circuits, and more specifically to refrigeration systems for condensing liquid water from water vapor in the atmosphere.

BACKGROUND

[0002] A refrigeration system using the vapor compression cycle includes an engine-driven compressor connected in series in a closed fluid circuit with a condenser, a refrigerant flow control valve, sometimes referred to as an expansion valve, and an evaporator. A working fluid is confined in the closed fluid circuit so as to prevent escape of the working fluid to the outside air. The working fluid transfers heat energy from one location to another within the closed fluid circuit, receives heat energy from an external heat source, for example air outside the refrigeration system, and transfers heat energy to an external heat sink. The working fluid, also referred to as refrigerant, enters the compressor in gaseous form, is compressed to high temperature and high pressure by the compressor, and is output from the compressor to the condenser. During its passage through the condenser, the refrigerant gives up heat energy to an external heat sink such as the outside air and condenses into a liquid at high pressure.

[0003] The liquid refrigerant flowing out of the condenser passes through an expansion valve, where a sudden pressure drop causes the refrigerant to cool and expand. The cooled, expanded refrigerant then flows into the evaporator, where the refrigerant absorbs heat energy from air flowing from the air inlet side of the evaporator to the air discharge side of the evaporator. The tubing through which the refrigerant flows in the evaporator may be fitted with fins to improve heat transfer between the refrigerant and external air. After giving up heat energy to the refrigerant, air discharged from the evaporator is at a lower temperature than the temperature of the inlet air to the evaporator. Absorbed heat energy returns the refrigerant to a gaseous state. Warmed, low pressure gaseous refrigerant flows out of the evaporator and enters the compressor's refrigerant inlet to complete the cooling cycle.

[0004] Before entering the compressor, the refrigerant may pass through a suction accumulator to convert any remaining liquid refrigerant to a gaseous state. Some refrigeration systems include a receiver connected in series between the condenser and the expansion valve. The receiver filters moisture and contaminants from the refrigerant flowing to the expansion valve.

[0005] Inlet air to the evaporator is generally drawn from the earth's atmosphere and therefore includes some water vapor. Water vapor in the inlet air condenses from a gaseous state to a liquid state when the temperature of the refrigerant in the evaporator and the exterior surface temperature of the evaporator are below the dew point temperature of the inlet air. Air discharged from the evaporator may therefore have a lower relative humidity than inlet air to the evaporator. For some refrigeration applications, for example dehumidification or atmospheric water generation, the energy efficiency of a refrigeration system may be defined as units of water condensate produced per unit of energy input to the system, for example liters of water condensed per kilowatt-hour of electrical energy used by the refrigeration system.

[0006] A refrigeration system may control the flow of refrigerant into the evaporator to achieve a specified setpoint value for the temperature of air discharged from the evaporator or, for some dehumidification systems, a specified setpoint value for the relative humidity of the air discharged from the evaporator. Such systems may therefore include a temperature sensor for measuring the temperature of the air discharged from the evaporator, a humidity sensor for measuring the relative humidity of the air discharged from the evaporator, or a sensor which measures both temperature and humidity of the air discharged from the evaporator. When the temperature of the inlet air to the evaporator is too low or the temperature of the refrigerant in the evaporator is below the freezing point of water, ice may form on exterior surfaces of the evaporator. Other problems, such as dirt or dust on the exterior of the evaporator, leakage of refrigerant from the refrigeration system's closed-loop fluid circuit, or reduced airflow over the evaporator, may also cause ice to form on the evaporator. Ice buildup may restrict airflow through the evaporator, inhibiting heat exchange between the refrigerant and the inlet air and possibly causing the compressor to run at a faster speed or for a longer time to achieve the same setpoint value of discharged air temperature or relative humidity. Ice may cause physical damage to the evaporator, possibly resulting in refrigerant leakage and causing the compressor to run faster or for a longer period of time.

[0007] Some refrigeration systems include a means for detecting and removing ice from the evaporator. For example, a temperature sensor may detect freezing temperatures in the evaporator, triggering an electric heater to melt the ice. The compressor may be turned off or operated at slow speed until the ice melts, or heat energy may be transferred from another part of the refrigeration system to the evaporator to melt the ice. These methods may increase the amount of electrical energy consumed by the refrigeration system or may for some period of time decrease the amount of water condensed by the system, thereby decreasing the energy efficiency of the refrigeration system.

SUMMARY

[0008] An example of an apparatus embodiment of the invention includes a refrigeration system with a first compressor and an evaporator connected in series in a closed fluid circuit, a humidity sensor positioned to measure a relative humidity value for inlet air to the evaporator, a first temperature sensor positioned to measure a temperature value for inlet air to the evaporator, a second temperature sensor positioned to measure a temperature value for refrigerant in the evaporator, and an electronic control module adapted to store a setpoint offset value. The electronic control module is electrically connected to the humidity sensor, the first temperature sensor, and the second temperature sensor. The electronic control module is adapted to compute a dew point temperature value from the relative humidity value and the temperature value for inlet air and to adjust an operating of speed of the first compressor until the temperature value for refrigerant is approximately equal to a compensated evaporator setpoint temperature calculated by subtracting the setpoint offset value from the dew point temperature. When the electronic control module receives a changed value of relative humidity from the humidity sensor, the electronic control module autonomously calculates a new dew point temperature and adjusts the operating speed of the first compressor until a new

temperature value for the refrigerant is approximately equal to a new compensated evaporator setpoint temperature.

[0009] Another example of an embodiment of the invention includes an electronic control module. The electronic control module includes a central processor unit with electronic semiconductor devices arranged in a digital logic circuit. The electronic control module further includes a humidity sensor signal input adapted for sending a value of relative humidity to the central processor unit and a plurality of temperature sensor inputs, each adapted for sending a value of temperature to said central processor unit. The embodiment of the invention further includes a compressor variable frequency drive (VFD) in data communication with the electronic control module, a humidity sensor for measuring a value of relative humidity of air entering an evaporator in a refrigeration system, a first temperature sensor for measuring a value of inlet air temperature, and a second temperature sensor for measuring a value of refrigerant temperature. The electronic control module is adapted to calculate a compensated evaporator setpoint value from the value of relative humidity and the value of inlet air temperature, and send a signal to the compressor VFD to increase an operating speed of a compressor until the value of refrigerant temperature is approximately equal to the compensated evaporator setpoint value.

[0010] An example of a method embodiment of the invention includes the steps of measuring a first value of relative humidity at an air inlet for an evaporator in a refrigeration system, measuring a first value of temperature at the air inlet for the evaporator, and determining a first value of dew point temperature from the first values of relative humidity and temperature at the air inlet for the evaporator. The method further includes the steps of assigning a value for setpoint offset, calculating a first compensated setpoint value by subtracting the value of setpoint offset from the first value of dew point temperature, and adjusting the flow of refrigerant in the refrigeration system until a measured value of refrigerant temperature in the evaporator is approximately equal to the first compensated setpoint value.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] FIG. **1** is a block diagram of an example of a refrigeration system in accord with the embodiments of the invention.

[0012] FIG. **2** is a block diagram of an example of an alternative embodiment of the invention.

DESCRIPTION

[0013] A refrigeration system in accord with an embodiment of the invention includes a compressor, a condenser, an electronic expansion valve, and evaporator connected in series in a closed-loop fluid circuit. An electronic control module, also referred to as a controller, measures the relative humidity and temperature of inlet air to the evaporator, calculates the dew point temperature of the inlet air, and controls the flow rate of refrigerant to maintain an average value of evaporator temperature that is at or below the dew point temperature, but not so low that ice forms on the evaporator. When the electronic control module determines that the relative humidity of the inlet air has changed, a new value of dew point temperature is calculated and the refrigeration system is operated at a new set point temperature related to the new dew point temperature. The efficiency of the refrigeration system improves as the relative humidity of the inlet air increases, in contrast to refrigeration systems previously known in the art which either maintain a same efficiency as relative humidity increases or suffer from decreased efficiency as relative humidity increases.

[0014] Embodiments of the invention are well suited to operation under conditions of atmospheric temperature or relative humidity that would cause evaporator icing or low rates of condensate production in previously known refrigeration systems. Embodiments of the invention provide a maximum amount of water condensate removed from inlet air at minimum electrical power consumption and are therefore advantageous for applications such as dehumidification or atmospheric water generation, that is, the extraction of water vapor from the atmosphere by condensation on a cold surface.

[0015] As used herein, a closed-loop refrigeration system operates on a vapor compression cycle using a working fluid confined to a closed-loop fluid circuit, i.e., the working fluid is confined to and flows within the fluid circuit without escaping from the fluid circuit. The working fluid, also referred to as refrigerant, undergoes temperature changes and phase changes as it flows all the way around the closed-loop fluid circuit in the refrigeration system.

[0016] An example of a refrigeration system in accord with an embodiment of the invention is shown as a block diagram in FIG. **1**. The example of an embodiment of the invention **100** in FIG. **1** represents a closed-loop refrigeration system with a refrigerant **190** flowing in a closed-loop fluid circuit comprising tubing or piping between a compressor **102**A connected in series with a condenser **108**, a refrigerant flow limiting device shown as an expansion valve **122**, and an evaporator **114**. Examples of an expansion valve include, but are not limited to, an electronic expansion valve, a thermal expansion valve, a capillary tube, and a manually operated expansion valve. An electronic expansion valve **122** includes an electrical interface circuit for receiving an electrical signal corresponding to a position of a valve member that restricts refrigerant flow through the valve and an actuator for moving the valve member, thereby enabling adjustment of refrigerant flow rate in response to the received electrical signal. For embodiments of the invention having a refrigerant flow limiting device which is not able to change a rate of refrigerant flow in response to a command from the controller **140**, the controller **140** may alternatively control a rate of refrigerant flow into the evaporator **114** by sensing compressor suction pressure with a pressure sensor **188** and control compressor speed in response to changes in suction pressure to achieve a selected setpoint value of evaporator refrigerant temperature.

[0017] An oil separator **136** may optionally be connected in series between the refrigerant outlet **106** of the compressor and the refrigerant inlet **110** of the condenser **108**. An oil return line **138** provides a fluid path for oil between the oil separator **136** and compressor **102**A. A receiver **132** may optionally be connected in series between the refrigerant outlet **112** of the condenser **108** and the refrigerant inlet **124** of the expansion valve **122**. The low pressure side of the expansion valve **122** is connected in series with the refrigerant inlet **120** on the evaporator **114**. An accumulator **130** may optionally be connected in series between the evaporator refrigerant outlet **118** and the compressor refrigerant inlet **104**. Embodiments of the invention may optionally include more than one compressor, represented by two compressors (**102**A, **102**B) in a parallel fluid circuit between the evaporator **114** and condenser **108**. An embodiment of the invention optionally includes more than two compressors. A pressure

sensor **188** measures a value of suction pressure at the refrigerant inlet to the compressors. An embodiment of the invention optionally includes more than one evaporator and more than one expansion valve connected in a parallel fluid circuit with the evaporator **114** and expansion valve **122** shown in FIG. **1**.

[0018] The refrigeration system **100** is operated to maximize efficiency, where efficiency of the refrigeration system **100** is defined as the ratio of the number of liters of water condensate produced to the number of kilowatt-hours of electrical energy consumed by the entire system **100**. An electronic control module, represented in FIG. **1** by controller **140**, measures parameters related to atmospheric conditions and system performance and controls the speeds of compressors and fans and refrigerant flow through the expansion valve to maximize the volume of water condensate produced per unit of electrical energy. As shown in the example of FIG. **1**, the controller **140** exchanges control commands and status data with a variable-frequency drive (VFD) **160** over an electrical connection **150** to vary an operating speed of the compressor **102**A, corresponding to an amount of pressure change in the refrigerant **190** produced by the compressor. For example, the controller **140** may command the VFD to increase compressor speed when the measured temperature of refrigerant in the evaporator is above a desired setpoint value, or to reduce compressor speed when refrigerant temperature is close to the freezing point of water. Another VFD with a separate electrical connection **150** to the controller **140** may be provided for each additional compressor, as shown by a second VFD **160** electrically connected to the controller **140** and to the second compressor **102**B. Each time another compressor is turned on to increase refrigerant pressure or flow rate, the controller may optionally start the newly added compressor at a slow running speed, increasing the speed gradually until the setpoint value of evaporator fin temperature is achieved. The controller may optionally reduce the speed of one compressor while ramping up speed of another compressor. Electrical connections **150** may be implanted as separate conductors or may alternatively be aggregated into a bus structure for implementing exchange of data and commands as digital logic signals.

[0019] A compressor may optionally be controlled from the controller **140** without an intervening VFD. For example, compressor **102**B is electrically connected to the controller **140** by an electrical signal connection **192**, which may be implemented as either a wired or wireless signal connection. In some embodiments of the invention, the controller adjusts an amount of refrigeration by turning one or more compressors on and off as required to achieve a selected evaporator refrigerant temperature. Any of the fans in FIG. **1** may optionally be operated without an intervening VFD, for example by the controller **140** turning a fan on and off to achieve airflow control. Eliminating one or more of the VFDs may save equipment cost, reduce power consumption, increase reliability, or decrease maintenance expense, and may be advantageous in embodiments of the invention **100** designed for low rates of condensate production.

[0020] The example of a controller **140** in FIG. **1** comprises hardware including a central processing unit CPU **164**, a computer-accessible memory **166** in data communication with the CPU **164**, and analog and digital input and output (I/O) circuits **168** in data communication with the CPU **164** and optionally with the memory **166**. Examples of analog and digital I/O circuits include, but are not limited to, sensor excitation or power supply circuits, an analog to digital converter, a digital to analog converter, a relay driver, a radio frequency transceiver for sending and receiving signals representative of data and commands, and a bidirectional computer communications port. The memory **166** comprises semiconductor memory devices and optionally comprises one or more of dynamic memory, a nonvolatile memory, for example flash memory, a removable solid state memory device, and rotating data storage media. The CPU **164** comprises semiconductor hardware devices arranged in a digital logic circuit and may optionally be implemented as one or more of, for example but not limited to, a microprocessor, a microcontroller, a gate array, and an application-specific integrated circuit.

[0021] The controller **140** controls the operating speed of a condenser fan **156** directing airflow through the condenser **108** by exchanging commands and status data with a condenser VFD **158** over an electrical connection **150**. An evaporator VFD **154** sets the operating speed of an evaporator fan **152** in response to commands received over an electrical connection **150** to the controller **140**. In the example of FIG. **1**, the evaporator fan **152** is positioned to push air into the air inlet **126** of the evaporator **114** and out the air discharge side **128**. The evaporator fan may alternatively be positioned near the air discharge side **128**, pulling air through the evaporator from the inlet side to the outlet side.

[0022] The controller **140** sets an amount of refrigerant **190** flowing into the evaporator **114** by exchanging command and status data with the expansion valve **122** over an electrical connection **150**. The evaporator **114** may optionally be equipped with a condensed water output valve **162**. The condensate output valve **162** may optionally be actuated in response to command signals over an electrical connection **150** to the controller **140**.

[0023] Some embodiments of the invention control evaporator temperature in response to changes in the dew point temperature of incoming air. A temperature sensor **146** attached to an evaporator fin or alternately to an evaporator tube, and in good thermal contact with the refrigerant flowing through the evaporator **114**, is electrically connected to a sensor input on the controller **140**. Examples of a temperature sensor **146** suitable for use in an embodiment of the invention **100** include, but are not limited to, a thermocouple, an RTD, a thermistor, and a noncontact temperature measuring device such as an infrared detector. Preferably, several temperature sensors are placed at different positions on the evaporator coils or fins to read temperatures at different locations along the refrigerant flow path. For example, at least one temperature sensor **146** may be located near the evaporator refrigerator inlet **120**, another near the evaporator refrigerant outlet **118**, another near the air inlet **126** of the evaporator, and another near the air discharge **128** of the evaporator. Preferably, at least one temperature sensor is positioned near the point in the evaporator's fluid circuit expected to have the lowest refrigerant temperature during operation of the refrigeration system **100**. Electrical signals representative of temperature may be sent to the controller **140** over wired connections **142** or by wireless data communication means **144**. Temperature sensors may alternatively be connected individually to the controller or electrically connected to one another and then connected as a group to the controller **140**.

[0024] A humidity sensor **148** positioned near or in the air inlet **126** of the evaporator **114** measures the relative humidity of air entering the evaporator, before the air has come into

contact with evaporator coils or fins and before the water content of the air has been reduced by operation of the refrigeration system **100**. The humidity sensor transmits an electrical signal representative of relative humidity over a wired connection to the controller **140**, or alternatively uses a wireless communication method such as radio frequency communication. The humidity sensor **148** may optionally be a combined sensor for measuring both the humidity and the temperature of the air entering the evaporator. The controller **140** determines a dew point temperature for the inlet air from the measured values of inlet air temperature and inlet air relative humidity. The controller also determines an average value of evaporator temperature by calculating the arithmetic mean of the outputs of the temperature sensors **146**.

[0025] Positioning the humidity sensor **148** on the inlet side of the evaporator is an important aspect of operating the refrigeration system **100** at maximum efficiency and differs from other refrigeration systems which control refrigerant flow in response to changes in temperature or relative humidity measured on the air discharge side of the evaporator. By positioning the humidity sensor on the air inlet side of the evaporator, embodiments of the invention are able to reduce power consumption when humidity increases. Consider an example in which a refrigeration system **100** in accord with an embodiment of the invention initially receives inlet air at a temperature of 100° F. (38° C.) and 30% relative humidity. At 100° F. and 30% relative humidity, the dew point temperature for the inlet air is approximately 63° F. (17° C.). The controller **140** may optionally calculate the dew point temperature from a suitable mathematical model or may interpolate a value from a look-up table in the controller's memory. A setpoint value for average evaporator temperature may optionally be chosen to be lower than the dew point temperature by a predetermined setpoint offset, for example an offset magnitude of 5° F., corresponding to an offset magnitude of 2.8° C. Applying a setpoint offset may improve efficiency by making sure that the entire heat exchanger in the evaporator is operating to condense water, that is, no part of the evaporator is below the freezing point of water or above the dew point of the inlet air.

[0026] After accounting for the selected magnitude of setpoint offset, the compensated temperature setpoint for the refrigeration system **100** is (63−5)° F.=58° F. (14° C.). Refrigerant flow may be adjusted by, for example but not limited to, controlling the speed of the compressor **102**, controlling the number of active compressors (**102**A, **102**B), controlling refrigerant flow through the expansion valve **122**, controlling the speed of one or more of the fans (**152**, **156**), controlling the on/off status of the compressor, controlling suction pressure as measured by the pressure sensor **188**, or a combination of these adjustments, until the average value of evaporator temperature is stable at the compensated setpoint temperature 58° F. With the refrigeration system operating at a stable compensated setpoint temperature of 58° F. determined from the dew point temperature of the inlet air, output of condensed water is maximized at minimum power consumption. The electrical power consumed by the refrigeration system is the quantity required to deliver (100−58)=42° F. of refrigeration, or (38−14)=24° C. of refrigeration, the calculated values corresponding to inlet air temperature minus compensated evaporator setpoint temperature.

[0027] Continuing the example, the refrigeration system **100** is next subjected to a change in the relative humidity of the inlet air to the evaporator. Suppose the measured relative humidity of the inlet air changes from 30% to 85%, still at 100° F. (38° C.). At 100° F. and 85% relative humidity, the dew point temperature for the inlet air is 95° F. (35° C.). After determining the new dew point temperature, the controller **140** in the refrigeration system **100** automatically sets the new compensated evaporator setpoint to (95−5)=90° F. (32° C.) and operates the refrigeration system to deliver only (100−90)=10° F. of refrigeration, compared to 42° F. of refrigeration at 30% relative humidity. At the new, higher value of relative humidity, the refrigeration system **100** operates at ($^{10}/_{42}$) or about 24% of the electrical power consumed at the previous, lower value of relative humidity.

[0028] Compare this result to a prior art refrigeration system which does not control evaporator temperature in response to changes in the relative humidity of the inlet air. Using the same initial conditions and calculations as above, the prior art system may deliver 42° F. of refrigeration for inlet air at 100° F. (38° C.) and 30% relative humidity. However, when the relative humidity of the inlet air changes to 85%, the prior art refrigeration system does not alter the setpoint for evaporator temperature and continues to draw sufficient power to provide 42° F. of refrigeration, nearly four times the amount of electrical power required to operate an embodiment of the invention under the same conditions. Furthermore, by chilling the refrigerant to a much lower temperature than necessary, the inlet air temperature at which ice begins to form on the evaporator in the prior art system is higher than for an embodiment of the invention, leading to additional inefficiency from impaired heat exchange between refrigerant in the evaporator and the air flowing through the evaporator when evaporator icing occurs.

[0029] In the preceding example, the temperature of the inlet air was held constant while the relative humidity was varied. Under more usual environmental conditions, the temperature and humidity of the inlet air to the evaporator both change with time, for example because of diurnal and seasonal temperature and humidity changes, transient weather events, moving the apparatus from one location to another, and so on. Embodiments of the invention are capable of detecting changes in inlet air parameters and autonomously selecting and implementing a new value of compensated evaporator setpoint temperature to operate the refrigeration system at maximum efficiency for collection of condensate. Neither human intervention, for example to manually adjust a temperature setpoint or enter humidity data, nor communication with an external control system, for example another computer system or instrument, are required for an embodiment of the invention to operate autonomously at maximum efficiency. An electronic control module **140** with modest computational resources, for example a module using a low power consumption microcontroller, is sufficient for measuring temperatures from multiple temperature sensors **146**, calculating a mean value of evaporator temperature, calculating a compensated setpoint value from offset and mean temperature values, and sending control commands to fans, compressors, and expansion valves to operate the refrigeration system at the compensated evaporator setpoint temperature.

[0030] An alternative embodiment of the invention comprises an apparatus for controlling evaporator temperature by responding to changes in the relative humidity of inlet air to the evaporator. Referring to FIG. **2**, the alternative embodiment of the invention **100** comprises an electronic control module **140**, also referred to as a controller **140**, an optional compressor VFD **160** electrically connected to a compressor

control output **176** of the controller **140**, an optional condenser fan VFD **158** electrically connected to a condenser fan control output **174** of the controller **140**, and an optional evaporator fan VFD **154** electrically connector to a condenser evaporator fan control output **178** of the controller **140**. An expansion valve control output **172** from the controller **140** is electrically connected to a valve position control input **170** on an optional electronic expansion valve **122**. Refrigerant flow through the expansion valve **122**, related to refrigerant temperature entering the evaporator **114**, is adjusted by a control signal sent from the expansion valve control output **172** to the valve position control input **170**. A control signal, for example a pulsewidth-modulated signal, sent from the condenser fan control output **174** to the condenser fan VFD **158** controls a fan speed of a fan driven from the condenser fan VFD. Another control signal, sent from the compressor control output **176**, controls an operating speed of a compressor driven from the compressor VFD **160**. A control signal sent from the evaporator fan control output **178** controls a speed of a fan driven from the evaporator fan VFD **154**.

[0031] Continuing with the example of FIG. **2**, a humidity sensor RH **148**, to be positioned in or near the air inlet **126** of an evaporator **114** is electrically connected to a humidity sensor input **186** of the controller **140**. An inlet air temperature sensor **180** is also to be positioned in or near the air inlet **126** and is connected to one of a plurality of temperature sensor inputs **184** on the controller **140**. The humidity sensor **148** and inlet air temperature sensor **180** are provided to measure the condition of inlet air before the air contacts the heat exchanger **182** in the evaporator **114**, which may be, for example but not limited to, a fin-and-tube heat exchanger or a heat exchanger without fins. The inlet air temperature sensor **180** and humidity sensor **148** may optionally be combined into one sensor housing to be located at the air inlet side of the evaporator **114**.

[0032] Another embodiment of the invention comprising steps in a method for maximizing the efficiency of a refrigeration system. The following example of the method includes the steps of:

[0033] measuring a first value of relative humidity at an air inlet for an evaporator in a refrigeration system;

[0034] measuring a first value of temperature at the air inlet for the evaporator;

[0035] determining a first value of dew point temperature from the first values of relative humidity and temperature at the air inlet for the evaporator;

[0036] assigning a value for setpoint offset;

[0037] calculating a first compensated setpoint value by subtracting the value of setpoint offset from the first value of dew point temperature; and

[0038] adjusting the flow of refrigerant in the refrigeration system until a measured value of refrigerant temperature in the evaporator is approximately equal to the first compensated setpoint value.

[0039] The method embodiment of the invention optionally further comprises the steps of:

[0040] measuring a plurality of temperature values in the evaporator, wherein each of said plurality of temperature values in the evaporator is approximately equal to a value of refrigerant temperature at a different location in the evaporator;

[0041] calculating an average value of evaporator temperature as the arithmetic mean of the plurality of temperature values; and

[0042] adjusting the flow rate of refrigerant in the refrigeration system until the average value of evaporator temperature is approximately equal to the first compensated setpoint value.

[0043] A value for setpoint offset may optionally be calculated to be equal to a magnitude of difference in temperature between refrigerant flowing into the evaporator and refrigerant flowing out of the evaporator.

[0044] Embodiments of the invention respond autonomously and efficiently to changes in inlet air conditions. The method embodiment of the invention optionally further comprises the steps of:

[0045] measuring a second value of relative humidity at the air inlet for the evaporator; and

[0046] comparing the first value of relative humidity to the second value of relative humidity and, when the magnitude of difference between the first and second values of relative humidity is greater than a selected magnitude of humidity change:

[0047] determining a second value of dew point temperature from the second value of relative humidity;

[0048] calculating a second compensated setpoint value by subtracting the value of setpoint offset from the second value of dew point temperature; and

[0049] adjusting the flow of refrigerant in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the second compensated setpoint value.

[0050] The previous steps represent an example of how an embodiment of the invention responds to a change in the relative humidity of the inlet air to the evaporator. Embodiments of the invention also respond autonomously to dew point changes implied from changes in the temperature of the inlet air to the evaporator by implementing the following optional steps:

[0051] measuring a second value of temperature at the air inlet for the evaporator;

[0052] comparing the first value of temperature at the air inlet to the second value of temperature at the air inlet, and when the magnitude of difference between the first and second values of temperature at the air inlet is greater than a selected magnitude of temperature change:

[0053] determining a second value of dew point temperature from the second value of temperature at the air inlet;

[0054] calculating a second compensated setpoint value by subtracting the value of setpoint offset from the second value of dew point temperature; and

[0055] adjusting the flow of refrigerant in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the second compensated setpoint value.

[0056] Embodiments of the invention may optionally increase the flow rate of refrigerant through an expansion valve when the measured value of refrigerant temperature in the evaporator is greater than the first compensated setpoint value. In addition to, or alternately instead of, changing refrigerant flow through the evaporator, a method embodiment of the invention may include the step of adjusting the operating speed of a first compressor in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the first compensated setpoint value.

[0057] The method optionally further comprises the step of comparing the operating speed of the first compressor to a

maximum operating speed, and when magnitude of difference between the maximum operating speed and the operating speed is greater than a selected safety factor, starting a second compressor in a parallel fluid circuit with the first compressor.

[0058] The method optionally further comprises the step of reducing the operating speed of the compressor when the measured value of refrigerant temperature in the evaporator is within a selected magnitude of temperature difference from 32° F. (0° C.).

[0059] The method optionally includes the step of reducing evaporator fan speed to increase a duration of time for inlet air to remain in contact with the heat exchanger in the evaporator, and reducing the operating speed of the compressor when fan speed is reduced to maintain a constant value for system efficiency.

[0060] When the relative humidity of the inlet air changes, an embodiment of the invention may adjust the flow of refrigerant to maintain a constant value for a rate of condensate collection, where a rate of condensate production may be expressed as a volume of liquid water collected per unit of time, e.g., liters/hour. Alternatively, when the relative humidity of the inlet air changes, an embodiment of the invention may adjust the flow of refrigerant to maintain a constant value for electrical power consumption, but at a new value for a rate of condensate production. Similarly, when the temperature of the inlet air changes, the flow of refrigerant may be adjusted to maintain a constant value for a rate of condensate collection, or the flow of refrigerant may be adjusted to maintain a constant value for electrical power consumption at a new rate of condensate production.

[0061] Unless expressly stated otherwise herein, ordinary terms have their corresponding ordinary meanings within the respective contexts of their presentations, and ordinary terms of art have their corresponding regular meanings.

What is claimed is:

1. An apparatus, comprising:

a refrigeration system comprising a first compressor and an evaporator connected in series in a closed fluid circuit;

a humidity sensor positioned to measure a relative humidity value for inlet air to said evaporator;

a first temperature sensor positioned to measure a temperature value for inlet air to said evaporator;

a second temperature sensor positioned to measure a temperature value for refrigerant in said evaporator; and

an electronic control module adapted to store a setpoint offset value, said electronic control module electrically connected to said humidity sensor, said first temperature sensor, and said second temperature sensor, said electronic control module adapted to compute a dew point temperature value from said relative humidity value and said temperature value for inlet air, said electronic control module adapted to adjust an operating of speed of said first compressor until said temperature value for refrigerant is approximately equal to a compensated evaporator setpoint temperature calculate by subtracting said setpoint offset value from said dew point temperature, and when said electronic control module receives a changed value of relative humidity from said humidity sensor, said electronic control module autonomously calculates a new dew point temperature and adjusts said operating speed of said first compressor until a new temperature value for said refrigerant is approximately equal to a new compensated evaporator setpoint temperature.

2. The apparatus of claim **1**, further comprising an electronic expansion valve connected to said closed fluid circuit in series between said first compressor and said evaporator, wherein said electronic control module further comprises an expansion valve control output electrically connected to said electronic expansion valve; and said electronic control module is adapted to adjust said electronic expansion valve and said operating speed of said first compressor until said new temperature value for said refrigerant is approximately equal to said new compensated evaporator setpoint temperature.

3. The apparatus of claim **1**, further comprising a plurality of temperature sensors thermally coupled to said evaporator at different positions in said evaporator, wherein said electronic control module is adapted to calculate an average evaporator temperature value equal to the arithmetic mean of the temperature measured by each of said plurality of temperature sensors.

4. The apparatus of claim **3**, wherein said electronic control module is adapted to adjust said operating of speed of said first compressor until said average evaporator temperature value is approximately equal to said compensated evaporator setpoint temperature.

5. The apparatus of claim **1**, further comprising a second compressor connected to said closed fluid circuit in parallel with said first compressor, wherein said electronic control module adjusts said operating speed of said first compressor and an operating speed of said second compressor until said temperature value for refrigerant is approximately equal to said compensated evaporator setpoint temperature.

6. An apparatus, comprising:

an electronic control module comprising:

a central processor unit comprising electronic semiconductor devices arranged in a digital logic circuit;

a humidity sensor signal input adapted for sending a value of relative humidity to said central processor unit; and

a plurality of temperature sensor inputs, each adapted for sending a value of temperature to said central processor unit;

a compressor variable frequency drive (VFD) in data communication with said electronic control module;

a humidity sensor for measuring a value of relative humidity of air entering an evaporator in a refrigeration system;

a first temperature sensor for measuring a value of inlet air temperature; and

a second temperature sensor for measuring a value of refrigerant temperature, said electronic control module adapted to calculate a compensated evaporator setpoint value from said value of relative humidity and said value of inlet air temperature and send a signal to said compressor VFD to increase an operating speed of a compressor until said value of refrigerant temperature is approximately equal to said compensated evaporator setpoint value.

7. The apparatus of claim **6**, further comprising an expansion valve control output in data communication with said electronic control module.

8. The apparatus of claim **6**, further comprising a condenser fan VFD in data communication with said electronic control module.

9. The apparatus of claim **6**, further comprising an evaporator fan VFD in data communication with said electronic control module.

10. A method, comprising the steps of:

measuring a first value of relative humidity at an air inlet for an evaporator in a refrigeration system;

measuring a first value of temperature at the air inlet for the evaporator;

determining a first value of dew point temperature from the first values of relative humidity and temperature at the air inlet for the evaporator;

assigning a value for setpoint offset;

calculating a first compensated setpoint value by subtracting the value of setpoint offset from the first value of dew point temperature; and

adjusting the flow of refrigerant in the refrigeration system until a measured value of refrigerant temperature in the evaporator is approximately equal to the first compensated setpoint value.

11. The method of claim **10**, further comprising the steps of:

measuring a plurality of temperature values in the evaporator, wherein each of said plurality of temperature values in the evaporator is approximately equal to a value of refrigerant temperature at a different location in the evaporator;

calculating an average value of evaporator temperature as the arithmetic mean of the plurality of temperature values; and

adjusting the flow rate of refrigerant in the refrigeration system until the average value of evaporator temperature is approximately equal to the first compensated setpoint value.

12. The method of claim **10**, wherein the setpoint offset is equal to a magnitude of difference in temperature between refrigerant flowing into the evaporator and refrigerant flowing out of the evaporator.

13. The method of claim **10**, further comprising the steps of:

measuring a second value of relative humidity at the air inlet for the evaporator; and

comparing the first value of relative humidity to the second value of relative humidity and, when the magnitude of difference between the first and second values of relative humidity is greater than a selected magnitude of humidity change:

determining a second value of dew point temperature from the second value of relative humidity;

calculating a second compensated setpoint value by subtracting the value of setpoint offset from the second value of dew point temperature; and

adjusting the flow of refrigerant in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the second compensated setpoint value.

14. The method of claim **15**, further comprising the steps of:

measuring a second value of temperature at the air inlet for the evaporator;

comparing the first value of temperature at the air inlet to the second value of temperature at the air inlet, and when the magnitude of difference between the first and second values of temperature at the air inlet is greater than a selected magnitude of temperature change:

determining a second value of dew point temperature from the second value of temperature at the air inlet;

calculating a second compensated setpoint value by subtracting the value of setpoint offset from the second value of dew point temperature; and

adjusting the flow of refrigerant in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the second compensated setpoint value.

15. The method of claim **10**, further comprising the step of increasing the flow rate of refrigerant through an expansion valve when the measured value of refrigerant temperature in the evaporator is greater than the first compensated setpoint value.

16. The method of claim **10**, further comprising the step of adjusting the operating speed of a first compressor in the refrigeration system until the measured value of refrigerant temperature in the evaporator is approximately equal to the first compensated setpoint value.

17. The method of claim **16**, further comprising the step of comparing the operating speed of the first compressor to a maximum operating speed, and when magnitude of difference between the maximum operating speed and the operating speed is greater than a selected safety factor, starting a second compressor in a parallel fluid circuit with the first compressor.

18. The method of claim **16**, further comprising the step of reducing the operating speed of the compressor when the measured value of refrigerant temperature in the evaporator is within a selected magnitude of temperature difference from 32° F. (0° C.).

19. The method of claim **10**, wherein when the relative humidity of the inlet air changes, adjusting the flow of refrigerant to maintain a constant value for a rate of condensate collection.

20. The method of claim **10**, wherein when the relative humidity of the inlet air changes, adjusting the flow of refrigerant to maintain a constant value for electrical power consumption.

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