



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
11.06.2025 Bulletin 2025/24

(51) International Patent Classification (IPC):
F25B 49/02 ^(2006.01)

(21) Application number: **24211132.6**

(52) Cooperative Patent Classification (CPC):
F25B 49/022; F25B 2600/025; F25B 2600/2513

(22) Date of filing: **06.11.2024**

(84) Designated Contracting States:
**AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL
NO PL PT RO RS SE SI SK SM TR**
Designated Extension States:
BA
Designated Validation States:
GE KH MA MD TN

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(30) Priority: **06.12.2023 GB 202318624**

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(54) **A METHOD AND CONTROLLER FOR CONTROLLING A VAPOUR-COMPRESSION SYSTEM WITH THERMODYNAMIC CONSTRAINTS SATISFACTION**

(57) The present disclosure relates to a method of controlling a vapour-compression system 400, 400', 400" for circulating a working fluid. The vapour-compression system 400, 400', 400" comprises a compressor 402, an expansion device 406 and an evaporator 408A, 408B configured to facilitate heat transfer from a thermal source 407A, 407B into the working fluid. The method comprises: determining or receiving 310 a cooling demand, the cooling demand being associated with a demand to cool the thermal source 407A, 407B; determining 350 a preliminary thermofluidic property objective

value based on the cooling demand; determining 200 a final thermofluidic property objective value based on the preliminary thermofluidic property objective value and one or more thermofluidic property objective value thresholds, wherein the final thermofluidic property objective value relates to a target thermofluidic property of the working fluid at a control location within the vapour-compression system; and controlling 800, 900 at least one of the compressor 402 and the expansion device 406 based on the final thermofluidic property objective value.

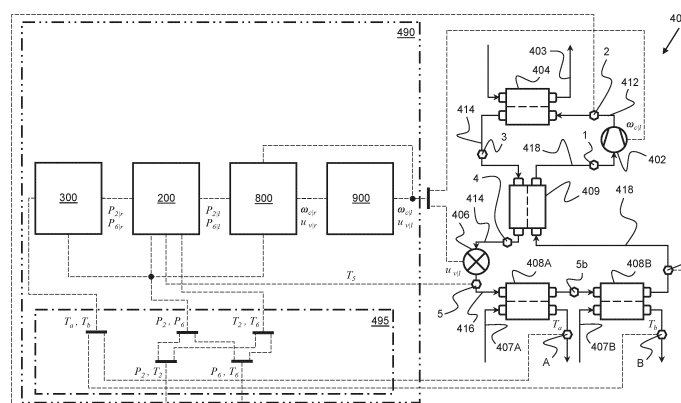


FIG. 2

Description

TECHNICAL FIELD

[0001] This disclosure relates to a method of controlling a vapour-compression system for circulating a working fluid. The disclosure also relates to a vapour-compression system comprising a controller which is configured to carry out such a method.

BACKGROUND

[0002] The increasing relevance of active thermal management in hybrid and electric vehicles has led to a focus on the development of improved control strategies for vapour-compression systems. A typical vapour-compression system may include a compressor, an expansion valve, an evaporator configured to provide cooling to a thermal source and a condenser/cooler configured to provide heating to a thermal sink. Some known control strategies include modulating a flow of fluid to the thermal sink or modulating a flow of a fluid in the thermal sink, for example by means of a fan (if the fluid is a gas, such as air), or a pump (if the fluid is a liquid). Other known control strategies include providing a cascaded control loop for the expansion valve so as to ensure a fixed amount of superheat of working fluid entering the compressor by tracking a pressure of the working fluid at an outlet of the evaporator.

[0003] However, despite various "advanced" control methods having been devised, the non-linear behaviour of vapour-compression systems remains a challenge. Such non-linear behaviour may be especially associated with the compressor(s) and/or the valve(s) of the vapour-compression system. It is desirable to provide a method of controlling a vapour-compression system which addresses these technical challenges.

[0004] US 8,096,141 B2 describes a control method which regulates an electronic expansion valve of a chiller to maintain the refrigerant leaving a DX evaporator at a desired or target superheat that is minimally above saturation. The expansion valve is controlled to convey a desired mass flow rate, wherein valve adjustments are based on the actual mass flow rate times a ratio of a desired saturation pressure to the suction pressure of the chiller. The suction temperature helps determine the desired saturation pressure. A temperature-related variable is asymmetrically filtered to provide the expansion valve with appropriate responsiveness depending on whether the chiller is operating in a superheated range, a saturation range, or in a desired range between the two.

SUMMARY

[0005] According to a first aspect of the present disclosure, there is provided a method of controlling a vapour-compression system for circulating a working fluid, the vapour-compression system comprising a compressor, an expansion device and an evaporator configured to facilitate heat transfer from a thermal source into the working fluid, the method comprising: determining or receiving a cooling demand, the cooling demand being associated with a demand to cool the thermal source; determining a preliminary thermofluidic property objective value based on the cooling demand; determining a final thermofluidic property objective value based on the preliminary thermofluidic property objective value and one or more thermofluidic property objective value thresholds, wherein the final thermofluidic property objective value relates to a target thermofluidic property of the working fluid at a control location within the vapour-compression system; and controlling at least one of the compressor and the expansion device based on the final thermofluidic property objective value.

[0006] The vapour-compression system may further comprise a cooler or a condenser. The final thermofluidic property objective value may relate to a target temperature of the working fluid at the control location.

[0007] The final thermofluidic property objective value may relate to a target pressure of the working fluid at the control location.

[0008] It may be that the method comprises: determining a compressor speed objective value based on the final thermofluidic property objective value; and controlling a speed of the compressor based on the compressor speed objective value.

[0009] In addition, or instead, it may be that the method comprises: determining an expansion device operating parameter objective value based on the final thermofluidic property objective value; and controlling an operating parameter of the expansion device based on the expansion device operating parameter objective value. The expansion device objective value may relate to a degree of opening of the expansion device.

[0010] It may be that the method comprises: monitoring a thermofluidic property of the working fluid at the control location, and determining the preliminary thermofluidic property objective value based on both the cooling demand and the monitored thermofluidic property of the working fluid at the control location.

[0011] It may be that determining the final thermofluidic property objective value includes applying an integral control aspect and a corrective anti-windup control aspect, the corrective anti-windup control aspect being based on the

monitored thermofluidic property of the working fluid at the control location.

[0012] The method may comprise determining the cooling demand based on: a temperature setpoint for the thermal source; and a monitored or predicted temperature of the thermal source.

[0013] It may be that determining the cooling demand is based on a difference between the temperature setpoint for the thermal source and the monitored or predicted temperature of the thermal source. The temperature setpoint for the thermal source may be a predetermined temperature setpoint.

[0014] It may be that the method comprises determining the or each thermofluidic property objective value threshold based on at least one of: a desired maximum temperature for working fluid in the vapour-compression system; a critical pressure for working fluid in the vapour-compression system; a superheat setpoint and/or a subcooling setpoint for the working fluid in the vapour-compression system; and a monitored temperature of the working fluid in the vapour-compression system.

[0015] The control location may be: at an outlet of the evaporator; on a suction line of the vapour-compression system, the suction line extending from the evaporator to the compressor; at an outlet of the compressor; or on a discharge line of the vapour-compression system, the discharge line extending from the compressor to a condenser or a cooler of the vapour-compression system.

[0016] It may be that the control location is at the outlet of the evaporator or on the suction line of the vapour-compression system, and also that the method comprises: controlling the expansion device based on the final thermofluidic property objective value.

[0017] It may be that the control location is at the outlet of the compressor or on the discharge line of the vapour-compression system, and also that the method comprises: controlling the compressor based on the final thermofluidic property objective value.

[0018] The method may comprise determining the final thermofluidic property objective value based on the preliminary thermofluidic property objective value, a lower thermofluidic property objective value threshold and an upper thermofluidic property objective value threshold. Determining the final thermofluidic property objective value may include: setting the final thermofluidic property objective value as being equal to the preliminary thermofluidic property objective value if the preliminary thermofluidic property objective value is in a range between the lower thermofluidic property objective value threshold and the upper thermofluidic property objective value threshold inclusive; setting the final thermofluidic property objective value as being equal to the lower thermofluidic property objective value threshold if the preliminary thermofluidic property objective value is less than the lower thermofluidic property objective value threshold; and setting the final thermofluidic property objective value as being equal to the upper thermofluidic property objective value threshold if the preliminary thermofluidic property objective value is greater than the upper thermofluidic property objective value threshold.

[0019] It may be that the method comprises: determining an additional final thermofluidic property objective value, wherein the additional final thermofluidic property objective value relates to a target thermofluidic property of the working fluid at an additional control location within the vapour-compression system; and controlling the compressor and/or the expansion device based on the final thermofluidic property objective value and the additional final thermofluidic property objective value.

[0020] It may also be that the method comprises: determining a compressor speed objective value based on both the final thermofluidic property objective value and the additional final thermofluidic property objective value; and controlling a speed of the compressor based on the compressor speed objective value.

[0021] Further, it may be that the method comprises: determining an expansion device operating parameter objective value based on both the final thermofluidic property objective value and the additional final thermofluidic property objective value; and controlling an operating parameter of the expansion device based on the expansion device operating parameter objective value.

[0022] The vapour-compression system may further comprise an additional evaporator configured to facilitate heat transfer from an additional thermal source into the working fluid. If so, the method may comprise: determining or receiving an additional cooling demand, the additional cooling demand being associated with a demand to cool the additional thermal source; determining an additional preliminary thermofluidic property objective value based on the additional cooling demand; and determining the additional final thermofluidic property objective value based on the additional preliminary thermofluidic property objective value and one or more additional thermofluidic property objective value thresholds.

[0023] In addition, it may be that the method comprises: determining the preliminary thermofluidic property objective value based on both the cooling demand and the additional cooling demand; and determining the additional preliminary thermofluidic property objective value based on both the additional cooling demand and the cooling demand.

[0024] It may be that the method comprises: determining a preliminary compressor speed objective value based on the final thermofluidic property objective value; determining a final compressor speed objective value based the preliminary compressor speed objective value and one or more compressor speed objective value thresholds; and controlling a speed of the compressor based on the final compressor speed objective value.

[0025] It may be that the method comprises: determining a preliminary expansion device operating parameter objective value based on the final thermofluidic property objective value; determining a final expansion device operating parameter objective value based the preliminary expansion device operating parameter objective value and one or more expansion device operating parameter objective value thresholds; and controlling an operating parameter of the expansion device based on the final expansion device operating parameter objective value.

[0026] According to a second aspect of the present disclosure, there is provided vapour-compression system for circulating a working fluid, the vapour-compression system comprising a compressor, an expansion device, an evaporator configured to facilitate heat transfer from a thermal source into the working fluid, and a controller configured to carry out a method in accordance with the first aspect. The vapour-compression system may further comprise a cooler or a condenser. The or each thermal source may be, or may include, a battery.

[0027] According to a third aspect of the present disclosure, there is provided a computer program comprising instructions which, when the program is executed by the controller of a vapour-compression system in accordance with the second aspect, cause the controller to carry out a method in accordance with the first aspect.

[0028] According to a fourth aspect of the present disclosure, there is provided a computer-readable medium having stored thereon a computer program in accordance with the third aspect.

[0029] The skilled person will appreciate that except where mutually exclusive, a feature described in relation to any one of the above aspects may be applied mutatis mutandis to any other aspect. Furthermore, except where mutually exclusive any feature described herein may be applied to any aspect and/or combined with any other feature described herein.

BREIF DESCRIPTION OF THE DRAWINGS

[0030] Embodiments will now be described by way of example only with reference to the accompanying drawings, which are purely schematic and not to scale, and in which:

Figure 1 shows a general arrangement of a turbofan engine for an aircraft;

Figure 2 shows an arrangement of a first example vapour-compression system and a block diagram for a first example controller;

Figure 3 is a schematic diagram showing a block diagram for an outer control logic of the first example controller;

Figure 4 is a schematic diagram showing a block diagram for a pressure objective limiting logic of the first example controller;

Figure 5 is an example pressure-enthalpy diagram for transcritical CO₂;

Figure 6 is an example pressure-temperature diagram for transcritical CO₂;

Figure 7 is an example pressure-enthalpy diagram for subcritical NH₃;

Figure 8 is a schematic diagram showing a block diagram for an inner control logic of the first example controller;

Figure 9 is a schematic diagram showing a block diagram for an actuator state objective limiting logic of the first example controller;

Figure 10 shows an arrangement of a second example vapour-compression system and a block diagram for a second example controller;

Figure 11 shows an arrangement of a third example vapour-compression system and a block diagram for a third example controller; and

Figure 12 is a highly schematic diagram of a machine-readable medium having stored thereon a computer program which, when executed by a controller, causes the controller to perform a method of controlling a vapour-compression system in accordance with the examples of Figures 2 to 11.

DETAILED DESCRIPTION

[0031] A general arrangement of an engine 101 for an aircraft is shown in **Figure 1**. The engine 101 is of turbofan configuration, and thus comprises a ducted fan 102 that receives intake air A and generates two pressurised airflows: a bypass flow B which passes axially through a bypass duct 103 and a core flow C which enters a core gas turbine.

[0032] The core gas turbine comprises, in axial flow series, a low-pressure compressor 104, a high-pressure compressor 105, a combustor 106, a high-pressure turbine 107, and a low-pressure turbine 108.

[0033] In operation, the core flow C is compressed by the low-pressure compressor 104 and is then directed into the high-pressure compressor 105 where further compression takes place. The compressed air exhausted from the high-pressure compressor 105 is directed into the combustor 106 where it is mixed with fuel and the mixture is combusted. The resultant hot combustion products then expand through, and thereby drive, the high-pressure turbine 107 and in turn the low-pressure turbine 108 before being exhausted to provide a small proportion of the overall thrust.

[0034] The high-pressure turbine 107 drives the high-pressure compressor 105 via an interconnecting shaft. The low-pressure turbine 108 drives the low-pressure compressor 104 via another interconnecting shaft. Together, the high-

pressure compressor 105, high-pressure turbine 107, and associated interconnecting shaft form part of a high-pressure spool of the engine 101. Similarly, the low-pressure compressor 104, low-pressure turbine 108, and associated interconnecting shaft form part of a low-pressure spool of the engine 101. Such nomenclature will be familiar to those skilled in the art. Those skilled in the art will also appreciate that whilst the illustrated engine has two spools, other gas turbine engines have a different number of spools, e.g., three spools.

[0035] The fan 102 is driven by the low-pressure turbine 108 via a reduction gearbox in the form of a planetary-configuration epicyclic gearbox 109. Thus, in this configuration, the low-pressure turbine 108 is connected with a sun gear of the gearbox 109. The sun gear is meshed with a plurality of planet gears located in a rotating carrier, which planet gears are in turn meshed with a static ring gear. The rotating carrier drives the fan 102 via a fan shaft 110. It will be appreciated that in alternative embodiments a star-configuration epicyclic gearbox (in which the planet carrier is static and the ring gear rotates and provides the output) may be used instead, and indeed that the gearbox 109 may be omitted entirely so that the fan 102 is driven directly by the low-pressure turbine 108.

[0036] It is increasingly desirable to facilitate a greater degree of electrical functionality on the airframe and on the engine. To this end, the engine 101 of the present embodiment comprises one or more rotary electric machines, generally capable of operating both as a motor and as a generator. The number and arrangement of the rotary electric machines will depend to some extent on the desired functionality. Some embodiments of the engine 101 include a single rotary electric machine 111 driven by the high-pressure spool, for example by a core-mounted accessory drive 112 of conventional configuration. Such a configuration facilitates the generation of electrical power for the engine and the aircraft and the driving of the high-pressure spool to facilitate starting of the engine in place of an air turbine starter. Other embodiments, including the one shown in Figure 1, comprise both a first rotary electric machine 111 coupled with the high-pressure spool and a second rotary electric machine 113 coupled with the low-pressure spool. In addition to generating electrical power and starting the engine 101, having both first and second rotary machines 111, 113, connected by power electronics, can facilitate the transfer of mechanical power between the high and lower pressure spools to improve operability, fuel consumption etc.

[0037] As mentioned above, in Figure 1 the first rotary electric machine 111 is driven by the high-pressure spool by a core-mounted accessory drive 112 of conventional configuration. In alternative embodiments, the first electric machine 111 may be mounted coaxially with the turbomachinery in the engine 101. For example, the first electric machine 111 may be mounted axially in line with the duct between the low- and high-pressure compressors 104 and 105. In Figure 1, the second electric machine 113 is mounted in the tail cone 114 of the engine 101 coaxially with the turbomachinery and is coupled to the low-pressure turbine 108. In alternative embodiments, the second rotary electric machine 113 may be located axially in line with low-pressure compressor 104, which may adopt a bladed disc or bladed drum configuration to provide space for the second rotary electric machine 113. It will of course be appreciated by those skilled in the art that any other suitable location for the first and (if present) second electric machines may be adopted.

[0038] The first and second electric machines 111, 113 are connected with power electronics. Extraction of power from or application of power to the electric machines is performed by a power electronics module (PEM) 115. In the present embodiment, the PEM 115 is mounted on the fan case 116 of the engine 101, but it will be appreciated that it may be mounted elsewhere such as on the core of the gas turbine, or in the vehicle to which the engine 101 is attached, for example.

[0039] Control of the PEM 115 and of the first and second electric machines 111 and 113 is in the present example performed by an engine electronic controller (EEC) 117. In the present embodiment the EEC 117 is a full-authority digital engine controller (FADEC), the configuration of which will be known and understood by those skilled in the art. It therefore controls all aspects of the engine 101, i.e., both of the core gas turbine and the first and second electric machines 111 and 113. In this way, the EEC 117 may holistically respond to both thrust demand and electrical power demand.

[0040] The one or more rotary electric machines 111, 113 and the power electronics 115 may be configured to output to or receive electric power from one, two or more dc busses. The dc busses allow for the distribution of electrical power to other engine electrical loads and to electrical loads on the airframe. The dc busses may further receive electrical power from, or deliver electrical power to, an energy storage system such as one or more battery modules or packs.

[0041] Those skilled in the art will appreciate that the gas turbine engine 101 described above may be regarded as a 'more electric' gas turbine engine because of the increased role of the electric machines 111, 113 compared with those of conventional gas turbines.

[0042] The gas turbine engine 101 may include one or more thermal sources which benefit from cooling in use. The one or more thermal sources may include, for example, a battery, an electrical device, an electric machine, a gearbox, an oil circulation system or a rotary component of or associated with the gas turbine engine 101. Various types of thermal management systems may be provided to the gas turbine engine 101 for the purpose of providing cooling to the one or more thermal sources. In particular, a vapour-compression circuit or system may be provided to the gas turbine engine for the purpose of providing cooling to the one or more thermal sources.

[0043] Figure 2 shows a schematic arrangement of a first example vapour-compression system 400 and a block diagram for a first example controller 490. The controller 490 is generally configured to control the vapour-compression

system 400 as described in further detail herein.

[0044] The first example vapour-compression system 400 is generally configured for circulating a working fluid. The working fluid may include, for instance, a refrigerant. The refrigerant may be, or include, carbon-dioxide and/or ammonia as referred to in the following description for exemplary purposes. However, other refrigerants may be used within the vapour-compression system 400. The first example vapour-compression system 400 comprises a compressor 402, a condenser/cooler 404, an expansion device 406, a primary evaporator 408A and a secondary evaporator 408B. The primary evaporator 408A may be simply referred to as the evaporator 408A and the secondary evaporator 408B may be referred to as the additional evaporator 408B.

[0045] A discharge line 412 extends from the compressor 402 to the condenser/cooler 404. A pre-expansion line 414 (which may sometimes be referred to as a liquid line 414) extends from the condenser/cooler 404 to the expansion device 406, whereas a post-expansion line 416 (which may sometimes be referred to as a distributor line 416) extends from the expansion device 406 to the primary evaporator 408A. A suction line 418 extends from the primary evaporator 408A, through the secondary evaporator 408B, to the compressor 402. Accordingly, the first and secondary evaporators 408A, 408B are fluidically connected in series. In other examples in accordance with the present disclosure, the first and secondary evaporators 408A, 408B are fluidically connected in parallel. The expansion device 406 may be, or comprise, a throttle valve or a turbine (e.g., a centrifugal-type turbine).

[0046] The first example vapour-compression system 400 also comprises an internal heat exchanger 409 (which may be referred to as an economiser heat exchanger 409). The pre-expansion line 414 extends through a side of the internal heat exchanger 409 and the suction line 418 extends through another side of the internal heat exchanger 409. The internal heat exchanger 409 is configured to facilitate heat exchange between working fluid in the pre-expansion line 414 and working fluid in the suction line 418 to provide an increased efficiency to the vapour-compression system 400, for reasons which will be generally similar to those skilled in the art. It will, however, be appreciated that in other example vapour-compression systems in accordance with the present disclosure, an internal heat exchanger may not be present or included.

[0047] The condenser/cooler 404 is generally configured to facilitate heat exchange between working fluid passing therethrough and a thermal sink. In particular, the condenser/cooler 404 is configured to facilitate heat transfer from the working fluid passing therethrough into the thermal sink. In the specific example of Figure 2, the thermal sink is a process fluid (e.g., a sink fluid) provided to the condenser/cooler 404 by a sink fluid passageway 403 which forms part of a sink fluid loop (not shown). Accordingly, in this particular example, the condenser/cooler 404 is configured to facilitate heat exchange between a pair of interfacing fluids. However, it will be appreciated that the thermal sink may not be, or may not include, a fluid. That is, the thermal sink may be, or may include, a solid structure. For ease of explanation, the sink fluid passageway 403 and the thermal sink may be referred to using the same reference sign herein.

[0048] Each evaporator 408A, 408B is generally configured to facilitate heat exchange between working fluid passing therethrough and respective thermal source. In particular, each evaporator 408A, 408B is configured to facilitate heat transfer into the working fluid passing therethrough from the respective thermal source. In the specific example of Figure 2, each thermal source is a process fluid (e.g., a source fluid) provided to the evaporators 408A, 408B for co-current flow with the working fluid of the vapour-compression system 400 by respective source fluid passageways 407A, 407B forming parts of respective source fluid loops (not shown). In other examples, the process fluid may be provided to the evaporators 408A, 408B for counter-current flow with the working fluid of the vapour-compression system 400 by the respective source fluid passageways 407A, 407B. Consequently, in this particular example, the evaporators 408A, 408B are configured to facilitate heat exchange between a pair of interfacing fluids. Nevertheless, it will be appreciated that the or each thermal source may not be, or may not include, a fluid. Namely, the or each thermal source may be, or may include, a solid structure. In particular, the or each thermal source may be, or may include, a battery or an oil circulation system associated with a gas turbine engine and/or an airframe to which a gas turbine engine is provided. For ease of explanation, the source fluid passageways 407A, 407B and the thermal sources may be referred to using the same reference signs herein. The thermal source 407A provided to the primary evaporator 408A may be referred to as the primary thermal source 407A, and the thermal source 407B provided to the secondary evaporator 408B may be referred to as the secondary thermal source 407B.

[0049] For the purposes of the following description, a plurality of monitoring locations on the vapour-compression system 400 are now defined. A first system monitoring location 1 is on the suction line 418 between the internal heat exchanger 409 and the compressor 402, a second system monitoring location 2 is on the discharge line 412, a third system monitoring location 3 is on the pre-expansion line 414 between the condenser/cooler 404 and the internal heat exchanger 409, a fourth system monitoring location 4 is on the pre-expansion line 414 between the internal heat exchanger 409 and the expansion device 406, a fifth system monitoring location 5 is on the post-expansion line 416 between the expansion device 406 and the primary evaporator 408A, an auxiliary fifth system monitoring location 5b is on the suction line 418 between the primary evaporator 408A and the secondary evaporator 408B, and a sixth system monitoring location 6 is on the suction line between the secondary evaporator 408B and the internal heat exchanger 409.

[0050] Also for the purposes of the following description, a plurality of monitoring locations on the thermal sources 407A, 407B are defined. A primary source monitoring location A is located on the primary source fluid passageway 407A

downstream of, and proximal to, a source-side outlet of the primary evaporator 408A and a secondary source monitoring location B is located on the secondary source fluid passageway 408A downstream of, and proximal to, a source-side outlet of the secondary evaporator 408B.

[0051] The controller 490 is configured to control both the compressor 402 and the expansion device 406 in accordance with the methodology (i.e., the method) described herein with reference to Figures 2 to 9. More particularly, the controller 490 is configured to control a flow rate (e.g., a mass-flow rate) of working fluid through the vapour-compression system 400 by controlling an operating parameter of the compressor 402. In the example of Figure 2, the operating parameter of the compressor 402 is a speed (i.e., a rotational speed) of the compressor 402. Moreover, the controller 490 is configured to control a pressure differential between working fluid within the vapour-compression system 400 on either side of the expansion device 406 (e.g., a pressure difference between working fluid at the fourth system monitoring location 4 and at the fifth system monitoring location 5) by controlling an operating parameter of the expansion device 406. In the example of Figure 2, the operating parameter of the expansion device 406 is a degree of opening of the expansion device 406. In other examples, the operating parameter of the expansion device 406 may relate to a position of a variable geometry feature of the expansion device 406 (e.g., if the expansion device is a turbine). The compressor 402 and the expansion device 406 are therefore two separate actuators operable by the controller 490 to control operation of the vapour-compression system 400.

[0052] In the example of Figure 2, the controller 490 comprises an outer control logic 300, a pressure limiting logic 200, an inner control logic 800 and an actuator operating parameter objective limiting logic 900. In various examples in accordance with the present disclosure, the controller 490 does not comprise the actuator operating parameter objective limiting logic 900. The controller 490 further comprises a signal processing module 495. The controller 490 may be understood as comprising two cascaded control loops (i.e., an outer control loop and an inner control loop). The inner control loop is implemented by the inner control logic 800, while the outer control loop is controlled by the outer control logic 300. Further, and as will be described in further detail below, the pressure limiting logic 200 enforces various thermofluidic constraints by selectively limiting pressure objective values provided to the inner control logic 800.

[0053] In this example, the controller 490 is configured to receive system input signals from respective system sensing arrangements at the second system monitoring location 2, at the fifth system monitoring location 5 and at the sixth system monitoring location 6. The controller 490 is also configured to receive source input signals from respective source sensing arrangements at the primary source monitoring location A and at the secondary source monitoring location B. At least some of the input signals are received and processed by the signal processing module 495 prior to being received by other aspects of the controller 490, as described in further detail below. In other examples in accordance with the present disclosure, the controller 490 is configured to receive such system input signals from system sensing arrangement at any one, combination, or all of the system monitoring locations 1-6.

[0054] Each system input signal comprises information relating to the pressure of the working fluid at the respective monitoring location 2, 6 and/or the temperature of the working fluid at the respective monitoring location 2, 5, 6. In the example of Figure 2, some of the system input signals are received by the signal processing module 495 in the form of a two-element array, with each element corresponding to either the pressure of the working fluid at the monitoring location 2, 6 or the temperature of the working fluid at the monitoring location 2, 6. That is, the signal processing module 495 receives a first system input signal (P_2, T_2) relating to both the temperature T_2 at the second system monitoring location 2 and the pressure P_2 at the second system monitoring location 2 as well as a second system input signal (P_6, T_6) relating to both the temperature T_6 at the sixth system monitoring location 6 and the pressure P_6 at the sixth system monitoring location 6. A third system input signal (T_5) is otherwise received by the controller 490.

[0055] Each source input signal comprises information relating to the temperature of the respective source 407A, 407B. In the example of Figure 2, each source input signal is received by the signal processing module 495 in the form of separate values, with each value corresponding to the temperature T_a at the primary source monitoring location A and the temperature T_b at the secondary source monitoring location B, respectively.

[0056] In the example of Figure 2, the signal processing module 495 receives and processes each of the input signals as follows. The first system input signal P_2, T_2 is demultiplexed (e.g., split) into the temperature T_2 and the pressure P_2 at the second system monitoring location 2. Similarly, the second system input signal P_6, T_6 is demultiplexed (e.g., split) into the temperature T_6 and the pressure P_6 at the sixth system monitoring location 6. The system temperatures T_2 and T_6 are multiplexed (e.g., concatenated) to form a two-element system temperature array T_2, T_6 comprising a first system temperature T_2 and a second system temperature T_6 . The system pressures P_2 and P_6 are multiplexed (e.g., concatenated) to form a two-element system pressure array P_2, P_6 . The source temperatures T_a and T_b , as received in the source input signals, are multiplexed to form a two-element source temperature array T_a, T_b .

[0057] In the example of Figure 2, the outer control logic 300 is configured to receive the source temperature array T_a, T_b from the signal processing module 495 as an input and to provide a preliminary pressure objective value array $P_{2|p}, P_{6|p}$ as an output to the pressure limiting logic 200. The preliminary pressure objective value array $P_{2|p}, P_{6|p}$ is a two-element array comprising a first preliminary pressure objective value $P_{2|p}$ for working fluid at the second system monitoring location 2 (e.g., a preliminary pressure objective value $P_{2|p}$) and a second preliminary pressure objective value $P_{6|p}$ for working fluid at

the sixth system monitoring location 6 (e.g., an additional preliminary pressure objective value $P_{6|l}$).

[0058] In turn, the pressure limiting logic 200 is configured to receive the system temperature array T_2, T_6 , the third system input signal/temperature T_5 , the preliminary pressure objective value array $P_{2|l}, P_{6|l}$ and the system pressure array P_2, P_6 from the signal processing module 495 as inputs and to provide a final pressure objective value array $P_{2|f}, P_{6|f}$ as an output to the inner control logic 800. The final pressure objective value array $P_{2|f}, P_{6|f}$ is a two-element array comprising a first final pressure objective value $P_{2|f}$ for working fluid at the second system monitoring location 2 (e.g., a final pressure objective value $P_{2|f}$) and a second final pressure objective value $P_{6|f}$ for working fluid at the sixth system monitoring location 6 (e.g., an additional final pressure objective value $P_{6|f}$). The first final pressure objective value $P_{2|f}$ relates to a target pressure of working fluid at the second system monitoring location 2, whereas the second final pressure objective value $P_{6|f}$ relates to a target pressure of working fluid at the sixth system monitoring location 6. The second system monitoring location 2 may therefore be referred to as a first control location 2 (e.g., a control location 2) and the sixth system monitoring location 6 may also be referred to as a second control location 6 (e.g., an addition control location 6). More generally, the first control location 2 may be anywhere on the discharge line 412 or at an outlet of the compressor 402 and the second control location 6 may be anywhere on the suction line 418 or at an outlet of the secondary evaporator 408B. Preferably, the second control location 6 is between the secondary evaporator 408B and the internal heat exchanger 409. As is described in further detail below, each final pressure objective value may be the same as (e.g., equal to) or different to (e.g., greater than or less than) the corresponding preliminary pressure objective value.

[0059] Further, the inner control logic 800 is configured to receive the system pressure array P_2, P_6 and the final pressure objective value array $P_{2|f}, P_{6|f}$ as inputs and to provide a preliminary actuator operating parameter objective array $\omega_{c|l}, u_{v|l}$ as an output to the actuator operating parameter objective limiting logic 900. The preliminary actuator operating parameter objective array $\omega_{c|l}, u_{v|l}$ is a two-element array comprising a preliminary compressor operating parameter objective value $\omega_{c|l}$ for the compressor 402 (e.g., a preliminary actuator operating parameter objective value $\omega_{c|l}$) and a preliminary expansion device operating parameter objective value $u_{v|l}$ for the expansion device 406 (e.g., an additional preliminary actuator operating parameter objective value $u_{v|l}$).

[0060] Finally, the actuator operating parameter objective limiting logic 900 is configured to receive the preliminary actuator operating parameter objective array $\omega_{c|l}, u_{v|l}$ as an input and to provide a final actuator operating parameter objective array $\omega_{c|f}, u_{v|f}$ as an output to the actuators 402, 406 of the vapour-compression system 400 (that is, to the compressor 402 and the expansion device 406). The final actuator operating parameter objective array $\omega_{c|f}, u_{v|f}$ is a two-element array comprising a final compressor operating parameter objective value $\omega_{c|f}$ for the compressor 402 (e.g., a final actuator operating parameter objective value $\omega_{c|f}$) and a final expansion device operating parameter objective value $u_{v|f}$ for the expansion device 406 (e.g., an additional final actuator operating parameter objective value $u_{v|f}$).

[0061] The outer control logic 300 is also configured to receive the system pressure array P_2, P_6 from the signal processing module 495 as a further input, whereas the inner control logic 800 is also configured to receive the final actuator operating parameter objective array $\omega_{c|f}, u_{v|f}$ from the actuator operating parameter objective limiting logic 900 as a further input.

[0062] The final actuator operating parameter objective array $\omega_{c|f}, u_{v|f}$ is then demultiplexed (e.g., split) into the final compressor operating parameter objective value $\omega_{c|f}$ and the final expansion device operating parameter objective value $u_{v|f}$. The compressor 402 is then controlled in accordance with the final compressor operating parameter objective value $\omega_{c|f}$ by a suitable compressor control scheme (represented by the dashed line extending from the controller 490 to the compressor 402 in Figure 2), for example to maintain the speed of the compressor 402 at, or within a tolerance range of, the final compressor operating parameter objective value $\omega_{c|f}$. Accordingly, the final compressor operating parameter objective value $\omega_{c|f}$ may be referred to as a compressor speed objective value $\omega_{c|f}$. In a similar way, the expansion device 406 is controlled in accordance with the final expansion device operating parameter objective value $u_{v|f}$ by a suitable expansion device control scheme (represented by the dashed line extending from the controller 490 to the expansion device 406 in Figure 2), for example to maintain the degree of opening of the expansion device 406 at, or within a tolerance range of, the final expansion device operating parameter objective value $u_{v|f}$.

[0063] The combined action of the outer control logic 300 and pressure limiting logic 200 can be conceived of as providing a non-linear transformation from the temperature domain to the pressure domain and providing objective limitation in the pressure domain. The further action(s) of the inner control logic 800 are then carried out in the pressure domain (e.g., with respect to pressure values). Nevertheless, this disclosure envisages that one or more, or all, of the control actions described herein as being carried out in the pressure domain could be carried out in the temperature domain. If so, the pressure limiting logic 200 may be replaced by a temperature limiting logic, with appropriate temperature constraints being applied by the temperature limiting logic using the functions described below with reference to the pressure limiting logic 200. In addition, if so, the final thermofluidic property objective value(s) may relate to a target temperature of the working fluid at the control location(s). However, superior performance of the controller 490 may be enabled by carrying out control actions in the pressure domain, because this variable typically changes faster than temperature and/or because suitable temperature sensors for the purposes described may typically have longer rise times than suitable pressure sensors suitable for these purposes. This is facilitated by use of the two cascaded control loops (i.e.,

the outer control loop and the inner control loop).

[0064] Figure 3 is a schematic diagram showing a detailed block diagram of the outer control logic 300. The outer control logic 300 includes determining, at block 310, a cooling demand array ΔT_a , ΔT_b . In this example, the cooling demand array ΔT_a , ΔT_b is determined as being a difference between the source temperature array T_a , T_b array and a setpoint temperature array $T_{a|s}$, $T_{b|s}$. Consequently, the cooling demand array ΔT_a , ΔT_b may be referred to as a temperature error array ΔT_a , ΔT_b .

[0065] The setpoint temperature array $T_{a|s}$, $T_{b|s}$ is a two-element array comprising a temperature setpoint value $T_{a|s}$ for the primary thermal source 407A (e.g., a first temperature setpoint value $T_{a|s}$) and a temperature setpoint value $T_{b|s}$ for the secondary thermal source 407B (e.g., a first temperature setpoint value $T_{b|s}$). Accordingly, the cooling demand array ΔT_a , ΔT_b is a two-element array comprising a temperature error value ΔT_a associated with the primary thermal source 407A (e.g., a primary cooling demand ΔT_a or, more simply, a cooling demand ΔT_a) and a temperature error value ΔT_b associated with the secondary thermal source 407B (e.g., a secondary cooling demand ΔT_b or, more simply, an additional cooling demand ΔT_b). Each cooling demand ΔT_a and ΔT_b is associated with a demand to provide cooling to (e.g., to cool) the corresponding thermal source 407A, 408B. In this example, each cooling demand ΔT_a and ΔT_b is determined based on (a difference between) the corresponding temperature setpoint $T_{a|s}$, $T_{b|s}$ and the corresponding monitored temperature T_a , T_b of the thermal source 407A, 407B. In other examples, the outer control logic 300 may determine the cooling demand(s) by receiving the cooling demand(s) from an external data processing apparatus and/or a dedicated sensing system provided to the thermal source(s) 407A, 408B. The setpoint temperatures $T_{a|s}$ and $T_{b|s}$ may be predetermined values stored within a memory of the controller 490 or may be received from an external data processing apparatus, such as a user-interface or a machine-interface to the controller 490 and/or the vapour-compression system 400. In the latter case, the setpoint temperatures $T_{a|s}$ and $T_{b|s}$ may vary in use.

[0066] The outer control logic 300 includes a proportional-integral (PI) action, represented by blocks 320, 330, 340 and 350, for determining the preliminary pressure objective value array $P_{2|r}$, $P_{6|r}$. The PI action is carried out with the intention of reducing each temperature error value (ideally to zero). The outer control logic 300 also includes an anti-windup action for correcting possible wind-up associated with the integral aspect of the PI action (e.g., a corrective anti-windup control aspect), which is implemented by application of a backstepping gain as described in further detail below. That is, including the integral aspect in the PI action may, in turn, cause problems when the setpoint temperature(s) $T_{a|s}$, $T_{b|s}$ are effectively unattainable and/or due to the action of the pressure limiting logic 200 described below. In this case, the temperature error array ΔT_a , ΔT_b will keep accumulating, causing a so-called windup effect. Therefore, an anti-windup action is also included, synthesized using a backstepping gain K_t^b as explained in further detail below.

[0067] To capture possible wind-up associated with any unattainability of the setpoint temperature(s) $T_{a|s}$, $T_{b|s}$ and the action of the pressure limiting control logic 200 (as well as the action(s) of the inner control logic 800 and the actuator operating parameter objective limiting logic 900), the backstepping gain K_t^b is advantageously applied in respect of the system pressure array P_2 , P_6 (in the example of Figure 3) such that the preliminary pressure objective value array $P_{2|r}$, $P_{6|r}$ is determined based on both the cooling demand array ΔT_a , ΔT_b and the system pressure array P_2 , P_6 . In other words, this approach covers not only a scenario in which pressure objective values are dynamically limited by the pressure limiting logic 200, but also when saturation occurs in the inner control logic 800 and/or in the actuator operating parameter objective limiting logic 900, as this saturation will be reflected on measured system pressure array P_2 , P_6 (i.e., the pressure(s) ultimately achieved in the working fluid circulated by the vapour-compression system 400). This approach contrasts with previously-considered (e.g., prior art) anti-windup approaches which rely on complex synthesis methods involving plant identification and dynamics inversion.

[0068] The application of a proportional gain K_t^p to the temperature error array ΔT_a , ΔT_b to produce a proportional preliminary pressure term array $P_{2|r}^p$, $P_{6|r}^p$ is represented by block 320. The preliminary pressure objective value array $P_{2|r}$, $P_{6|r}$ is subtracted from the system pressure array P_2 , P_6 at block 360 to yield a backstepping pressure array P_2^b , P_6^b . In turn, the application of a backstepping gain K_t^b to the backstepping pressure array P_2^b , P_6^b to produce a backstepping temperature array T_a^b , T_b^b is represented by block 370. The temperature error array ΔT_a , ΔT_b and the backstepping temperature array T_a^b , T_b^b are added at block 380 to produce a backstepped temperature error array ΔT_a^b , ΔT_b^b . The time-integration of the backstepped temperature error array ΔT_a^b , ΔT_b^b and the application of an integral gain K_t^i to a time-integral temperature error array to produce an integral preliminary pressure term array $P_{2|r}^i$, $P_{6|r}^i$ is represented by blocks 330 and 340, respectively. The proportional preliminary pressure term array $P_{2|r}^p$, $P_{6|r}^p$ and the integral preliminary pressure term array $P_{2|r}^i$, $P_{6|r}^i$ are then added, as represented by block 350, to produce the preliminary pressure objective value array $P_{2|r}$, $P_{6|r}$. As a result, the preliminary pressure objective value array $P_{2|r}$, $P_{6|r}$ is determined based on both the cooling demand array ΔT_a , ΔT_b and the monitored pressure P_2 , P_6 of the working fluid at the control locations 2, 6. Each of the gains K_t^p , K_t^b , K_t^i described above are in the form of 2 by 2 matrices. Application of the gains K_t^p , K_t^b , K_t^i at blocks 320, 340 and 370 is performed using matrix multiplication of the relevant arrays and gain matrices.

[0069] It follows that each of the first preliminary pressure objective value $P_{2|r}$ and the second preliminary pressure objective value $P_{6|r}$ are determined based on both the primary cooling demand ΔT_a and the second cooling demand ΔT_b . In other words, the first preliminary pressure objective value $P_{2|r}$ is influenced by both the primary cooling demand ΔT_a and

the second cooling demand ΔT_b and the second preliminary pressure objective value $P_{6|p}$ is influenced by both the primary cooling demand ΔT_a and the second cooling demand ΔT_b . For this reason, the outer control logic 300 described with respect to Figures 2 and 3 may be referred to as a multivariable outer control logic 300 or a multiple-input multiple-output (MIMO) outer control logic 300.

[0070] Figure 4 is a schematic diagram showing a detailed block diagram of the pressure limiting control logic 200. The pressure limiting control logic 200 is generally adapted to enforce safe and effective thermofluidic constraints for working fluid circulated by the vapour-compression system 400. There are various thermofluidic constraints that may be imposed (e.g., enforced) in respect of the working fluid in the vapour-compression system 400. The aim of enforcing some of these thermofluidic constraints is to ensure safe operation of specific components of the vapour-compression system 400, while the aim of enforcing some of these thermofluidic constraints is to achieve a particular operational regime for the working fluid at a given locations within the vapour-compression system 400.

[0071] In a previously-considered vapour-compression system, such thermofluidic constraints were considered during the design phase by appropriate sizing of components. Some safety-critical constraints were then enforced by the use of physical elements like liquid receivers.

[0072] In future aerospace applications, and electric vehicles in general, the cooling demand(s) associated with the thermal source(s) are likely to vary dynamically in a relatively wide range. In addition, the broader operating conditions, especially in the case of aerospace applications, will also change in a much wider range due to the changes in the environment as altitude and speed vary. All these dynamic changes in respect of the thermal source(s) and the sink(s) make it highly beneficial for the controller to incorporate some functionality to enforce compliance with relevant thermofluidic constraints.

[0073] To address this challenge, other previously-considered control methodologies attempted to make use of model predictive control techniques. However, such techniques often require a deep understanding of the theoretical framework underpinning the vapour-compression system in order to deploy the control logic, as well as an accurate model of the system to make appropriate predictions (in addition to providing the vapour-compression system with controller(s) with powerful enough processors to run optimisation in real-time).

[0074] In contrast, the implementation proposed in the present disclosure simplifies the approach by explicitly defining thermofluidic limits (e.g., in the pressure domain) and tuning the two cascaded control loops accordingly. Moreover, the implementation proposed in the present disclosure allows the controller 490 to be readily adapted for use with a range of different types of working fluids (e.g., refrigerants) to be circulated by the vapour-compression system 400 using only minor adaptations to the pressure limiting logic 200 (e.g., by modifying the thermofluidic constraints to be enforced by the pressure limiting logic 200 according to the characteristics of the working fluid to be used).

[0075] Exemplary thermofluidic constraints employed in the present disclosure relate to any of the following:

(i) compressor protection: it is preferable that the working fluid is in an entirely gaseous form before entering the compressor 402. A thermofluidic constraint on this basis may be imposed as a superheat condition at the outlet of the evaporators 408A, 408B (i.e., at the second control location 6). Namely, the working fluid should be at a temperature greater than (e.g., a (predetermined) specified amount greater than) the saturation temperature of the working fluid at the second control location 6, as defined according to the current operating pressure of the working fluid at the second control location 6.

(ii) temperature protection: some working fluids may start to degrade if and when a certain temperature threshold is exceeded (e.g., a maximum working fluid temperature threshold). Further, internal components of the compressor 402 may suffer from reduced performance and/or be liable to damage when the working fluid passing through the compressor 402 is at a high temperature. It is thus desirable to impose a constraint on the highest temperature of the system, which is on the discharge line 412 (e.g., at the second monitoring location 2).

(iii) operating regime: it might be also desired to operate the working fluid charged in the vapour-compression system 400 in a trans-critical or sub-critical regime, depending on the working fluid (e.g., the refrigerant) being used. If a trans-critical regime is desired, the pressure of working fluid on the "high-pressure" side of the vapour-compression system 400 (which may be referred to as the cooling pressure of the condensation pressure) should be always above the critical pressure of the fluid, whereas for a sub-critical regime, the condensation pressure should always be below the critical pressure.

(iv) expansion device protection: for a sub-critical regime, it might also be preferable to have the fluid as fully liquid before entering the expansion device, and thus a certain amount of subcooling is usually required. This may be enforced by ensuring that the temperature of working fluid in the pre-expansion line 414 (e.g., at the third monitoring location 3) is below the saturation temperature of the working fluid at the condensation pressure.

(v) thermal runaway protection: when a certain mass flow of working fluid circulating in the vapour-compression system 400 is exceeded, the vapour-compression system 400 may be at risk of spiralling into a thermal runaway (i.e., increasing the temperature of the refrigerant when increasing the mass flow). This is associated with non-linear behaviour that results from the decrease in heat rejection in the condenser/cooler 404 when mass flow is increased.

One possible way of ensuring that this risk is mitigated is by limiting the amount of superheat in the primary evaporator 408A (e.g., not allowing the primary evaporator 408A to have the fluid inside as full vapour). This can be enforced by imposing a maximum superheat constraint of working fluid in the post-expansion line 416 (e.g., at the fifth monitoring location 5).

(vi) minimum performance: the vapour-compression system may be most efficient when the working fluid inside the evaporator(s) 408A, 408B is in mixed phase and becomes vapour at the outlet of the secondary evaporator 408B. However, for safety reasons, it may be desired to have a minimum amount of superheat of the working fluid in this monitoring location (e.g., at the sixth monitoring location 6). In order to not deviate too significantly from optimum performance, it might also be desirable to define a maximum superheat amount for the working fluid, which is enforced by not allowing the temperature of working fluid at the outlet of the evaporators 408A, 408B (e.g., on the suction line 418 at the sixth monitoring location 6) to be above the saturation temperature plus a predetermined maximum difference.

[0076] The expression and enforcement of all the thermofluidic constraints into the pressure domain, as in preferred examples of the present disclosure, is possible given the fact that the saturation temperature increases monotonically with the saturation pressure, even if this increase is non-linear. This allows to translate various temperature inequality requirements into pressure constraints, adding these to the constraints defined explicitly in pressure.

[0077] To illustrate this point, **Figure 5** shows a pressure-enthalpy diagram for an example idealised transcritical regime carbon dioxide (CO₂) working fluid vapour-compression system having an architecture which corresponds to that of the vapour-compression system 400 shown by Figure 2 (i.e., having two evaporators 408A, 408B in series, an internal heat exchanger 409 and the monitoring locations 1-6).

[0078] Figure 5 shows some of the exemplary thermofluidic constraints: the saturation line is a minimum energy condition for the sixth monitoring location/second control location 6, and a maximum energy conditions for the fifth monitoring location 5. The maximum temperature line is a maximum energy condition for the second monitoring location 2, and the critical pressure is a minimum pressure for each of the second, third and fourth monitoring locations 2, 3 and 4.

[0079] Each of these thermofluidic constraints can be formulated in either the temperature or the pressure domain. This can be clearly seen in **Figure 6**, where the same cycle from Figure 5 is represented in the pressure-temperature plane (the specific enthalpy isolines are plotted here without value for ease of understanding).

[0080] It can be seen that the saturation line (separating liquid and vapour areas) is a monotonic line in the pressure-temperature space, allowing to project a temperature restriction into a pressure restriction when this restriction refers to the saturation line (this is, all superheat and subcooling conditions can be formulated as pressure limits). Regarding the maximum temperature (e.g., the maximum allowed temperature or the maximum desired temperature), it can also be formulated as a limit in pressure if one looks at the same specific-enthalpy lines (for each enthalpy isoline there is a maximum pressure, when this isoline crosses the maximum temperature line). Following this reasoning, a strictly positive and monotonic function $T_{sat}(P)$ can be defined as the temperature in the saturation line for pressure that range between the minimum pressure of the working fluid and the critical pressure of the working fluid. In the same manner, a strictly positive and monotonic function $P_{sat}(T)$ can be defined as the pressure in the saturation line for a temperature ranging between the minimum temperature of the working fluid and the critical temperature of the working fluid.

[0081] Further, it can be said that the two functions are inverses to each other. In other words, $P = P_{sat}(T_{sat}(P))$ and $T = T_{sat}(P_{sat}(T))$. Using these two functions, all of the thermofluidic constraints related to the saturation line can be easily translated into pressure as follows.

[0082] Starting with a minimum and/or a maximum superheat amount at a monitoring location i . A superheat amount sh_i can be defined as a difference between the temperature T_i of working fluid at the relevant monitoring location and the saturation temperature at the current pressure $T_{sat}(P_i)$, per Equation **Error! Reference source not found.**.

$$sh_i = T_i - T_{sat}(P_i) \quad (1)$$

[0083] Defining a minimum desired amount of superheat sh_i^{min} at a particular monitoring location is essentially equivalent to saying that the temperature T_i of the working fluid at the relevant monitoring location should be at least at the saturation temperature $T_{sat}(P_i)$ plus a predetermined minimum superheat amount/superheat setpoint sh_i^{min} , per Equation **Error! Reference source not found.** below.

$$T_i \geq T_{sat}(P_i) + sh_i^{min} \quad (2)$$

Moving the superheat setpoint sh_i^{min} to the left side, and applying the pressure function defined previously to both sides

of the remaining inequality (which can be done without changing the sign of the inequality due to the properties defined before), Equation **Error! Reference source not found.** may be rewritten as Equation **Error! Reference source not found.**

$$P_{sat}(T_i - sh_i^{min}) \geq P_i \quad (3)$$

where the superheat condition has been translated into a maximum pressure condition at monitoring location P_i which is determined dynamically by the current temperature T_i and the superheat requirement sh_i^{min} .

[0084] In a similar way to the previously-described constraint, a maximum superheat (sh_i^{max}) requirement at a given monitoring location can be translated into a minimum pressure limit at the said monitoring location (that is, turning Equation **Error! Reference source not found.** into Equation **Error! Reference source not found.** as shown below).

$$T_i \leq T_{sat}(P_i) + sh_i^{max} \quad (4)$$

$$P_{sat}(T_i - sh_i^{max}) \leq P_i \quad (5)$$

[0085] Combining Equations **Error! Reference source not found.** and **Error! Reference source not found.** yields Equation **Error! Reference source not found.**, which succinctly defines two limits that can be imposed on the pressure at the relevant monitoring location i in order to guarantee that the superheat amount lies within an appropriate range.

$$P_{sat}(T_i - sh_i^{max}) \leq P_i \leq P_{sat}(T_i - sh_i^{min}) \quad (6)$$

[0086] Like the above-described approach for expressing the superheat-related thermofluidic constraints as pressure limits, subcooling-related thermofluidic constraints can be similarly enforced at any of the monitoring locations 1-6 by translating them into the pressure domain. Subcooling may be defined as a difference between the current temperature of working fluid at the relevant monitoring location and the saturation temperature at the same relevant pressure, per Equation **Error! Reference source not found.**

$$sc_i = T_{sat}(P_i) - T_i \quad (7)$$

[0087] It can be noted that, according to the definitions given in Equations **Error! Reference source not found.** and **Error! Reference source not found.**, subcooling may be defined as a negative superheat such that $sc_i = -sh_i$. Therefore, following the same reasoning as that followed above for the superheat, and knowing the equivalence with subcooling, Equation (1) may be arrived at. Equation (8) defines the limits for the pressure of working fluid at the monitoring location i if subcooling conditions are to be imposed thereat (e.g., a minimum subcooling amount/subcooling setpoint).

$$P_{sat}(T_i + sc_i^{min}) \leq P_i \leq P_{sat}(T_i + sc_i^{max}) \quad (1)$$

[0088] Restrictions for the maximum working fluid temperature can also be defined in the pressure domain by using several transformations. One specific methodology described herein includes first obtaining the specific enthalpy of the monitoring location to be limited using the function $h(T, P) \in \{\mathbb{R}^2 \rightarrow \mathbb{R}^1\}$, which can only be defined in single-phase regions (this function can be seen in Figure 6, where the isolines are the values for the specific enthalpy for each combination of temperature and pressure in single-phase stages).

[0089] An additional function that provides the pressure value equivalent to the maximum temperature for a given specific enthalpy is also defined. That is, a function is defined that describes the maximum temperature isotherm $P_{T_{max}}(h)$ (as seen in Figure 5 for the 420K isotherm).

[0090] With these two functions defined, it can then be said that the pressure of working fluid at the monitoring location to be constrained should be below the pressure of the isotherm representing the maximum temperature for the current specific enthalpy, as per Equation (2) below.

$$P_i \leq P_{T_{max}}(h(T_i, P_i)) \quad (2)$$

[0091] The same principle can be applied to a minimum temperature for the working fluid by simply defining a pressure function defining the minimum temperature isotherm $P_{T_{min}}(h)$ as given by Equation (10). This is possible due to the monotonic relationship between pressure and specific enthalpy for a constant temperature (see Figure 5), regardless of the phase of the working fluid in a single-phase regime.

$$P_i \geq P_{T_{min}}(h(T_i, P_i)) \quad (3)$$

[0092] On the other hand, if the relevant monitoring location is at a point in the vapour-compression system 400 where the working fluid is dual-phase, the translation is even simpler, as the function $P_{sat}(T)$ defined for the superheat above can be used to constraint the pressure between the pressures equivalent to the minimum and maximum temperatures, as per Equation (4) below.

$$P_{sat}(T_{min}) \leq P_i \leq P_{sat}(T_{max}) \quad (4)$$

[0093] A further type of thermofluidic constraint that may be imposed by the pressure limiting logic 200 is one which enforces a specific operating regime of the vapour-compression system 400, such as enforcing a subcritical regime (all pressures below the critical pressure value), a trans-critical regime (evaporation stages below the critical pressure, and cooling monitoring locations in above the critical pressure), or supercritical regimes (all pressures above the critical pressure value). Since each of these constraints are defined directly in the pressure domain, it is straight-forward to include them in a set of pressure limitations to be applied by the pressure limiting logic 200 by simply imposing the minimum or maximum pressure constraints at the relevant monitoring locations.

[0094] By way of example, if a transcritical regime is to be employed, pressure constraints may be added in accordance with Equations (12) and (13) below, which define a subcritical constraint at the first monitoring location 1 (on the suction line 418 and/or at the compressor inlet), and a supercritical constraint at the second monitoring location 2 (on the discharge line 412 and/or as the compressor outlet).

$$P_1 \leq P_{crit} \quad (5)$$

$$P_2 \geq P_{crit} \quad (6)$$

[0095] By way of another example, if a subcritical regime is to be employed, pressure constraints may be added in accordance with Equations (14) and (15) below, which define a subcritical constraint at the first monitoring location 1 (on the suction line 418 and/or at the compressor inlet), and a subcritical constraint at the second monitoring location 2 (on the discharge line 412 and/or as the compressor outlet).

$$P_1 \leq P_{crit} \quad (14)$$

$$P_2 \leq P_{crit} \quad (15)$$

[0096] For completeness, **Figure 7** shows a pressure-enthalpy diagram for an example idealised subcritical regime ammonia (NH₃) working fluid vapour-compression system having an architecture which corresponds to that of the vapour-compression system 400 shown by Figure 2 (i.e., having two evaporators 408A, 408B in series, an internal heat exchanger 409 and the monitoring locations 1-6).

[0097] These functions, relationships and equivalences can be used to enforce all the thermofluidic constraints outlined above, providing a dynamic definition of a maximum and minimum value for both the evaporation pressure (that is, the pressure of the working fluid in the "low-pressure" side of the system 400 at the sixth monitoring location 6) and the condensation/cooling pressure (that is, the pressure of the working fluid in the "high-pressure" side of the system 400 at the second monitoring location 2). For instance, the above-described thermofluidic constraints can be enforced by defining them in the pressure domain for the two system pressures (e.g., the evaporation pressure at the second control location 6 and the condensation pressure at the first control location 2), as outlined in

[0098] Table 1 for a transcritical working fluid regime (e.g., using carbon dioxide as at least part of the working fluid) and as outlined in Table 2 for a subcritical regime (e.g., using ammonia as at least part of the working fluid).

Table 1 - Example definition of thermofluidic constraints for a transcritical regime.

	Compressor inlet protection	Maximum temperature protection	Operating regime (transcritical)	Thermal runaway protection	Constraints
Low pressure	Superheat setpoint for sixth monitoring location 6 (sh_6^{min})	-	Maximum evaporating pressure (P_{crit})	Superheat setpoint for fifth monitoring location 5 (sh_5^{max})	$\leq \min (P_{crit}, P_{sat}(T_6 - sh_6^{min}))$
High pressure	-	Maximum temperature at second monitoring location 2 (T_{max})	Minimum cooling pressure (P_{crit})	-	$P_{crit} \leq P_2 \leq P_{Tmax}(h(T_2, P_2))$

Table 2 - Example definition of thermofluidic constraints for a subcritical regime.

	Compressor inlet protection	Maximum temperature protection	Expansion device protection	Operating regime (subcritical)	Thermal runaway protection	Constraints
Low pressure	Superheat setpoint for sixth monitoring location 6 (sh_6^{min})	-	-	Maximum evaporating pressure (P_{crit})	Superheat setpoint for fifth monitoring location 5 (sh_5^{max})	$\leq \min (P_{crit}, P_{sat}(T_6 - sh_6^{min}))$
High pressure	-	Maximum temperature at second monitoring location 2 (T_{max})	Subcooling setpoint for third monitoring location 3 (sc_3^{min})	Maximum cooling pressure (P_{crit})	-	$\leq \min (P_{crit}, P_{Tmax}(h(T_2, P_2)))$

[0099] Means of translating all of the desired thermofluidic constraints into limits for the two working pressures in the vapour-compression system 400 (e.g., the evaporation pressure at the second control location 6 and the condensation pressure at the first control location 2) of the vapour-compression system 400 are therefore provided. In use, these limits are enforced by the pressure limiting logic 200 so as to trim the preliminary pressure objective values $P_{2|l}$, $P_{6|l}$ outputted by the outer control logic 300 before these are subsequently provided to the inner control logic 800 as final pressure objective values $P_{2|f}$, $P_{6|f}$.

[0100] Returning now to Figure 4, the pressure limiting logic 200 is shown as comprising a first comparator 210 and a second comparator 220. The first comparator 210 receives the first preliminary pressure objective value $P_{2|l}$ as an input and provides the first final pressure objective value $P_{2|f}$ as an output. In a similar way, the second comparator 220 receives the second preliminary pressure objective value $P_{6|l}$ as an input and provides the second final pressure objective value $P_{6|f}$ as an output. Each comparator 210, 220 is configured to determine the respective final pressure objective value $P_{2|f}$, $P_{6|f}$ based on the respective preliminary pressure objective value $P_{2|l}$, $P_{6|l}$ and one or more thermofluidic property objective value thresholds as described in further detail below.

[0101] The first comparator 210 is configured to determine the first final pressure objective value $P_{2|f}$ in accordance with conditional Equation (16) below. Namely, the first comparator 210 is configured to set the first final pressure objective value $P_{2|f}$ as being equal to the first preliminary pressure objective value $P_{2|l}$ if (e.g., when) the first preliminary thermofluidic property objective value $P_{2|l}$ is in a range between a first lower thermofluidic property objective value threshold $P_{2|th,l}$ and a first upper thermofluidic property objective value threshold $P_{2|th,u}$ inclusive. Further, the first comparator 210 is configured to set the first final pressure objective value $P_{2|f}$ as being equal to the first lower thermofluidic property objective value threshold $P_{2|th,l}$ if (e.g., when) the first preliminary thermofluidic property objective value $P_{2|l}$ is less than the first lower thermofluidic property objective value threshold $P_{2|th,l}$. Additionally, the first comparator 210 is configured to set the first final pressure objective value $P_{2|f}$ as being equal to the first upper thermofluidic property objective value threshold $P_{2|th,u}$ if (e.g., when) the first preliminary thermofluidic property objective value $P_{2|l}$ is greater than the first upper thermofluidic

property objective value threshold $P_{2|th,u}$.

[0102] More specifically, and as an example, in order to enforce the thermofluidic constraints discussed above for a transcritical regime, the first lower thermofluidic property objective value threshold $P_{2|th,l}$ may be defined in accordance with Equation (16a) and the first upper thermofluidic property objective value threshold $P_{2|th,u}$ may be defined in accordance with Equation (16b).

$$P_{2|l} = \begin{cases} P_{2|th,l}, & P_{2|r} < P_{2|th,l} \\ P_{2|r}, & P_{2|th,l} \leq P_{2|r} \leq P_{2|th,u} \\ P_{2|th,u}, & P_{2|th,u} < P_{2|r} \end{cases} \quad (16)$$

$$P_{2|th,l} = P_{crit} \quad (16a)$$

$$P_{2|th,u} = P_{T_{max}}(h(T_2, P_2)) \quad (16b)$$

[0103] As another example, in order to enforce the thermofluidic constraints discussed above for a subcritical regime, the first lower thermofluidic property objective value threshold $P_{2|th,l}$ may be defined according to Equation (16c) and the first upper thermofluidic property objective value threshold $P_{2|th,u}$ may be defined according to Equation (16d).

$$P_{2|th,l} = P_{sat}(T_3 + sc_3^{min}) \quad (16c)$$

$$P_{2|th,u} = \min(P_{crit}, P_{T_{max}}(h(T_2, P_2))) \quad (16d)$$

[0104] In a similar way, the second comparator 220 is configured to determine (e.g., set) the second final pressure objective value $P_{6|l}$ in accordance with conditional Equation (17) below. Namely, the second comparator 220 is configured to set the second final pressure objective value $P_{6|l}$ as being equal to the second preliminary pressure objective value $P_{6|r}$ if (e.g., when) the second preliminary thermofluidic property objective value $P_{6|r}$ is in a range between a second lower thermofluidic property objective value threshold $P_{6|th,l}$ and a second upper thermofluidic property objective value threshold $P_{6|th,u}$ inclusive. Further, the second comparator 220 is configured to set the second final pressure objective value $P_{6|l}$ as being equal to the second lower thermofluidic property objective value threshold $P_{6|th,l}$ if (e.g., when) the second preliminary thermofluidic property objective value $P_{6|r}$ is less than the second lower thermofluidic property objective value threshold $P_{6|th,l}$. Additionally, the second comparator 220 is configured to set the second final pressure objective value $P_{6|l}$ as being equal to the second upper thermofluidic property objective value threshold $P_{6|th,u}$ if (e.g., when) the second preliminary thermofluidic property objective value $P_{6|r}$ is greater than the second upper thermofluidic property objective value threshold $P_{6|th,u}$.

[0105] More specifically, in order to enforce the thermofluidic constraints discussed above for a transcritical regime, the second lower thermofluidic property objective value threshold $P_{6|th,l}$ may be defined in accordance with Equation (17a) and the second upper thermofluidic property objective value threshold $P_{6|th,u}$ may be defined in accordance with Equation (17b). The same definitions may be used for a subcritical regime.

$$P_{6|l} = \begin{cases} P_{6|th,l}, & P_{6|r} < P_{6|th,l} \\ P_{6|r}, & P_{6|th,l} \leq P_{6|r} \leq P_{6|th,u} \\ P_{6|th,u}, & P_{6|th,u} < P_{6|r} \end{cases} \quad (17)$$

$$P_{6|th,l} = P_{sat}(T_5 - sh_5^{max}) \quad (17a)$$

$$P_{6|th,u} = \min(P_{crit}, P_{sat}(T_6 - sh_6^{min})) \quad (17b)$$

[0106] **Figure 8** is a schematic diagram showing a detailed block diagram of the inner control logic 800. The inner control logic 800 includes determining, at block 810, a pressure error array ΔP_2 , ΔP_6 as being a difference between the final pressure objective value array $P_{2|l}$, $P_{6|l}$ and system pressure array P_2 , P_6 .

[0107] In a similar way to the outer control logic 300, the inner control logic 800 includes a proportional-integral (PI)

action, represented by blocks 820, 830, 840 and 850, for determining the preliminary actuator operating parameter objective array ω_{clr}, u_{vlr} . The PI action is carried out with the intention of reducing each pressure error value (ideally to zero). The inner control logic 800 further includes an anti-windup action for correcting possible wind-up associated with the integral aspect of the PI action, which is implemented by application of a backstepping gain as described in further detail below. That is, including the integral aspect in the PI action may, in turn, cause problems when the final pressure objective values P_{2lf}, P_{6lf} are effectively unattainable and/or due to the action of the actuator operating parameter objective limiting logic 900 described below. In this case, the pressure error array $\Delta P_2, \Delta P_6$ will tend to keep increasing, causing the so-called windup effect. Therefore, an anti-windup action is also included, synthesized using a backstepping gain K_p^b as explained in further detail below.

[0108] To capture possible wind-up associated with any unattainability of the final pressure objective values P_{2lf}, P_{6lf} and the action of the actuator operating parameter objective limiting logic 900, the backstepping gain K_p^b is applied in respect of the final actuator operating parameter objective array ω_{clr}, u_{vlr} .

[0109] The application of a proportional gain K_p^p to the pressure error array $\Delta P_2, \Delta P_6$ to produce a proportional preliminary actuator parameter term array $\omega_{clr}^p, u_{vlr}^p$ is represented by block 820. The preliminary actuator operating parameter objective array ω_{clr}, u_{vlr} is subtracted from the final actuator operating parameter objective array $\omega_{clr}^b, u_{vlr}^b$ at block 860 to yield a backstepping actuator operating parameter array ω_c^b, u_v^b . In turn, the application of a backstepping gain K_p^b to the backstepping actuator operating parameter array ω_c^b, u_v^b to produce a backstepping pressure array P_2^b, P_6^b is represented by block 870. The pressure error array $\Delta P_2, \Delta P_6$ and the backstepping pressure array P_2^b, P_6^b are added at block 880 to produce a backstepped pressure error array $\Delta P_2^b, \Delta P_6^b$. The time-integration of the backstepped pressure error array $\Delta P_2^b, \Delta P_6^b$ and the application of an integral gain K_p^i to a time-integral pressure array to produce an integral preliminary actuator parameter term array $\omega_{clr}^i, u_{vlr}^i$ is represented by blocks 830 and 840, respectively. The proportional preliminary actuator parameter term array $\omega_{clr}^p, u_{vlr}^p$ and the integral preliminary actuator parameter term array $\omega_{clr}^i, u_{vlr}^i$ are then added, as represented by block 850, to produce the preliminary actuator operating parameter objective array ω_{clr}, u_{vlr} .

[0110] As a result, the preliminary actuator operating parameter objective array ω_{clr}, u_{vlr} is determined based on both the final pressure objective value array P_{2lf}, P_{6lf} and the final actuator operating parameter objective array ω_{clr}, u_{vlr} . Each of the gains K_p^p, K_p^b, K_p^i described above are in the form of 2 by 2 matrices, and application of the gains K_p^p, K_p^b, K_p^i at blocks 820, 840 and 870 is performed using matrix multiplication of the relevant arrays and gain matrices.

[0111] It follows that each of the preliminary compressor operating parameter objective value ω_{clr} and the preliminary expansion device operating parameter objective value u_{vlr} are determined based on both the first final pressure objective value P_{2lf} and the second final pressure objective value P_{6lf} . In other words, the preliminary compressor operating parameter objective value ω_{clr} is influenced by both the first final pressure objective value P_{2lf} and the second final pressure objective value P_{6lf} and the preliminary expansion device operating parameter objective value u_{vlr} is influenced by both the first final pressure objective value P_{2lf} and the second final pressure objective value P_{6lf} . For this reason, the inner control logic 800 described with respect to Figures 2 and 8 may be referred to as a multivariable inner control logic 800 or a multiple-input multiple-output (MIMO) inner control logic 800.

[0112] This multivariable nature of the inner control logic 800 addresses coupling effects when using both actuators 402, 406 simultaneously and allows for faster time responses to changes in the operating conditions of the vapour-compression system 400. Further, including an anti-windup action in the multivariable inner control logic 800 permits the minimisation of the pressure error array $\Delta P_2, \Delta P_6$ (in a multivariable sense) in case of one of the actuators 402, 406 becoming saturated (e.g., due to the action of the actuator operating parameter objective limiting logic 900).

[0113] Figure 9 is a schematic diagram showing a detailed block diagram of the actuator operating parameter objective limiting logic 900. The actuator operating parameter objective limiting logic 900 is generally adapted to enforce safe and effective operating parameter constraints for the actuators 402, 406.

[0114] The actuator operating parameter objective limiting logic 900 is shown as comprising a compressor parameter comparator 910 and an expansion device parameter comparator 920. The compressor parameter comparator 910 receives the preliminary compressor operating parameter objective value ω_{clr} as an input and provides the final compressor operating parameter objective value ω_{cl} as an output. In a similar way, the expansion device parameter comparator 920 receives the preliminary expansion device operating parameter objective value u_{vlr} as an input and provides the final expansion device operating parameter objective value u_{vl} as an output.

[0115] The compressor parameter comparator 910 is configured to determine the final compressor operating parameter objective value ω_{cl} based on the preliminary compressor operating parameter objective value ω_{clr} and one or more compressor speed objective value thresholds. The one or each compressor speed objective value threshold may be defined according to physical limitations of the compressor 402 or maximum recommended operational conditions for the compressor 402, the latter being recommended for safety and/or performance purposes. Similarly, the expansion device parameter comparator 920 is configured to determine the final expansion device operating parameter objective value u_{vl} based on the preliminary expansion device operating parameter objective value u_{vlr} and one or more expansion device operating parameter objective value thresholds. The one or each expansion device operating parameter objective value

threshold may be defined according to physical limitations of the expansion device 406 or maximum recommended operational conditions for the expansion device 406, with the latter being recommended for safety and/or performance purposes in a similar way to that described immediately above with respect to the compressor 402.

[0116] Preferred embodiments of the present disclosure relate to a two cascaded control loop method for controlling a vapour-compression system 400, with a pressure limiting logic which is configured to enforce particular thermofluidic constraints. This is associated with a variety of advantages as follows.

[0117] Organising the controller 490 in two cascaded control logics (e.g., inner and outer control logics 300, 800) and choosing the pressure as intermediate variable (that is, as the variable which links both control logics 300, 800), enables explicit thermofluidic constraint enforcement in the pressure domain. More particularly, these thermofluidic constraints will be implicitly enforced by the inner control logic 800 when the inputs thereto are selectively limited by the pressure limiting logic 200. Managing system constraints in an explicit manner is a preferred strategy in practical industry, in contrast to "indirect" constraints handling techniques such as model predictive control.

[0118] The arrangement described herein for the pressure limiting logic 200 allows for the translation of any superheat, subcooling, temperature and/or pressure conditions into the pressure domain, by a set of transformations using appropriate fluid functions. These transformations allow to define the minimum and maximum values for the two system pressures in an intuitive manner, providing a better understanding on the conditions to be imposed on the working fluid for safe and/or efficient operation of the vapour-compression system 400.

[0119] The configuration of the outer control logic 300 and/or the inner control logic 800 as multivariable control logics enables more effective control performance, as any coupling between physical effects in the vapour-compression system 400 caused by the different actuators is attenuated. This enables improved multivariable performance of the controller 490. Further, the present disclosure described the addition of an observer-based anti-windup action to each control logic, which in the case of the outer control logic 300, does not rely on any transformations to signals associated with the inner control logic 800, but instead directly uses the measurements from the vapour-compression system 400. The design of each of the outer and inner control logic gains is straightforward using readily available synthesis tools, permitting an intuitive tuning process.

[0120] Since the thermofluidic constraints are explicitly managed by the pressure limiting control logic 200, there is no need to dedicate one of the actuators 402, 406 to track (e.g., maintain) a specific level of superheat (which is the common rule of thumb in the technical field). Instead, in accordance with the present disclosure, the two degrees of freedom of control available in the vapour-compression system 400 (which are the two pressures in the outer-loop controller), can be entirely devoted to attempting to track two different temperature targets in two thermal sources 407A, 407B, attached to separate evaporators 408A, 408B that may be arranged in series as shown in Figure 2 (and are therefore effectively working at the same pressure). This provides a benefit of allowing cooling of an additional source to be provided by the vapour-compression system 400 without significantly increasing system complexity or compromising system safety.

[0121] Although it has been described, with reference to the accompanying drawings, that the outer control logic 300 and the inner control logic 800 each include a PI action, this need not necessarily be the case. Namely, this disclosure contemplates that either or both of the outer control logic 300 and the inner control logic 800 may include additional and/or alternative actions, such as a proportional-integral-derivative (PID) action or a linear-quadratic regulation (LQR) action. The methodologies described herein are equally applicable to such actions, including the application of backstepping gain(s) as discussed above.

[0122] The present disclosure also anticipates that the respective temperatures T_a , T_b of the thermal sources 407A, 407B may be predicted based on other parameters of the thermal sources 407A, 407B rather than being directly monitored using temperature sensing apparatus. For instance, if the or each thermal source 407A, 407B comprises an electrical device, the temperatures T_a , T_b of the thermal sources 407A, 407B may be predicted based on a power consumption of the or each electrical device.

[0123] Figure 10 shows a schematic arrangement of a second example vapour-compression system 400' and a block diagram for a second example controller 490'. The second example vapour-compression system 400' is generally similar to the first example vapour-compression system 400 described above with reference to Figure 2, with like reference signs indicating common or similar features. Likewise, the second example controller 490' is generally similar to the first example controller 490, with like reference signs denoting common or similar features.

[0124] However, in the second example controller 490', the functionality of the outer control logic 300, the pressure limiting logic 200, the inner control logic 800 and the actuator operating parameter objective limiting logic 900 described with respect to the first example controller 490' is split between a pair of outer control logics 300, 300', a pair of pressure limiting logics 200, 200', a pair of inner control logics 800, 800' and a pair of actuator operating parameter objective limiting logics 900, 900'.

[0125] That is, each outer control logic 300, 300' is configured to receive a respective source temperature T_a , T_b from the signal processing module 495 as an input and to provide a respective preliminary pressure objective value $P_{2|p}$, $P_{6|p}$ as output to the corresponding pressure limiting logic 200, 200'. In turn, the pressure limiting logics 200, 200' are each configured to receive a respective system temperature T_2 , T_6 , a respective preliminary pressure objective value $P_{2|p}$, $P_{6|p}$

and a respective system pressure P_2, P_6 from the signal processing module 495 as inputs and to provide a respective final pressure objective value $P_{2|f}, P_{6|f}$ as an output to the inner control logic 800, 800'. Each inner control logic 800, 800' is configured to receive a respective system pressure P_2, P_6 and a respective final pressure objective value $P_{2|f}, P_{6|f}$ as inputs and to provide a respective preliminary actuator operating parameter objective $\omega_{c|f}, u_{v|f}$ as an output to the respective actuator operating parameter objective limiting logic 900, 900'. Lastly, the actuator operating parameter objective limiting logics 900, 900' are each configured to receive a respective preliminary actuator operating parameter objective $\omega_{c|f}, u_{v|f}$ as an input and to provide a respective final actuator operating parameter objective $\omega_{c|f}, u_{v|f}$ as an output to the respective actuator 402, 406 of the vapour-compression system 400.

[0126] Consequently, in the example of Figure 10, each outer control logic 300, 300' may be referred to as a univariable outer control logic 300, 300' or a single-input single-output (SISO) outer control logic 300, 300'. For the same reasoning, each inner control logic 800, 800' may be referred to as a univariable inner control logic 800, 800' or a single-input single-output (SISO) inner control logic 800, 800'.

[0127] In particular, each one of the pairs of control logics forms a part of a separate control path of the controller 490'. A first control path comprises a first of the outer control logics 300, a first of the pressure limiting logics 200, a first of the inner control logics 800 and a first of the actuator operating parameter objective limiting logics 900. Conversely, a second control path comprises a second of the outer control logics 300', a second of the pressure limiting logics 200', a second of the inner control logics 800' and a second of the actuator operating parameter objective limiting logics 900'. The first control path relates to control of the expansion device 406 alone, whereas the second control path relates to control of the compressor 402 alone. In some examples in accordance with the present disclosure, each control path may be implemented using a separate controller and/or a separate processor.

[0128] Figure 11 shows a schematic arrangement of a third example vapour-compression system 400" and a block diagram for a third example controller 490". The third example vapour-compression system 400' is generally similar to the first example vapour-compression system 400 described above with reference to Figure 2 and the second example vapour-compression system 400' described above with reference to Figure 10, with like reference signs indicating common or similar features. Likewise, the third example controller 490" is generally similar to the first example controller 490 and the second example controller 490', with like reference signs denoting common or similar features.

[0129] Nevertheless, in contrast to the first example vapour-compression system 400 and the second example vapour-compression system 400', the third example vapour-compression system 400" comprises only a single evaporator 408A. As a consequence, the third example controller 490" is configured differently to the first example controller 490. Namely, the outer control logic 300 is configured to only receive the first source temperature T_a from the signal processing module 495 as an input and to provide the first preliminary pressure objective value $P_{2|f}$ as output to the pressure limiting logic 200. Moreover, the pressure limiting logic 200 is only configured to receive the first system temperature T_2 , the first preliminary pressure objective value $P_{2|f}$ and the system pressure array P_2, P_6 from the signal processing module 495 as inputs and to provide the first final pressure objective value $P_{2|f}$ as an output to the inner control logic 800. The inner control logic 800 is also configured to receive the second final pressure objective value $P_{6|f}$ from a dedicated pre-processing logic 496, such that the inner control logic 800 is configured to receive the complete final pressure objective value array $P_{2|f}, P_{6|f}$. Accordingly, in the example of Figure 11, the outer control logic 300 is as a univariable outer control logic 300 as described with respect to Figure 10 while the inner control logic 800 is as a multivariable inner control logic 800 as described with respect to Figure 2.

[0130] The dedicated pre-processing logic 496 is configured to receive the second system temperature T_6 from the appropriate system sensing arrangement and to output the second final pressure objective value $P_{6|f}$ to the inner control logic 800. The dedicated pre-processing logic 496 determines the second final pressure objective value $P_{6|f}$ based on the

second system temperature T_6 by application of Equation (18), where sh_6^{min} is the superheat setpoint for the working fluid at the sixth monitoring location 6, and the function P_{sat} is as described above in respect of the examples of Figures 5 to 7.

$$P_{6|f} = P_{sat}(T_6 - sh_6^{min}) \quad (18)$$

[0131] Figure 12 shows, highly schematically, a machine-readable medium 600 having stored thereon a computer program 60 comprising instructions which, when executed by the controller 490 provided to a vapour-compression system in accordance with the example vapour-compression systems as described above with reference to Figures 2, 10 and 11, cause the controller 490 to execute a method of controlling the vapour-compression system as described herein with reference to Figures 2 to 11.

[0132] Various examples have been described, each of which feature various combinations of features. It will be appreciated by those skilled in the art that, except where clearly mutually exclusive, any of the features may be employed separately or in combination with any other features and the disclosure extends to and includes all combinations and

subcombinations of one or more features described herein.

[0133] The examples described above have been provided in the context of vapour-compression systems comprising either a single evaporator 408 or both a primary evaporator 408A and a secondary evaporator 408B (i.e., both primary evaporator 408A and a secondary evaporator 408B). Nevertheless, this disclosure envisages that the methodologies described herein may be applied to vapour-compression systems comprising more than two evaporators. That is, vapour-compression system in accordance with the present disclosure may comprise more than one additional evaporators, with each optionally being configured to facilitate heat transfer from a respective additional thermal source into the working fluid, and methods of control thereof may include controlling the compressor, the expansion device and/or additional actuators provided to the vapour-compression system (e.g., valves) in accordance with the methodologies described herein.

[0134] It will also be appreciated that whilst the disclosure has been described with reference to aircraft and aircraft propulsion systems, the techniques described herein could be used for many other applications. These include, but are not limited to, automotive, marine and land-based applications.

Claims

1. A method of controlling a vapour-compression system for circulating a working fluid, the vapour-compression system comprising a compressor, an expansion device and an evaporator configured to facilitate heat transfer from a thermal source into the working fluid, the method comprising:

determining or receiving a cooling demand, the cooling demand being associated with a demand to cool the thermal source;

determining a preliminary thermofluidic property objective value based on the cooling demand;

determining a final thermofluidic property objective value based on the preliminary thermofluidic property objective value and one or more thermofluidic property objective value thresholds, wherein the final thermofluidic property objective value relates to a target thermofluidic property of the working fluid at a control location within the vapour-compression system; and

controlling at least one of the compressor and the expansion device based on the final thermofluidic property objective value.

2. The method of Claim 1, wherein the final thermofluidic property objective value relates to a target pressure of the working fluid at the control location.

3. The method of Claim 1 or Claim 2, comprising:

monitoring a thermofluidic property of the working fluid at the control location, and

determining the preliminary thermofluidic property objective value based on both the cooling demand and the monitored thermofluidic property of the working fluid at the control location.

4. The method of any one of the preceding claims, comprising:
determining the cooling demand based on:

a temperature setpoint for the thermal source; and

a monitored or predicted temperature of the thermal source.

5. The method of any one of the preceding claims, comprising:

determining the or each thermofluidic property objective value threshold based on at least one of:

a desired maximum temperature for working fluid in the vapour-compression system;

a critical pressure for working fluid in the vapour-compression system;

a superheat setpoint and/or a subcooling setpoint for the working fluid in the vapour-compression system; and

a monitored temperature of the working fluid in the vapour-compression system.

6. The method of any one of the preceding claims, wherein the control location is:

at an outlet of the evaporator;

on a suction line of the vapour-compression system, the suction line extending from the evaporator to the

compressor;
at an outlet of the compressor; or
on a discharge line of the vapour-compression system, the discharge line extending from the compressor to a condenser or a cooler of the vapour-compression system.

7. The method of any one of the preceding claims, wherein the control location is at the outlet of the evaporator or on the suction line of the vapour-compression system, and wherein the method comprises:
controlling the expansion device based on the final thermofluidic property objective value.

8. The method of any one of the preceding claims, wherein the control location is at the outlet of the compressor or on the discharge line of the vapour-compression system, and wherein the method comprises:
controlling the compressor based on the final thermofluidic property objective value.

9. The method of any one of the preceding claims, comprising:
determining the final thermofluidic property objective value based on the preliminary thermofluidic property objective value, a lower thermofluidic property objective value threshold and an upper thermofluidic property objective value threshold.

10. The method of Claim 9, wherein determining the final thermofluidic property objective value includes:

setting the final thermofluidic property objective value as being equal to the preliminary thermofluidic property objective value if the preliminary thermofluidic property objective value is in a range between the lower thermofluidic property objective value threshold and the upper thermofluidic property objective value threshold inclusive;

setting the final thermofluidic property objective value as being equal to the lower thermofluidic property objective value threshold if the preliminary thermofluidic property objective value is less than the lower thermofluidic property objective value threshold; and

setting the final thermofluidic property objective value as being equal to the upper thermofluidic property objective value threshold if the preliminary thermofluidic property objective value is greater than the upper thermofluidic property objective value threshold.

11. The method of any one of the preceding claims, comprising:

determining an additional final thermofluidic property objective value, wherein the additional final thermofluidic property objective value relates to a target thermofluidic property of the working fluid at an additional control location within the vapour-compression system; and

controlling the compressor and/or the expansion device based on the final thermofluidic property objective value and the additional final thermofluidic property objective value.

12. The method of Claim 11, wherein the vapour-compression system further comprises an additional evaporator configured to facilitate heat transfer from an additional thermal source into the working fluid, and wherein the method comprises:

determining or receiving an additional cooling demand, the additional cooling demand being associated with a demand to cool the additional thermal source;

determining an additional preliminary thermofluidic property objective value based on the additional cooling demand; and

determining the additional final thermofluidic property objective value based on the additional preliminary thermofluidic property objective value and one or more additional thermofluidic property objective value thresholds.

13. The method of Claim 12, wherein the method comprises:

determining the preliminary thermofluidic property objective value based on both the cooling demand and the additional cooling demand; and

determining the additional preliminary thermofluidic property objective value based on both the additional cooling demand and the cooling demand.

14. The method of any one of the preceding claims, comprising:

determining a preliminary compressor speed objective value based on the final thermofluidic property objective value;

determining a final compressor speed objective value based the preliminary compressor speed objective value and one or more compressor speed objective value thresholds; and

controlling a speed of the compressor based on the final compressor speed objective value.

15. A vapour-compression system for circulating a working fluid, the vapour-compression system comprising a compressor, an expansion device, an evaporator configured to facilitate heat transfer from a thermal source into the working fluid, and a controller configured to carry out the method of any one of the preceding claims.

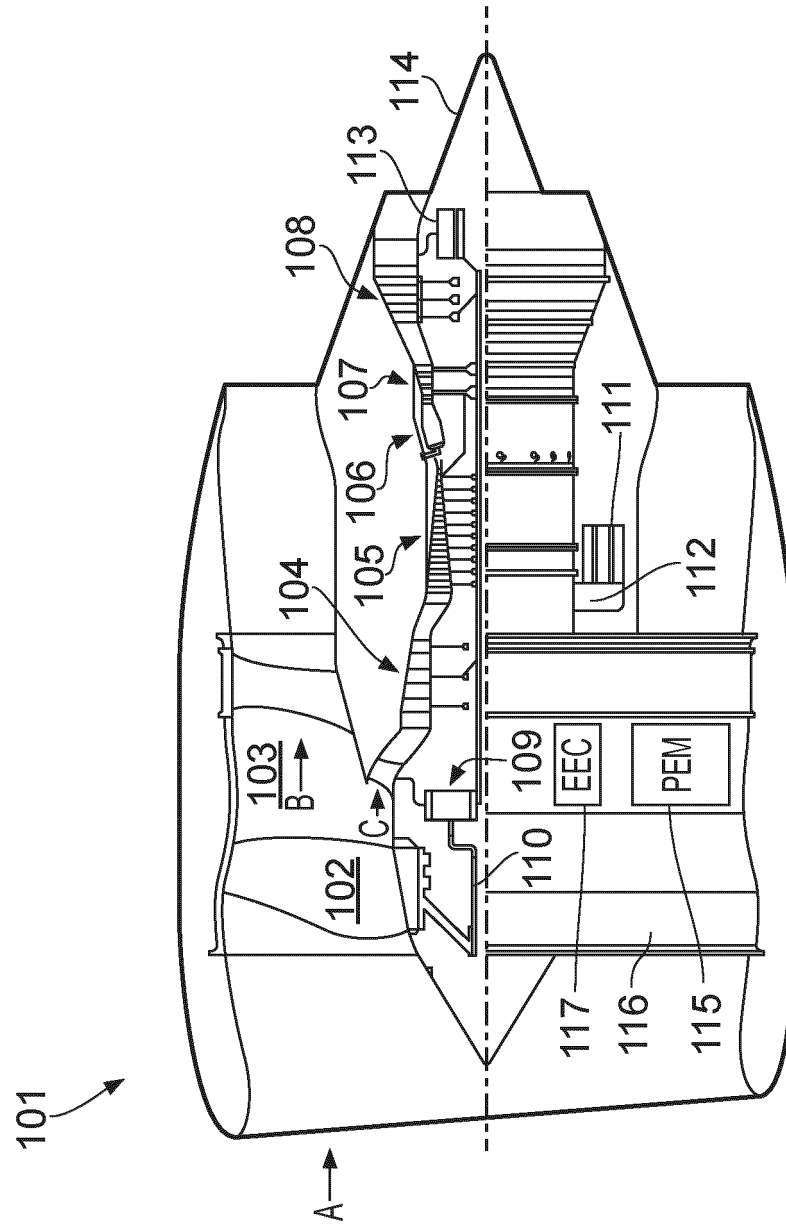


FIG. 1

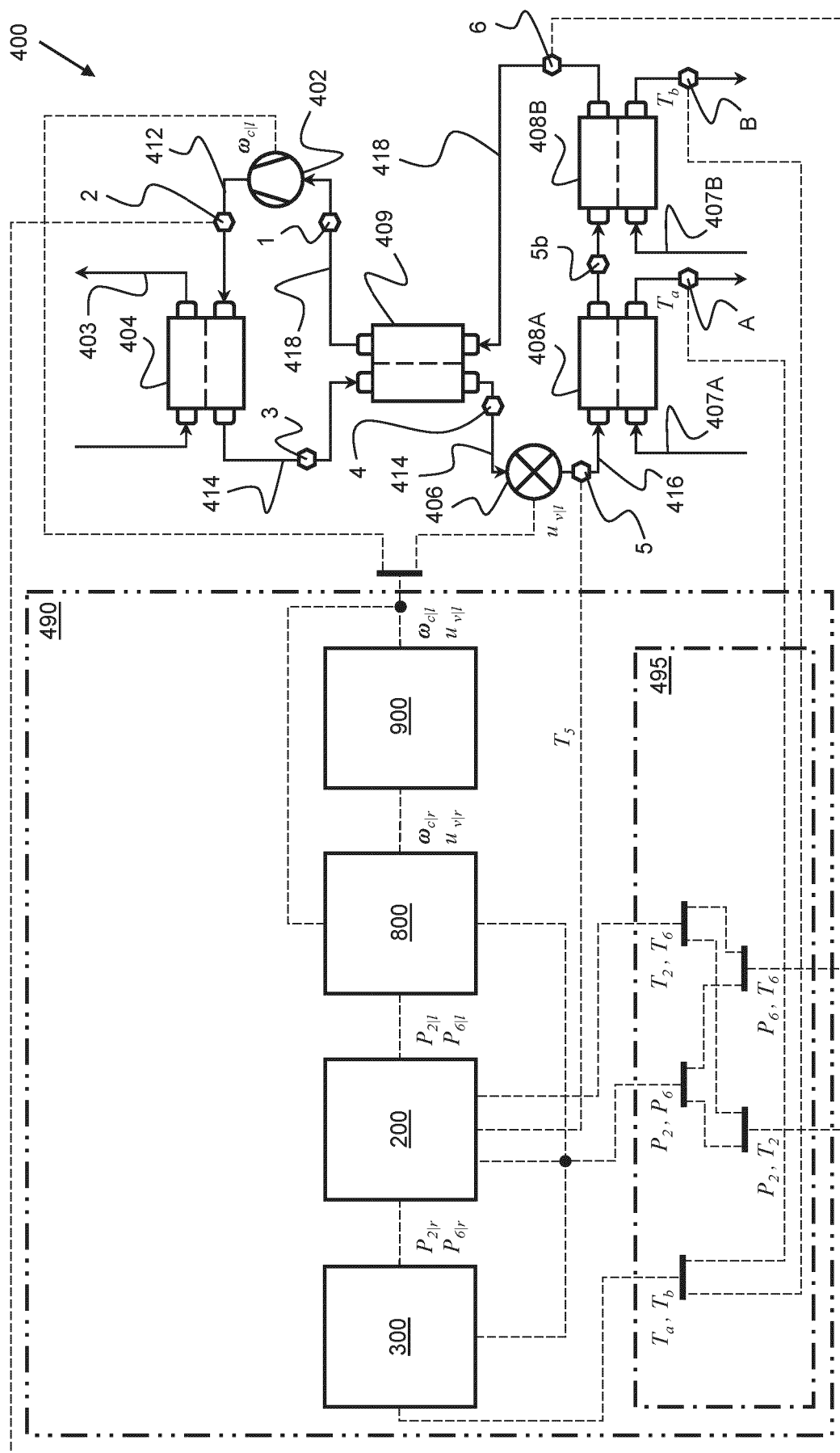


FIG. 2

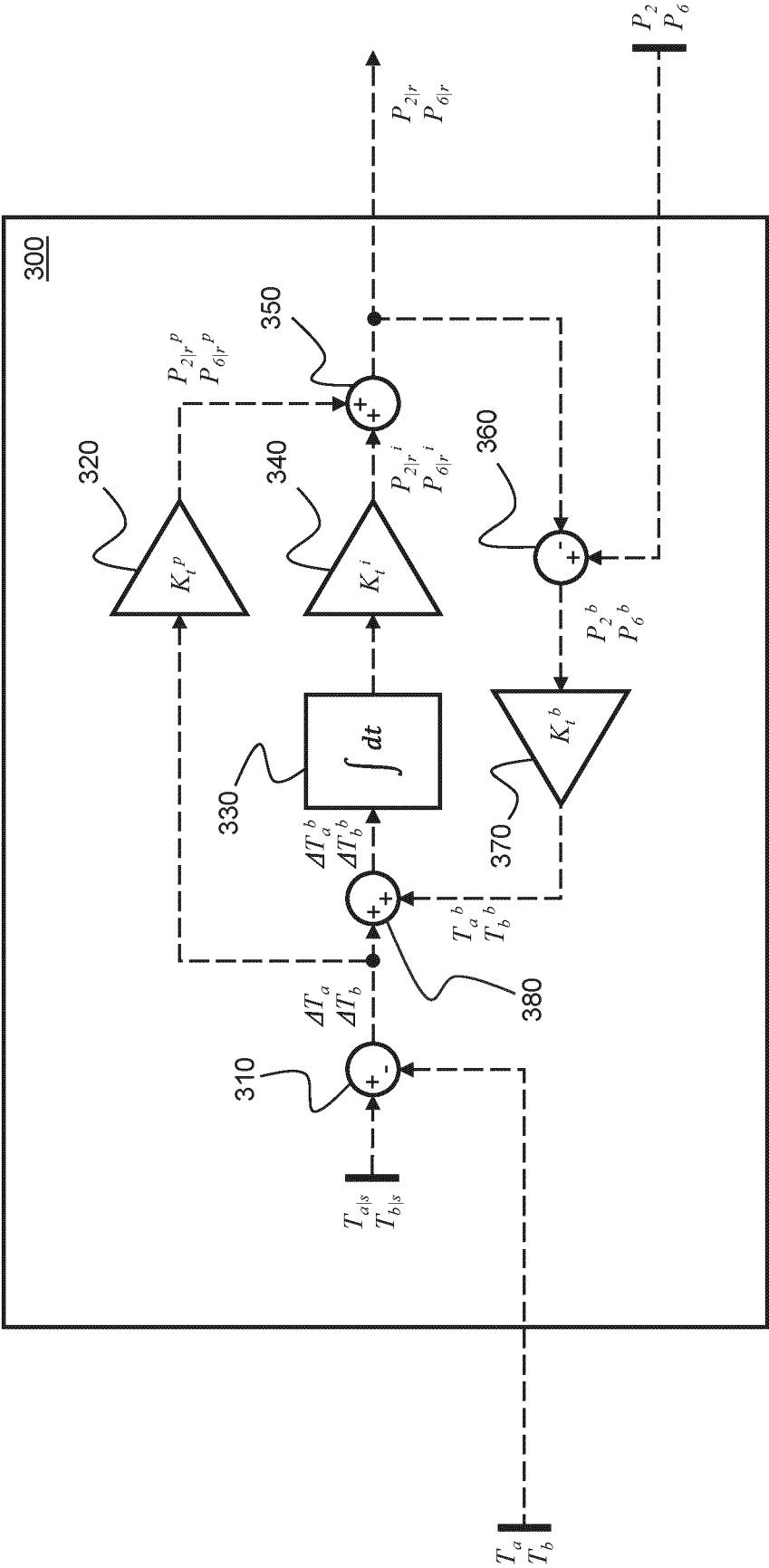


FIG. 3

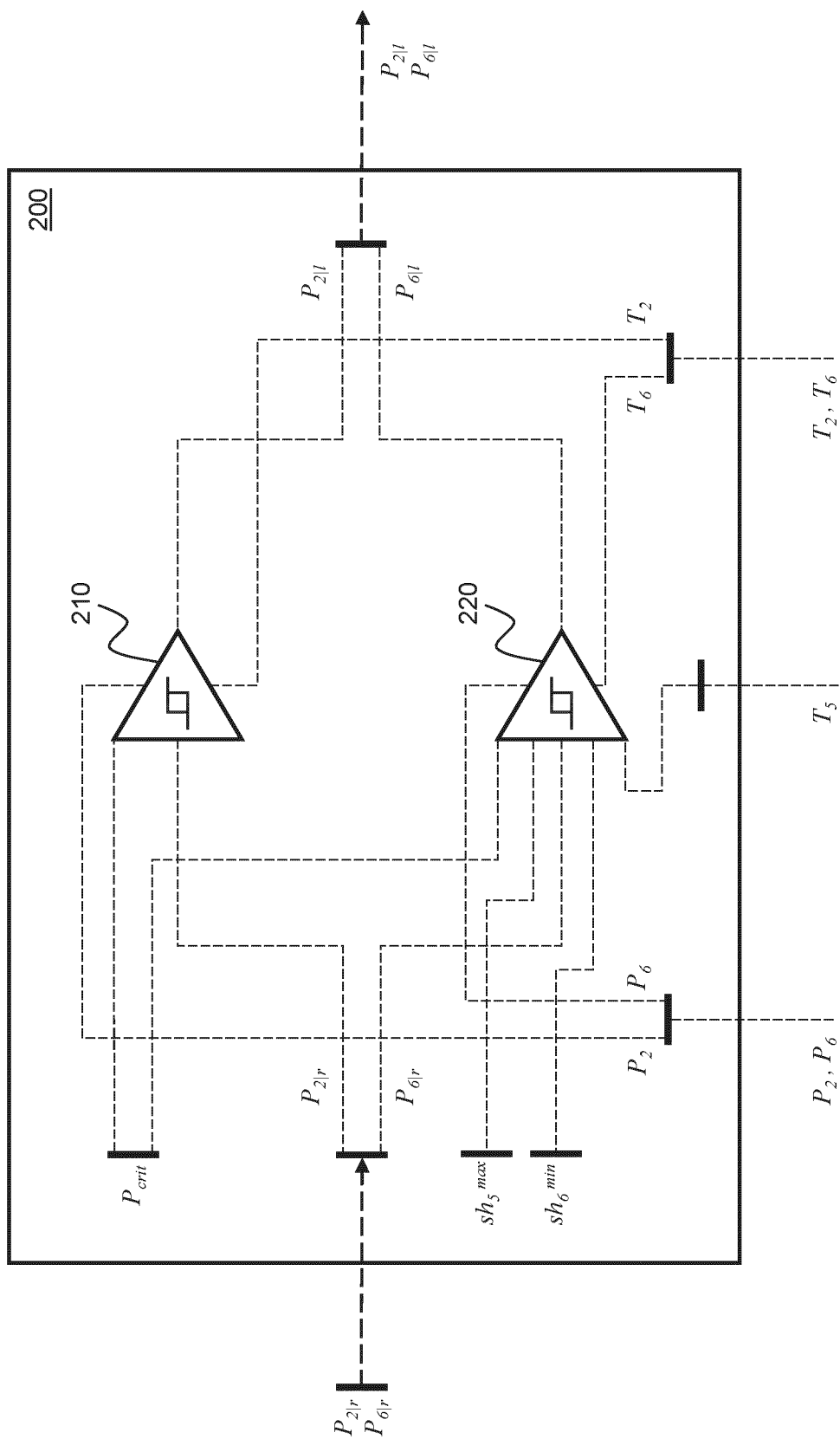


FIG. 4

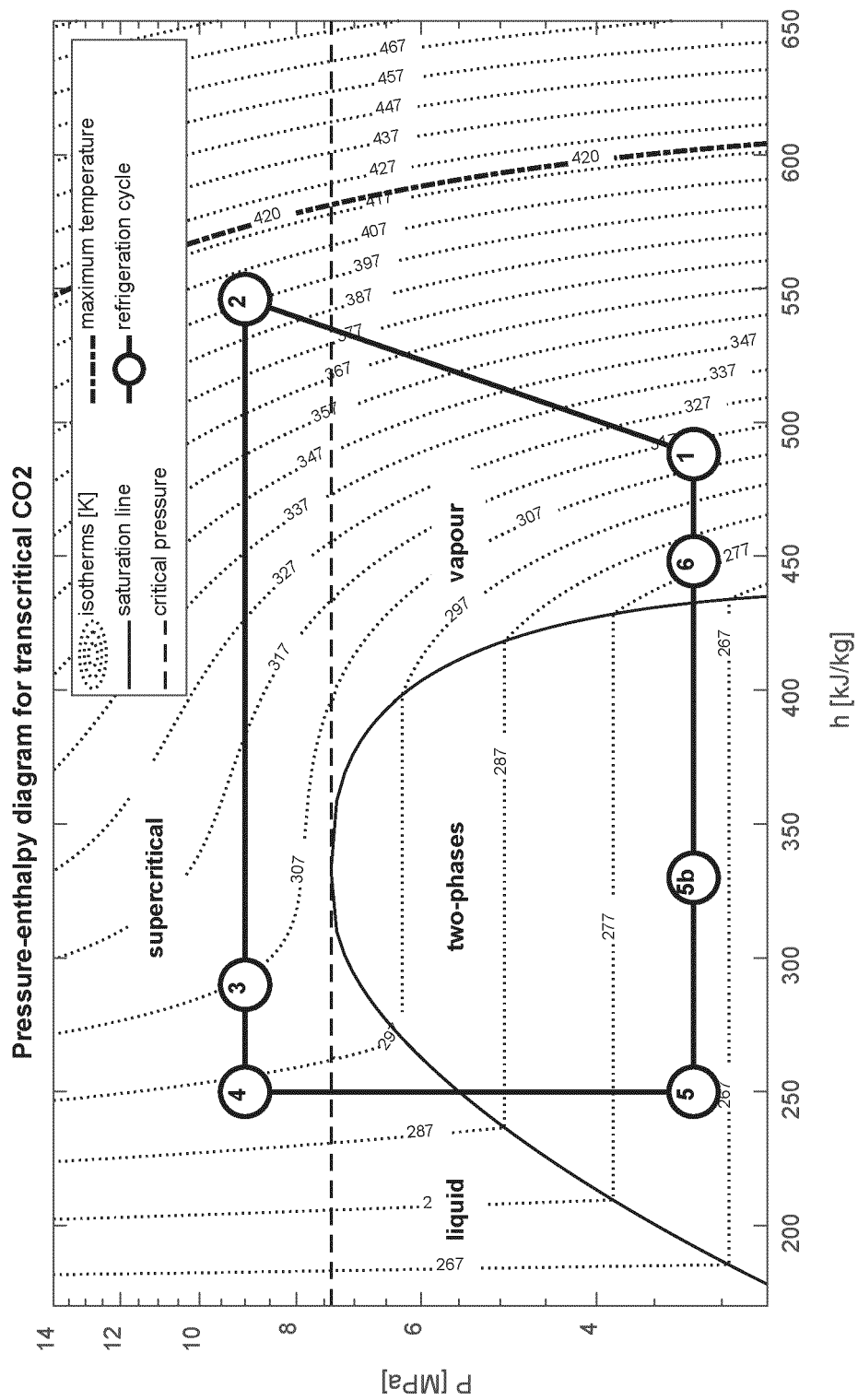


FIG. 5

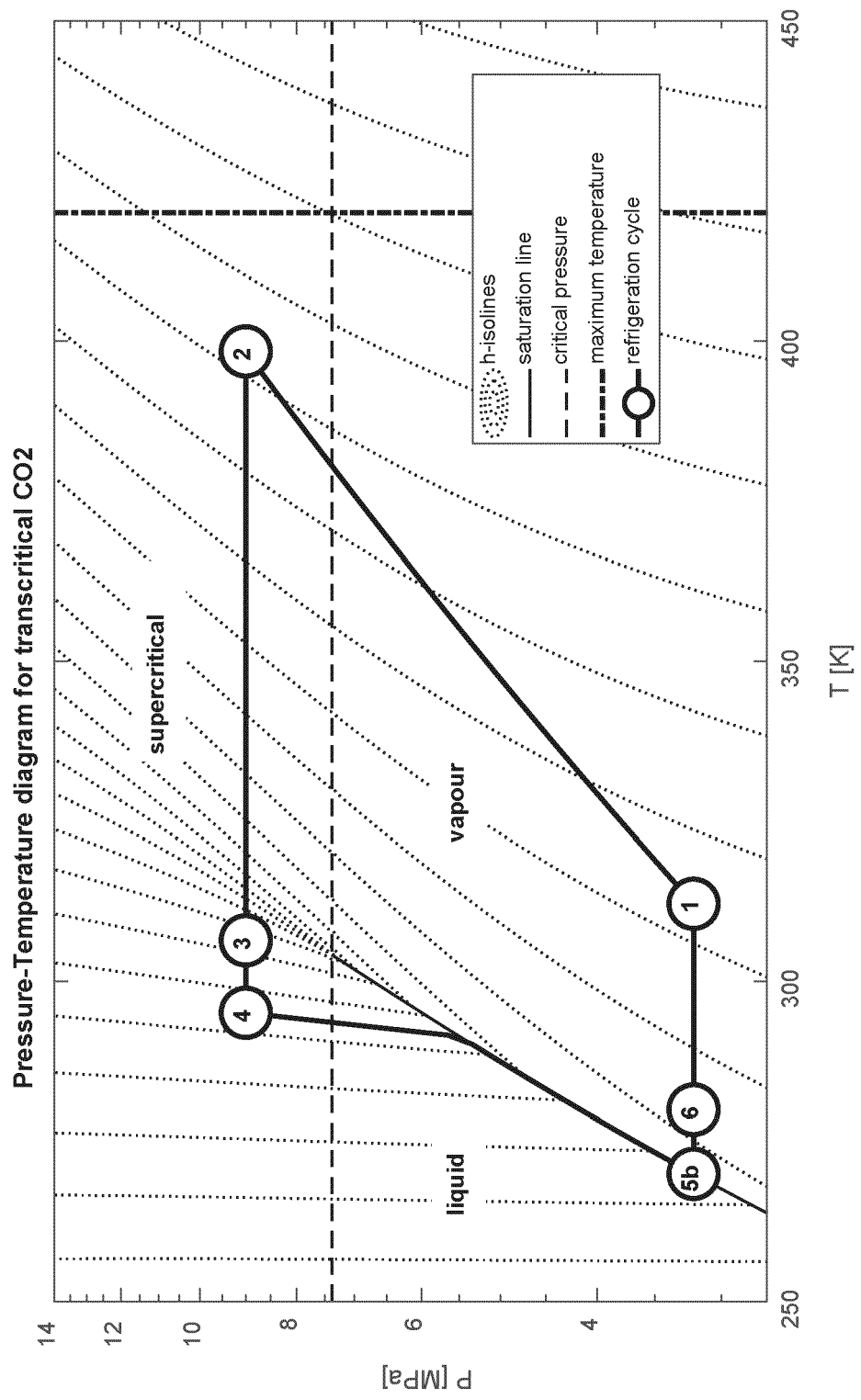


FIG. 6

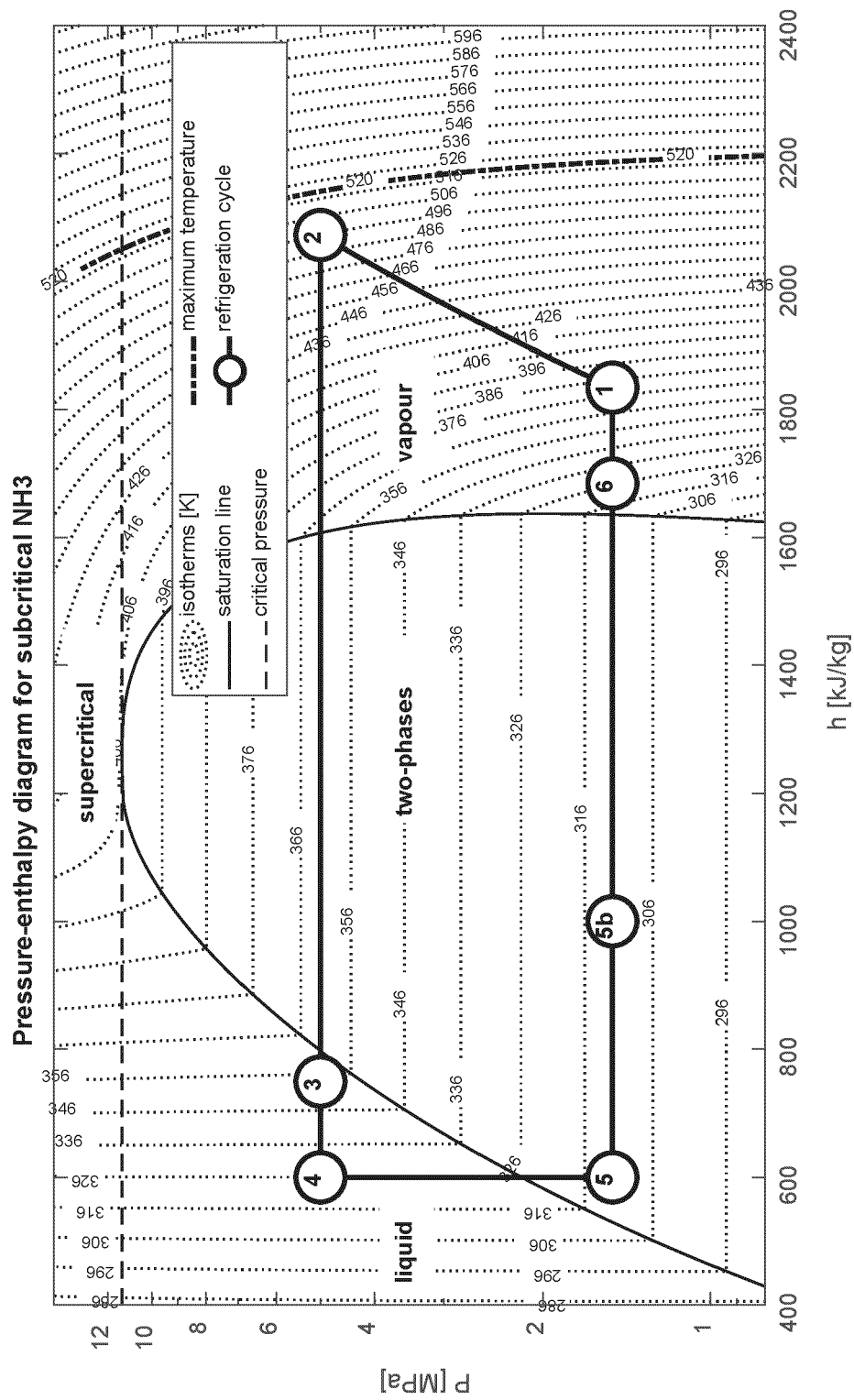


FIG. 7

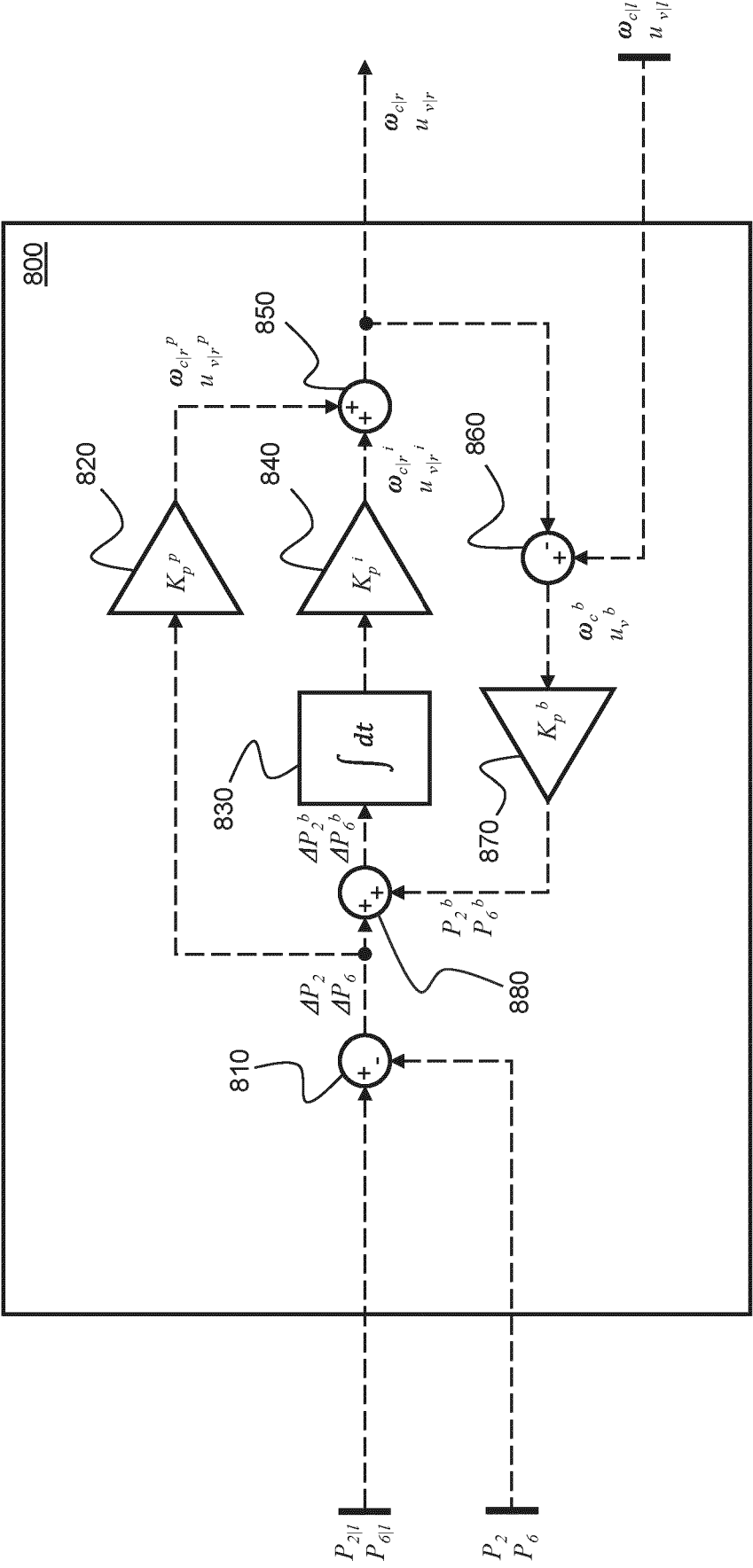


FIG. 8

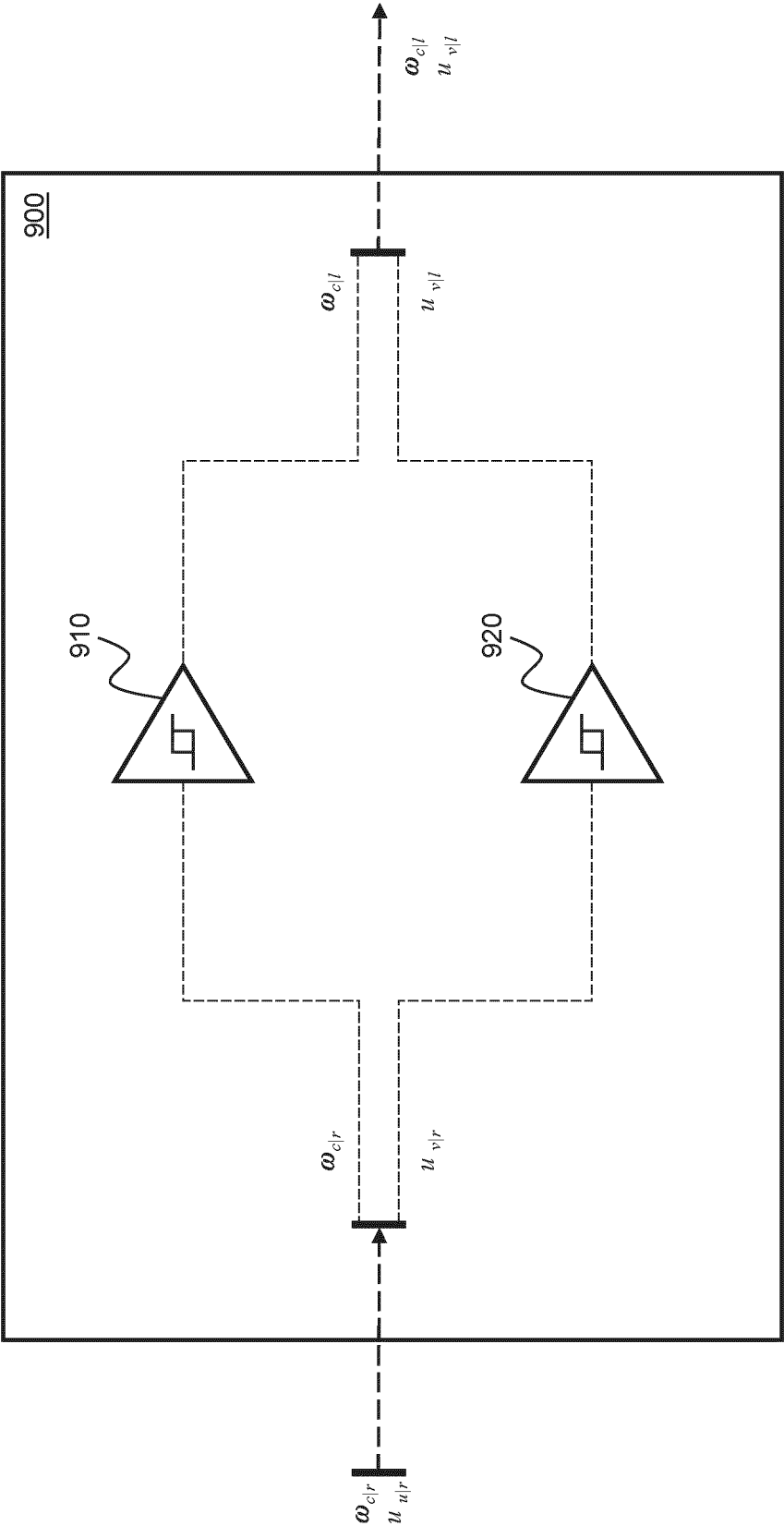


FIG. 9

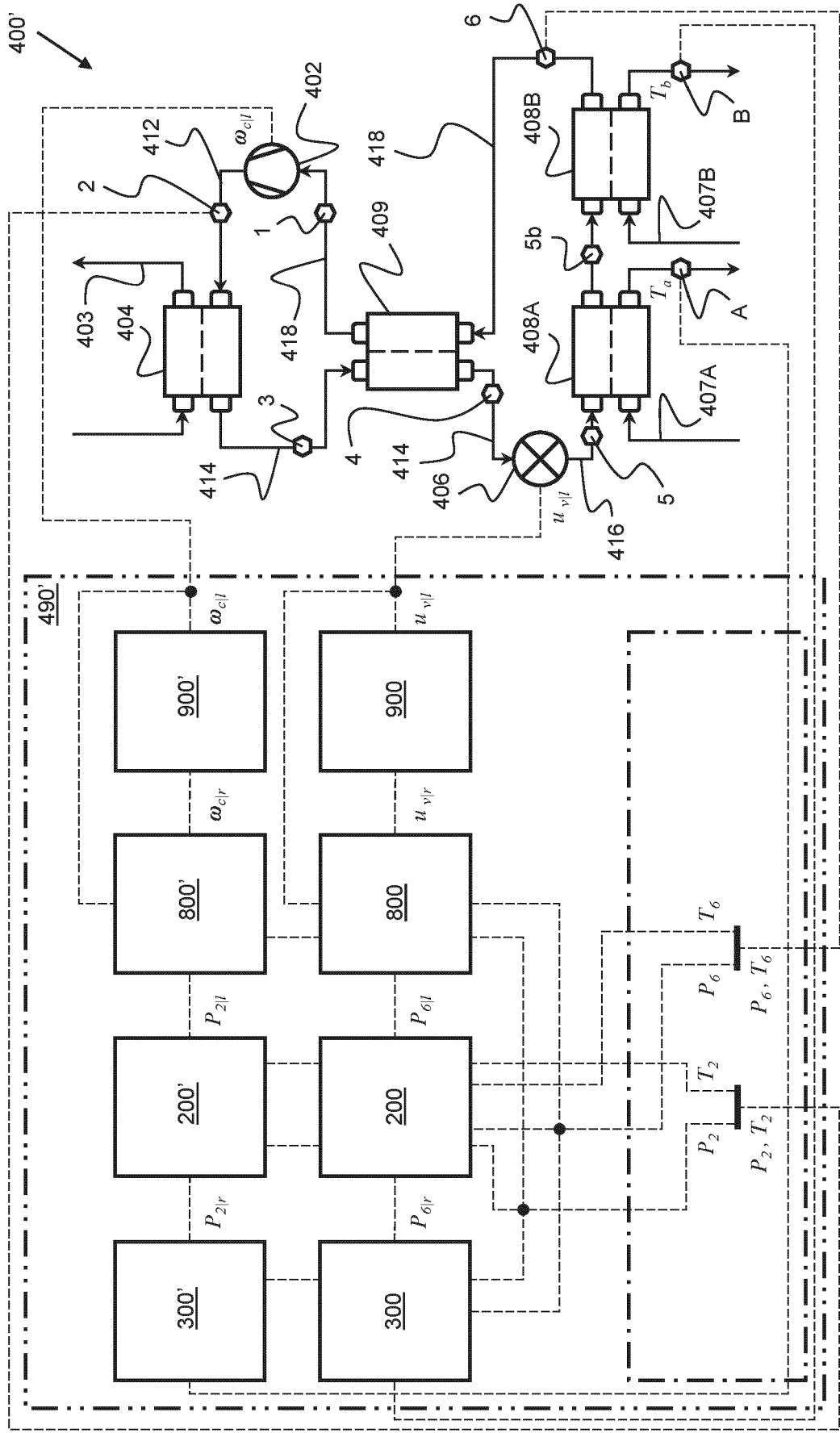


FIG. 10

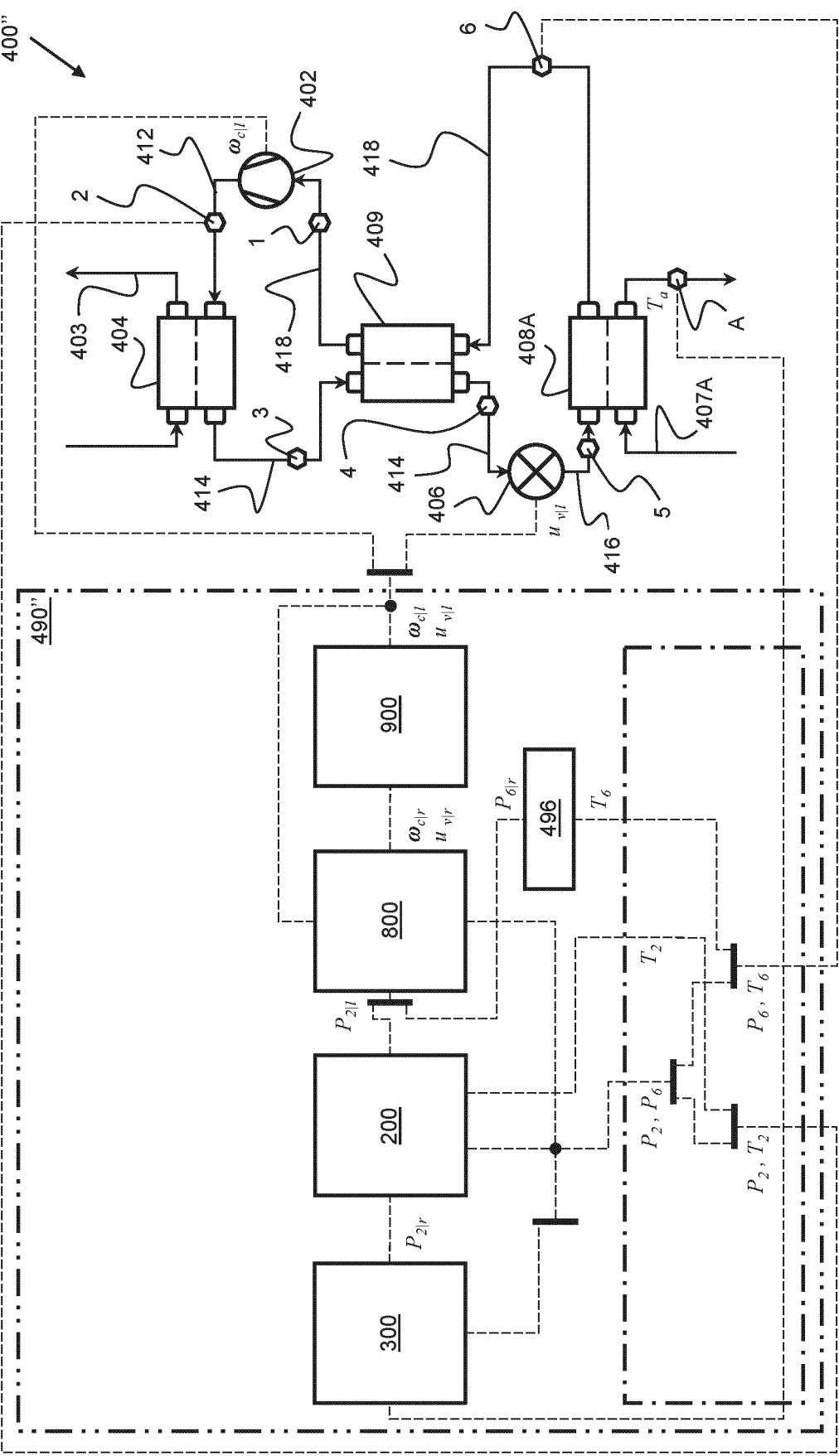


FIG. 11

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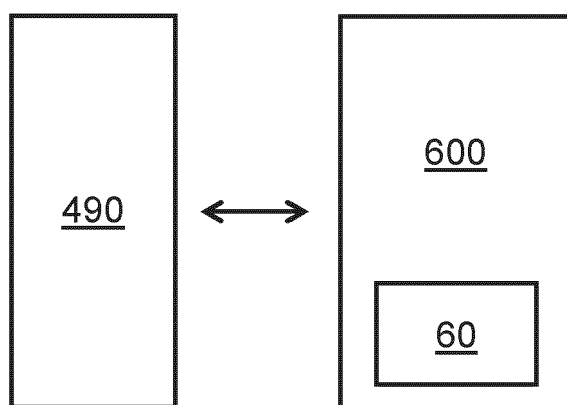


FIG. 12



EUROPEAN SEARCH REPORT

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23 - 04 - 2025

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REFERENCES CITED IN THE DESCRIPTION

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