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METHOD AND APPARATUS FOR COOLING DOWN A CRYOGENIC HEAT EXCHANGER AND METHOD OF LIQUEFYING A HYDROCARBON STREAM

ABSTRACT

The present invention relates to a method and apparatus for cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, such as a natural gas stream.

The method comprises:

(i) receiving one or more refrigerant temperature indications, providing an indication of the temperature of the refrigerant,

(ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and

(iii) based on the outcome of the comparison under (ii) selecting one of an automated warm cooling down procedure of the cryogenic heat exchanger and an automated cold cooling down procedure of the cryogenic heat exchanger.

METHOD AND APPARATUS FOR COOLING DOWN A CRYOGENIC HEAT EXCHANGER AND METHOD OF LIQUEFYING A HYDROCARBON STREAM

[0001] This is a divisional application of Australian Patent Application No. 2015373431, the entire contents of which being incorporated herein by reference.

FIELD

[0002] The present invention relates to a method and apparatus for cooling down a cryogenic heat exchanger.

[0003] In various embodiments specifically disclosed herein, the cryogenic heat exchanger is adapted to liquefy a hydrocarbon stream, such as a natural gas stream.

[0004] In another aspect, the present invention relates to a method of liquefying such a hydrocarbon stream.

BACKGROUND

[0005] Several types of cryogenic heat exchangers are known. Such cryogenic heat exchangers may be used in methods of liquefying a natural gas stream to produce liquefied natural gas (LNG). In such a case, the cryogenic heat exchanger is generally able to receive the hydrocarbon stream to be liquefied, to heat exchange the hydrocarbon stream against an at least partly evaporating refrigerant thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream.

[0006] Depending on the type of hydrocarbons in the stream, and the pressure level under which the hydrocarbon stream passes through the cryogenic heat exchanger, a typical temperature at which for instance natural gas starts to liquefy may be at –135 °C.

[0007] However, before it is ready for normal operation of cooling and/or liquefying the hydrocarbon stream, the cryogenic heat exchanger needs to be cooled down, e.g. as part of a plant start-up routine.

[0008] In order to prevent damage to the cryogenic heat exchanger, including for instance leaks that may result from thermal expansion and contraction distributions over the cryogenic heat exchanger, operators and manufacturers of such cryogenic heat exchangers typically recommend to avoid as much as possible to exceed a certain specified maximum temperature rate of change over time.

[0009] On the other hand, in order to minimize the non-productive or sub-optimal productive period of the cryogenic heat exchanger, operators typically want to cool down their cryogenic heat exchanger at the highest rate possible.

[0010] US Patent 4,809,154 describes an automated control system for the control of mixed refrigerant-type liquefied natural gas production facilities, wherein functional parameters are optimized. Optimization is accomplished by adjusting parameters including mixed refrigerant inventory, composition, compression ratio, and compressor turbine speeds to achieve the highest product output value for each unit of energy consumed by the facility.

[0011] In more detail, process controller system of US Pat. ‘154 is implemented in a parallel processing computer system allowing parallel control processes to be executed on multiple processors having access to a common storage wherein values representative of the current state of every sensor and every controller associated with the production facility are stored. To manage the parallel control processes, a request queue and a return queue are maintained, as well as a priority table, which is used to resolve contention among parallel operating process loops.

[0012] The process controller system of US Pat. ‘154 may work satisfactorily to optimize or keep optimal quantity or quality of the liquefied gas being produced while the liquefaction process runs. However, the process controller system of US Pat. ’154 is not suitable for controlling the cryogenic heat exchanger during initial cooling down at start up, because that requires a sequence of steps to be carried out which cannot be handled using the system of priority tables and request and return queues.

[0013] WO2009/098278 describes a method and apparatus for cooling down a cryogenic heat exchanger. Cooling down is done in an automated manner and allows to cool down at the highest rate possible without exceeding the specified maximum rate of temperature change.

SUMMARY

[0014] It is an object of the invention to provide an apparatus and method for cooling down a cryogenic heat exchanger in a more flexible and time efficient manner, in particular in situations wherein operation of the cryogenic heat exchanger is restarted after an interruption, while the refrigerant is still well below ambient temperature. This may for instance be the case if operation has been interrupted for a relatively short period of time (for instance for maintenance, after a compressor induced trip, pit stop or a shutdown normally required) or even after longer interruptions (days) during which proper box-up is done to maintain the low temperature as much as possible.

[0014a] An aspect of the present invention provides a method of cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, the method comprising the steps of:

receiving, by the cryogenic heat exchanger, the hydrocarbon stream to be liquefied and a refrigerant, to exchange heat between the hydrocarbon stream and the refrigerant, thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream and a spent refrigerant that has passed through the cryogenic heat exchanger,

recirculating, by a refrigerant recirculation circuit, the spent refrigerant back to the cryogenic heat exchanger, wherein the refrigerant recirculation circuit comprises at least a compressor, a compressor recycle valve, a cooler, and a first Joule Thomson (JT) valve;

performing a comparison step by a programmable controller, said comparison step comprising:

(i) receiving one or more refrigerant temperature indications, and providing an indication of a temperature of the refrigerant,

(ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and

(iii) based on an outcome of the comparison under (ii) selecting one of an automated warm cooling down procedure of the cryogenic heat exchanger and an automated cold cooling down procedure of the cryogenic heat exchanger;

wherein the automated cold cooling down procedure is adapted to reduce a temperature of the cryogenic heat exchanger from a cold condition down to LNG production point and is allowed to start with an opened first JT valve, wherein the automated warm cooling down procedure and the automatedcold cooling down procedure comprise an initial opening step, the initial opening step comprises imposing an initial opening of the first JT valve, wherein the initial opening step of the first JT valve according to the automated warm cooling down procedure differs in size of the initial opening from the initial opening step of the first JT valve according to the automated cold cooling down procedure; and

wherein as part of the initial opening step, performing, by the programmable controller, a TROC step comprising adjusting the opening of the first JT valve based on a determined temperature rate of change (TROC) of the refrigerant over the first JT valve in accordance with an adjustment scheme, wherein the automated warm cooling down procedure and the automated cold cooling down procedure comprise a plurality of different adjustment schemes.

[0015] The present invention provides an apparatus for cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, such as a natural gas stream, which cryogenic heat exchanger is arranged to receive the hydrocarbon stream to be liquefied and a refrigerant, to exchange heat between the hydrocarbon stream and the refrigerant, thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream and spent refrigerant that has passed through the cryogenic heat exchanger, the apparatus comprising:

- a refrigerant recirculation circuit to recirculate spent refrigerant back to the cryogenic heat exchanger, the refrigerant recirculation circuit comprising at least a compressor, a compressor recycle valve, a cooler, and a first JT valve;
- a programmable controller arranged to perform a comparison step, comprising:
    (i) receive one or more refrigerant temperature indications, providing an indication of the temperature of the refrigerant,
    (ii) compare the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and
    (iii) based on the outcome of the comparison under (ii) select one of an automated warm cooling down procedure of the cryogenic heat exchanger and an automated cold cooling down procedure of the cryogenic heat exchanger.

[0016] After step (iii) the programmable controller is arranged to execute the selected cooling down procedure. It is noted that the warm and the cold cooling down procedure are similar procedures which may involve similar actions, but the actions are executed in a different way, in particular differing in one of the following aspects: different step sizes for opening/closing valves, different timing for opening/closing valves, different threshold values for deciding on further opening/closing valves, in particular different TROC-values.

[0017] In particular, the cold cooling down procedure differs from the warm cooling down procedure as the warm cooling down procedure comprises a step in which it is ensured that the JT valve is closed (closed automatically or by prompting an operator to close the JT valve), while the cold cooling down procedure allows to start with an opened JT valve. The cold cooling down procedure allows to start reducing the cryogenic heat exchanger temperature from the (still) cold condition (e.g. -80°C to -130°C) down to LNG production point (approximately -165 °C). This will be explained in more detail below.

[0018] The term warm cooling down procedure is used to refer to a cool down procedure where the initial temperature of the refrigerant is relatively high, e.g. above the predetermined threshold value, possibly requiring a pre-cool down procedure. An example of a warm cooling down procedure is explained in detail in WO2009/098278 which is hereby incorporated by reference.

[0019] The term cold cooling down procedure is used to refer to a cool down procedure where the initial temperature of the refrigerant is relatively low, e.g. below the predetermined threshold value and no pre-cool down procedure is required.

[0020] A warm cooling down procedure is typically employed when first starting a newly built apparatus or at the end of a relatively long maintenance period. However, during the lifespan of the apparatus, relatively short maintenance operations are to be carried out, at the end of which, the refrigerant is still relatively cold, i.e. well below ambient temperatures. Instead of waiting for the refrigerant to reach a temperature allowing carrying out a warm cooling down procedure, a cold cooling down procedure is now proposed which makes it possible to cool down the refrigerant from a relatively cold starting point. This is relatively time efficient. It also adds flexibility since it allows for an automated cool down for warm and cold conditions.

[0021] After the cryogenic heat exchanger has been cooled down with the method as defined above and/or using the apparatus defined above, the hydrocarbon stream may be liquefied in one or more steps including heat exchanging the hydrocarbon stream in the cryogenic heat exchanger, in order to produce a liquefied hydrocarbon product.

[0022] In another aspect, the invention provides a method of cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, such as a natural gas stream, comprising the steps of

- providing a cryogenic heat exchanger arranged to receive the hydrocarbon stream to be liquefied and a refrigerant, to exchange heat between the hydrocarbon stream and the refrigerant, thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream and spent refrigerant that has passed through the cryogenic heat exchanger,
- providing a refrigerant recirculation circuit to recirculate spent refrigerant back to the cryogenic heat exchanger, the refrigerant recirculation circuit comprising at least a compressor, a compressor recycle valve, a cooler, and a first JT valve;
- performing a comparison step (502), the comparison step comprising:
    - (i) receiving input signals representing sensor signals of one or more refrigerant temperature indications, providing an indication of the temperature of the refrigerant,
    - (ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and
    - (iii) based on the outcome of the comparison under (ii) selecting one of an automated warm cooling down procedure of the cryogenic heat exchanger and an automated cold cooling down procedure of the cryogenic heat exchanger.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The present invention will now be illustrated by way of example only, and with reference to embodiments and the accompanying non-limiting schematic drawings in which:

[0024] Fig. 1 schematically shows a cryogenic heat exchanger arrangement according to one embodiment;

[0025] Fig. 2 schematically shows a cryogenic heat exchanger arrangement according to another embodiment;

[0026] Fig. 3 schematically shows a block diagram for automatically cooling down the cryogenic heat exchanger of Fig. 1 or Fig. 2

[0027] Fig. 4 schematically shows a main cryogenic heat exchanger arrangement according to another embodiment of the invention as used in a test;

[0028] Fig. 5 schematically shows the line-up of Fig. 4 illustrating monitored temperatures and pressures;

[0029] Fig. 6 shows a block diagram for automatically cooling down the cryogenic heat exchanger of Fig. 4 or Fig. 5.

DETAILED DESCRIPTION

[0030] For the purpose of this description, a single reference number will be assigned to a line (conduit) as well as a stream carried in that line (conduit). Same reference numbers refer to similar components, streams or lines (conduits).

[0031] Described are methods and apparatuses employing a programmable controller that is arranged to receive input signals, such as user input and measurement readings, to process the input signals and produce control signals, such as data output and valve control signals.

[0032] The programmable controller may be formed as a computer comprising an input/output device for receiving/transmitting signals, a memory arranged to store data and a processor arranged to communicate with the input/output device and memory (reading, writing). The processor is arranged to read and execute program lines, e.g. stored in the memory, to perform the method as described. The memory may also be (partially) located as a separate unit which is accessible by the programmable controller.

[0033] The programmable controller may be embedded in a distributed control system (DCS), wherein for instance modules provide output via an interface server, such as an OLE (object-linking and embedding) for process control (OPC) that may communicate between the computer program and various interface blocks that may be present in the DCS. In such an arrangement, the DCS can take back control without waiting for the programmable controller to transfer control as may be desired during emergencies or the like.

[0034] Automated cooling down of a cryogenic heat exchanger advantageously facilitates cooling down the cryogenic heat exchanger at the highest rate possible without exceeding the specified maximum rate of temperature change. When cooling down the cryogenic heat exchanger under manual control, an operator typically has to maintain a wider margin between the rate of temperature change and the specified maximum.

[0035] Moreover, thanks to the automation as described in this document, an even more time-efficient cooling down is provided.

[0036] Moreover, the methods and apparatuses disclosed herein may also be used to avoid one or more spatial temperature gradients in or around the cryogenic heat exchanger to exceed a recommended maximum value(s).

[0037] The advantages of the methods and apparatuses described herein are more pronounced for cooling down counter-current cryogenic heat exchangers, preferably using an external refrigerant, wherein the evaporating refrigerant flows counter-currently relative to the stream or streams that is/are to be cooled in the cryogenic heat exchanger against the evaporating refrigerant, than for cooling down co-current cryogenic heat exchangers.

[0038] As will be appreciated by the person skilled in the art, the maximum temperature rate of change and/or maximum spatial temperature gradient is generally dependent on the type and/or specific design of the heat exchanger that is subject to the process of cooling down. Specific recommendations regarding such values may be provided by the manufacturer.

[0039] Where the cryogenic heat exchanger comprises a shell side for evaporating refrigerant and a tube side for auto-cooling the refrigerant, the selected spatial temperature gradient may reflect the temperature differential between a shell side of the cryogenic heat exchanger and a refrigerant-containing tube side.

[0040] There are other preferred temperature gradients to be used, for instance in line-ups wherein downstream of the cooler and upstream of the first JT valve a liquid/vapour separator is provided in the refrigerant recirculation circuit, to receive a partly condensed refrigerant and separate the partly-condensed refrigerant stream into a liquid heavy refrigerant fraction and a gaseous light refrigerant fraction and to discharge the liquid heavy refrigerant fraction via a liquid outlet and the gaseous light refrigerant fraction via a gas outlet, which fractions are passed to the cryogenic heat exchanger, wherein the first JT valve is arranged to control passage of one of these fractions, preferably the light refrigerant fraction.

[0041] The selected spatial temperature gradient may in such a line-up reflect one or more of: the temperature differential between the spent refrigerant and the refrigerant between the gas outlet and the gaseous refrigerant inlet of the cryogenic heat exchanger; and the temperature differential between spent refrigerant and the refrigerant between the liquid outlet and the liquid refrigerant inlet of the cryogenic heat exchanger.

[0042] Other possible controlled variables include variables indicative of operating conditions of one or more compressors, such as surge conditions. A so-called surge deviation parameter may be determined based on sensor data to quantify the deviation between surge and actual operating condition of the compressor. Typical sensor data that is taken into account for determining the surge deviation parameter includes the flow through the relevant compressor stage and inlet and discharge pressure of the relevant stage.

[0043] For automatically cooling a cryogenic heat exchanger, the one or more manipulated variables may comprise one or both of: a first JT valve setting that represents a measure of amount of opening of the first JT valve; and a compressor recycle valve setting that represents a measure of amount of closing of the compressor recycle valve. The amount of opening of the first JT valve quite directly affects the rate of cooling of the cryogenic heat exchanger because it is one of the factors that determine the Joule-Thomson effect that the JT valve has on the refrigerant stream as it passes through the JT valve, which determines the cooling power of the refrigerant. The amount of closing of the compressor recycle valve also affects the rate of cooling of the cryogenic heat exchanger because it also influences the JT effect at the first JT valve because it is one way of controlling the pressure and flow rate of the refrigerant.

[0044] Of course, there are other manipulated variables that can control the pressure and/or flow rate of the refrigerant, such as compressor speed. Thus compressor speed may also be used as one of the manipulated variable(s). However, in contrast to speed, a valve is a very suitable item to manipulate in a control sequence that has relatively immediate effect on the pressure.

[0045] The methods and apparatuses disclosed herein may be used in a method of liquefying a hydrocarbon stream such as a natural gas stream. In such a case, the cooling down of the cryogenic heat exchanger is followed by normal operation wherein the hydrocarbon stream is cooled in the cryogenic heat exchanger until it is liquefied, preferably followed by sub-cooling in the cryogenic heat exchanger or in a subsequent heat exchanger.

[0046] It is desirable to liquefy a natural gas stream for a number of reasons. As an example, natural gas can be stored and transported over long distances more readily as a liquid than in gaseous form, because it occupies a smaller volume and does not need to be stored at a high pressure.

[0047] Usually natural gas, comprising predominantly methane, enters an LNG plant at elevated pressures and is pre-treated to produce a purified feed stock suitable for liquefaction at cryogenic temperatures. The purified gas is processed through a plurality of cooling stages using heat exchangers to progressively reduce its temperature until liquefaction is achieved. The liquid natural gas is then optionally further cooled, and expanded through one or more expansion stages to final atmospheric pressure suitable for storage and transportation. The flashed vapour from each expansion stage can be used as a source of plant fuel gas.

[0048] It is remarked that US 2006/0213223 A1 discloses a liquefaction plant and method for producing liquefied natural gas. Control of the plant may be fully or partially automated, such as by using an appropriate computer, a programmable logic circuit (PLC), using closed-loop and open-loop schemes, using proportional, integral, derivative (PID) control. However, US 2006/0213223 does not teach a computer program or an algorithm as described in the present application.

[0049] As schematically shown in Fig. 1, there is provided a cryogenic heat exchanger 1 arranged to receive, via conduit 2 and hydrocarbon stream inlet 7, the hydrocarbon stream that is to be liquefied, in order to exchange heat between the hydrocarbon stream and an at least partly evaporating refrigerant 3. As a result of the heat exchanging, the hydrocarbon stream may be at least partially liquefied. The preferably at least partially liquefied hydrocarbon stream is discharged via hydrocarbon stream outlet 8 into conduit 4. In the embodiment as drawn, conduit 2 and conduit 4 connect via a tube side 29. However, other types of heat exchangers are possible.

[0050] The cryogenic heat exchanger 1 comprises a refrigerant inlet 5 for an external refrigerant and a refrigerant outlet 6 for spent refrigerant that has passed through the cryogenic heat exchanger. A refrigerant recirculation circuit 10 is provided to recirculate spent refrigerant back to the inlet 5. The refrigerant recirculation circuit 10 comprises, at least, a compressor 11, a compressor recycle valve 12, a cooler 13, and a first Joule-Thompson (first JT) valve 14.

[0051] In practical embodiments of the invention, a JT valve may be used in combination with an expander. However, in particular during the cooling down of the heat exchanger, the JT valve is preferably used for controlling the cooling.

[0052] In practical embodiments of the invention, the compressor may consist of a plurality of compression stages, for instance 15 compression stages or more. A number of these stages, for instance 15 of these stages, may be provided in the form of an axial compressor or centrifugal compressor in one casing. Each stage may comprise a dedicated recycle valve, and/or a single recycle valve may be shared by any number of subsequent stages. Several compressors or compressor casings may be arranged in series one after another to form a compressor train. Each casing (or compressor stage) may be followed by any number of optional coolers (or intercoolers), and optional knock-out drums to remove any liquid from the compressed vapour before passing the compressed vapour to the next compression stage. After the last compression stage, the compressed refrigerant stream may be cooled.

[0053] However, for the purpose of illustrating the present invention, a schematically simplified compressor line-up is depicted in Figs. 1 and 2, with only one compressor drawn in and one recycle valve. An example comprising two compression stages will be described in more detail with reference to Fig.'s 4 - 6.

[0054] In operation, spent (at least partly evaporated) refrigerant is drawn from the heat exchanger 1 via outlet 6, and at least a part of it is passed to a suction inlet of compressor 11 via conduit 25.

[0055] The gaseous part of the spent refrigerant stream in conduit 25 is compressed to yield a compressed refrigerant stream 16 that is subsequently cooled in one or more coolers, here depicted as cooler 13, thereby at least partially condensing the compressed refrigerant stream 16 to form an at least partially condensed refrigerant stream 17. The at least partially condensed refrigerant stream 17 is expanded over first JT valve 14 and subsequently led into the heat exchanger 1 via inlet 5.

[0056] As shown in Fig. 1, the refrigerant stream flows co-currently with the hydrocarbon stream (from left to right) through the heat exchanger 1. However, the flow may be arranged counter-currently instead, such as is for example the case in Fig. 2.

[0057] In Fig. 2 an alternative cryogenic heat exchanger arrangement is shown that comprises the same elements as the embodiment of Fig. 1, and in addition includes a refrigerant tube side 15 for auto-cooling the refrigerant. Both the hydrocarbon stream 2 and the refrigerant are heat exchanged against the evaporating refrigerant in the heat exchanger 1. The compressed refrigerant stream 16 is subsequently cooled in one or more coolers, here depicted as cooler 13, followed by cooling in the heat exchanger 1, via tube side 15, thereby at least partially condensing the compressed refrigerant stream 16 to form the at least partially condensed refrigerant stream 17. The auto-cooled, at least partially condensed refrigerant stream 17, is drawn from the heat exchanger at outlet 18 and led through first JT valve 14 before it is passed, via inlet 5, into the heat exchanger 1, where it is allowed to at least partially evaporate.

[0058] Optionally, a refrigerant make-up system may be provided which is capable of changing the inventory of the refrigerant in particular in the case of a mixed refrigerant.

[0059] The current invention relates to an apparatus or method for cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream 2, 7, 29, 8, 4, such as a natural gas stream, which cryogenic heat exchanger 1 is arranged to receive the hydrocarbon stream to be liquefied and a refrigerant, to exchange heat between the hydrocarbon stream and the refrigerant, thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream and spent refrigerant that has passed through the cryogenic heat exchanger, the apparatus comprising

- a refrigerant recirculation circuit to recirculate spent refrigerant back to the cryogenic heat exchanger, the refrigerant recirculation circuit comprising at least a compressor 11, a compressor recycle valve 12, a cooler 13, and a first JT valve 14.

[0060] The refrigerant recirculation circuit may circulate a single component refrigerant, such as methane, ethane, propane, or nitrogen; or a multi-component mixed refrigerant, sometimes referred to simply as mixed refrigerant (MR), based on two or more components. These components may preferably be selected from the group comprising nitrogen, methane, ethane, ethylene, propane, propylene, butane and pentane.

[0061] The refrigerant circuit may involve any number of separate lines or streams of refrigerant to cool different hydrocarbon streams, and any number of common elements or features, including compressors, coolers, expanders, etc. Some refrigerant streams may be common and some may be separate.

[0062] In a particular embodiment of the present invention, the described method of cooling down a cryogenic heat exchanger is part of a method of liquefying a hydrocarbon stream such as natural gas from a feed stream. Likewise, the apparatus as described herein may be used in such a method of liquefying a hydrocarbon stream.

[0063] The hydrocarbon stream may be any suitable hydrocarbon-containing, preferably methane-containing, stream to be liquefied, but is usually drawn from a natural gas stream obtained from natural gas or petroleum reservoirs. As an alternative, the natural gas stream may also be obtained from another source, also including a synthetic source such as a Fischer-Tropsch process.

[0064] Usually natural gas is comprised substantially of methane. Preferably the feed stream comprises at least 60 mol% methane, more preferably at least 80 mol% methane.

[0065] A hydrocarbon feed stream may be liquefied by passing it through a number of cooling stages. Any number of cooling stages can be used, and each cooling stage can involve one or more heat exchangers, as well as optionally one or more steps, levels or sections. Each cooling stage may involve two or more heat exchangers either in series, or in parallel, or a combination of same.

[0066] Various types of suitable heat exchangers able to cool and liquefy a hydrocarbon feed stream are known in the art and the present invention may be applied to any one of them. Examples of such heat exchanger types are heat exchangers available from Air Products & Chemicals Inc. and Linde AG, typically comprising one, or two, or three, or more bundles.

[0067] Various arrangements of suitable heat exchangers able to cool and liquefy a feed stream such as a hydrocarbon stream such as natural gas are known in the art, including single mixed refrigerant (SMR) arrangements, dual mixed refrigerant (DMR) arrangements, propane-mixed refrigerant arrangements (C3-MR), arrangements based on three or more cycles, such as e.g. a so-called APX arrangement launched by Air Products & Chemicals Inc. based on C3-MR-N2 cycles, and cascade arrangements including those with a sub-cooling cycle. The present invention may be applied to any heat exchanger in any of such arrangements, and other suitable arrangements, with some minor modifications that are within the reach of the person skilled in the art.

[0068] In various arrangements, the cooling and liquefying of the hydrocarbon feed stream involves two (or more) cooling stages comprising a pre-cooling stage and a main cooling stage. Typically, the pre-cooling stage cools the hydrocarbon stream to below 0 °C, for instance to a temperature in the range -10°C to -35°C, and the second stage, which may be referred to as a main cryogenic stage from -10°C to -35°C down to -145°C to -160°C or even -170°C to liquefy the hydrocarbon stream.

[0069] The present invention may involve one or more other or further refrigerant circuits, for example in a pre-cooling stage. Any other or further refrigerant circuits could optionally be connected with and/or concurrent with the refrigerant circuit for cooling the hydrocarbon stream.

[0070] As indicated above, according to the present embodiments, an apparatus and method are provided for cooling down the heat exchanger 1. This cooling down is needed before operating the heat exchanger to actual liquefy the hydrocarbon stream. The cooling down procedures may be controlled by a programmable controller. Depending on the temperature of the refrigerant different cooling down procedures can be employed.

[0071] Fig. 3 schematically shows a block scheme representing the steps that may be carried out. After a start signal is generated in step 501 (see Fig. 3), a comparison step 502 is performed which comprises:

(i) receiving one or more refrigerant temperature indications, providing an indication of the temperature of the refrigerant,

(ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and

(iii) based on the outcome of the comparison under (ii), selecting one of an automated warm cooling down procedure 503 of the cryogenic heat exchanger or an automated cold cooling down procedure 504 of the cryogenic heat exchanger.

[0072] Step 502 may comprise a condition check, such as checking whether an appropriate start signal is generated by the distributed control system (DCS) and/or checking if a heartbeat signal is present, i.e. checking if all the relevant software modules are still active.

[0073] Step (i) may comprise obtaining one or more refrigerant temperature indications comprising at least one of a refrigerant temperature indication of the refrigerant

- at a suction side of the JT valve 14;
- at a discharge side of the JT valve 14;
- at an entry side of the cryogenic heat exchanger 1;
- at a point inside the cryogenic heat exchanger 1;
- at a discharge side of the cryogenic heat exchanger 1.

[0074] For each received refrigerant temperature indication, one or more suitable temperature sensors may be provided, producing an indication of the temperature of the refrigerant at that location.

[0075] Refrigerant temperature indications can be obtained by performing temperature measurements on the refrigerant directly.

[0076] Step (i) may further comprise obtaining an indication of the temperature difference between shell side and tube side of the heat exchanger and/or a bottom temperature of the heat exchanger. These temperatures may be used throughout the procedure. All actions may have a condition check, including a temperature difference check.

[0077] For each received refrigerant temperature indication, a predetermined threshold value is available and each received refrigerant temperature indication is compared to the associated threshold value. Comparing includes determining if the received value is above or below the threshold value.

[0078] For instance, the temperature of the refrigerant at the entry side of the cryogenic heat exchanger can be compared to a threshold value of -50˚C to determine if the temperature is above or below -50˚C. Alternatively, the predetermined threshold value may have any suitable value, e.g. -80˚C or -130˚C.

[0079] If the temperature is below the threshold value the automated cold cooling down procedure 504 is selected and if the temperature is above the threshold value the warm cooling down procedure 503 is selected.

[0080] According to a further example, the temperature of the refrigerant can be compared to a first and second threshold value to determine if the temperature is between the first and second threshold value. For instance, the temperature of the refrigerant at the discharge side of the cryogenic heat exchanger can be compared to a first threshold value of -15˚C and to a second threshold value of -55˚C to determine if the temperature is between -15˚C and -55˚C or not. This is done to prevent too high temperature differences from occurring between the refrigerant and the heat exchanger. Of course, the exact values depend on the type of heat exchanger that is used.

[0081] The warm cooling down procedure will not be described in detail here. Reference is made to WO2009/098278 which provides a detailed explanation of the warm cooling down procedure. The warm cooling down procedure comprises similar steps as the cold cooling down procedure, but the warm and cold cooling down procedures are not identical, as will be explained in more detail below.

[0082] First action of the cold cooling down procedure is an initial conditions definition action 505 in which the initial conditions are defined. This action may use information on critical and non-critical initial conditions, which may be stored on the memory accessible by the programmable controller.

[0083] In case of occurrence of a critical condition, the programmable controller interrupts the procedure. The procedure may be resumed and/or restarted after the critical condition has been resolved or acknowledged, and the initial conditions have been acknowledged by an operator, either manually or by running an automated control procedure to restore the initial condition. In case of a non-critical initial condition, a warning may be issued. This action 505 may further initiate the monitoring of critical variables. Only once all critical variables are within predetermined ranges, the next action (initial opening step 506) is commenced.

[0084] Examples of critical initial conditions are:

- first JV valve 14 is not sufficiently closed (e.g. more than 0.1 % open or other suitable number);
- pressure in the refrigerant circuit is lower than the compressor 11 discharge;
- compressor 11 is not on-line and running, as can be determined by measuring compressor speed (e.g. compressor running at least 3400 rpm or other suitable speed) and verifying that the suction and discharge valves on the compressors are open;
- refrigerant pressure is too high (e.g. above 20 barg, or other suitable figure);
- compressor inlet guide vane (IGV) is open.

[0085] Examples of non-critical initial conditions are:

- various actual temperatures, e.g. temperature of the refrigerant directly upstream of and directly downstream of the first JV valve 14, and/or temperature differentials;
- compressor recycle valves are not fully open (e.g. less than 99 % open or any other suitable value); and
- compressed refrigerant pressure below a pre-determined minimum value (as this may unnecessarily slow down the cool-down processes). A typically suitable minimum value is 18 barg.

[0086] The warm and cold cooling down procedure comprise an initial opening step 506, the initial opening step 506 comprises imposing an initial opening of the first JT valve 14, wherein the initial opening step of the first JT valve 14 according to the automated warm cooling down procedure 503 differs from the initial opening step of the first JT valve 14 according to the automated cold cooling down procedure 504.

[0087] According to an embodiment the initial opening of the first JT valve is greater in the automated warm cooling down procedure 503 than in the automated cold cooling down procedure 504.

[0088] For instance, the initial opening imposed on the JT valve 14 according to the automated cold cooling down procedure 503 may be in the range of 1 – 2%, while the initial opening imposed on the JT valve according to the automated warm cooling down procedure 504 may be in the range of 3 – 5%.

[0089] In the warm cooling down procedure 503 the JT valve 14 is initially opened relatively much, as to check if a Joule-Thompson effect is actually present.

[0090] The opening of the valve is expressed in %, which indicates the relative position of the valve plug (moveable part of the valve) with respect to its valve seat (stationary part of the valve). As will be understood, 0% means that the valve is fully closed (valve plug against valve seat), 100% means that the valve is fully opened (valve plug farthest away from valve seat). It will understood that the relation between the valve opening [%] and the flow rate depend on the type of valve used (e.g. ball valve, butterfly valve, linear globe type of valve, fast opening globe type of valve) and may thus differ from a 1:1 relation.

[0091] According to an alternative embodiment the initial opening step 506 of the first JT valve 14 in the automated warm cooling down procedure 503 comprises imposing a predetermined initial opening of the first JT valve 14 (e.g. 3 – 5%), wherein the initial opening step 506 of the first JT valve 14 in the automated cold cooling down procedure 504 comprises determining a current opening of the first JT valve 14 and imposing the determined current opening of the first JT valve 14.

[0092] This allows starting the cold cooling down procedure without adjusting the setting of the first JT valve. In any case, the predetermined initial opening of the cold cooling down procedure is smaller than the predetermined initial opening of the warm cooling down procedure.

[0093] According to an embodiment the initial opening step 506 of the cold cooling down procedure 504 further comprises opening the compressor recycle valve 12.

[0094] This forms a difference with the warm cooling down procedure 503 wherein the compressor recycle valve 12 remains closed or is actively closed in the initial opening step of the warm cooling down procedure. In the cold cooling down procedure, the compressor recycle valve 12 may already be opened during the initial opening step 506 of the cold cooling down procedure 504.

[0095] Opening the compressor recycle valve as part of the initial opening step 506 will be done mainly in case of a minor trip. Usually the compressor recycle valve will be closed in the initial opening step 506.

[0096] According to an embodiment the programmable controller is arranged to, as part of the initial opening step 506, perform a TROC step comprising adjusting the opening of the first JT valve 14 based on a determined temperature rate of change (TROC) of the refrigerant over the first JT valve 14 in accordance with an adjustment scheme, wherein the automated warm cooling down procedure 503 and the automated cold cooling down procedure 504 comprise different adjustment schemes.

[0097] Both the warm and cold cooling down procedures 503, 504 comprise comparable TROC steps, but both TROC steps use different conditions to decide on how to adjust the opening of the JT valve 14.

[0098] According to an embodiment determining the temperature rate of change (TROC) of the refrigerant over the first JT valve 14 is done by comparing two refrigerant temperature indications obtained at a respective first t1 and second t2 moment in time, the first and second moments in time being separated by a predetermined time interval, wherein the predetermined time interval according to the cold cooling down procedure 504 is shorter than the predetermined time interval according to the warm cooling down procedure 503.

[0099] The time interval according to the cold cooling down procedure may be less than 50% of the time interval according to the warm cooling down procedure.

[0100] The time interval according to the cold cooling down procedure may typically be 2 minutes, while the time interval according to the warm cooling down procedure may typically be 5 minutes. So, according to this example, the TROC according to the warm cooling down procedure 503 is calculated as follows: TROCwarm(t) = (Tt-5-Tt)*12 [°C/h], where the TROC according to the cold cooling down procedure 504 is calculated as follows: TROCcold(t) = (Tt-2-Tt)*30[°C/h], wherein ti is time in minutes and T is temperature.

[0101] The determined TROC is compared to a predetermined TROC threshold value to prevent too rapid cooling. For instance, according to the cold cooling down procedure 503, the predetermined TROC threshold value may be 28°C. The adjustment scheme may prescribe that if the TROCcold is above the predetermined TROC threshold value, e.g. above 28°C, the first JT valve 14 will be closed with a certain predetermined closing amount (e.g. 0.5%) and a predetermined waiting time is initiated (e.g. 5 minutes) before continuing with opening the first JT valve 14 with a predetermined opening amount (e.g. 0.2%), the predetermined closing amount being greater than the predetermined opening amount.

[0102] The temperature measurements used to determine the relevant temperature rate of change (TROC) can be obtained by measuring the temperature of the refrigerant at one or more of the following locations:

- at a suction side of the JT valve 14;
- at a discharge side of the JT valve 14;
- at an entry side of the cryogenic heat exchanger 1;
- at a point inside the cryogenic heat exchanger 1;
- at a discharge side of the cryogenic heat exchanger 1.

[0103] According to an embodiment the adjustment scheme of the cold cooling down procedure comprises waiting a predetermined time interval between imposing an initial opening of the first JT valve and initiating the TROC step. The TROC step comprises (as explained above) adjusting the opening of the first JT valve 14 based on a monitored temperature rate of change (TROC) of the refrigerant over the first JT valve 14.

[0104] Waiting a predetermined time interval is done to allow pressure to seep through. A high pressure difference will cause a high JT effect and further opening too fast could cause a TROC which is too high.

[0105] The end of the initial opening step 506 can be determined by determining the TROC and verify it is less than a predetermined value or falls within a predetermined range.

[0106] Once the initial opening step 506 is finished the automated cold cool down procedure comprises performing an adjustment step 507 which comprising simultaneously

- adjusting and closing recycle valve (509) and
- further adjusting the first JT valve (508).

[0107] As will be discussed in more detail below with reference to Fig.'s 4 – 6, action 509 may comprise adjusting and closing a plurality of recycle valves (509) and/or action 508 may comprise further adjusting a plurality of JT valves, in particular a first and second JT valve.

[0108] In action 508 the first JT valve 14 is further adjusted. In particular in the embodiment of Fig. 2, strong cooling may cause condensation of the refrigerant. Just before condensation occurs, the valve movements are preferably slowed down, and the moment that condensation is detected the valve may be closed partially to avoid too high a cooling rate that would otherwise be caused by a sudden increase in flow rate due to condensation (an increase of 100 tpd (tonnes per day) 10 secs is not uncommon). After condensation is detected, the valve opening may be normalized and continued until the JT effect of the valve opening in diminished. The JT effect may be monitored during the further opening of the JT valve, for instance based on a temperature difference between the temperature of the refrigerant upstream of the JT valve and the temperature of the refrigerant downstream of the JT valve. An assumption may be made that the JT effect is present if the temperature difference exceeds 8 ºC.

[0109] Condensation may be detected by deferment from one or both of a temperature and flow measurement at the JT valve. For the refrigerant that flows through the first JT valve 14, the temperature of the refrigerant downstream of the JT valve 14 may be used and/or the flow through the JT valve, which in turn may be estimated by determining a pressure differential over the JT valve 14.

[0110] In preferred embodiments, the JT valve 14 can't be closed further than a minimum opening corresponding to the opening at the start of this module.

[0111] The changes in JT effect upon further opening of the JT valve may be small. However, at the same time the refrigerant pressure is increased as simultaneously action 509 is performed by manipulating the recycle valve 12 to meet a target surge deviation of the compressor (or number of compression stages). This module monitors the surge deviation of the compressor 11, and closes the recycle valve 12 if the surge deviation exceeds a pre-determined maximum deviation. A suitable predetermined maximum deviation is 0.3.

[0112] If there are multiple recycle valves, e.g. on multiple compressor stages, each recycle valve may be manipulated individually (but simultaneously) taking into account a dedicated surge deviation parameter for the corresponding stage through which each particular recycle valve controls the recirculation.

[0113] Since the closing of recycle valve 12 affects the compressor suction pressure, this pressure is preferably monitored to not go below a recommended limit, such as e.g. 1.8 barg. Closing the recycle valve decreases the suction pressure as well. Therefore, the closing of the recycle valve is made conditional to avoid causing the suction pressure to go below predetermine target value. The objective is to maintain a ramp (increase) on the discharge pressure by closing the recycle valves steadily while monitoring surge deviation. When the surge deviation is below the considered minimum level (e.g. 0.1) then the module activity is stopped. However surge deviation is monitored throughout the whole final cool down procedure, and the recycle valves closed when allowed by the surge deviation and the suction pressure is within a predetermined range.

[0114] When the temperature of the cryogenic heat exchanger 1 has met its operating temperature, an end signal is generated. This may be done as part of actions 508 and 509, each action generating a separate end signal, or a single end signal may be generated as part of one of the actions or by a separate action (not shown). When the end signal(s) is/are triggered, the programmable controller may end the automated cold cooling down procedure (action 510 in Fig. 3).

[0115] End action 510 may fully close the recycle valve 12 as much as possible, provided that the surge deviation does not stop this from occurring. If the surge deviation prevents further closing of the recycle valve, in case the surge value is too low (typically below 0.1), a warning message may be generated and outputted to alert the operator that an IGV adjustment may be necessary. An IGV movement has a similar effect as the closing of the recycle valve 12. However, any IGV movement may be constrained by the molecular weight of the passing refrigerant that must exceed a pre-determined minimum value. A typical MR minimum molecular weight is 24 g/mol. Obviously this warning signal may not be a useful option if no IGV is present on the compressor in use.

[0116] Since an IGV movement is considered to be a last resource, it has been contemplated to only alert the operator to the possible necessity of an IGV movement instead of attempting to execute any IGV movement under the control of the automatic procedure as described herein.

[0117] Once the recycle valve is fully closed or closed sufficiently, control may be handed over an operator and/or present a status output or generate an operator alerting signal to inform the operator that normal operation of the cryogenic heat exchanger may proceed, or the like. Alternatively, a subsequent control procedure or the like may be started, e.g. normal operating control such as advanced process control as described in e.g. US Pat. 7,266,975 and/or US Pat. 6,272,882 or any other type of module.

[0118] Figure 4 shows a larger type of cryogenic heat exchanger 100, embedded in a system of various pre-cooling heat exchangers, serviced by such a further refrigerant circuit, and other equipment, as may be found in a hydrocarbon liquefaction plant. The further refrigerant circuit may hereinafter be referred to as the “pre-cooling refrigerant circuit” or “pre-cooling refrigerant cycle”. Likewise, items such as compressors and the refrigerant may also be referred to as “pre-cooling refrigerant compressor” or “pre-cooling refrigerant”.

[0119] The cryogenic heat exchanger 100 of this embodiment will hereinafter be referred to as the main cryogenic heat exchanger 100, to distinguish it from any other heat exchangers present in the embodiment. The main cryogenic heat exchanger 100 comprises a warm end 33, a cold end 50 and a mid-point 27. The wall of the main cryogenic heat exchanger 100 defines a shell side 110. In the shell side 110 are located:

- a first tube side 29 extending from the warm end 33 to the cold end 50, preferably extending between a hydrocarbon stream inlet 7 and a hydrocarbon stream outlet 8;
- a second tube side 28 extending from the warm end 33, preferably from a gaseous refrigerant inlet 49a at the warm end 33, to the mid-point 27; and
- a third tube side 15 extending from the warm end 33, preferably from a liquid refrigerant inlet 49b at the warm end 33, to the cold end 50.

[0120] A refrigerant compressor train, as shown here symbolically comprising first and second compressors 30 and 31, is provided to compress the refrigerant. Each of these compressors is provided with a number of recycle valves, which are here schematically represented by recycle valves 130 and 131 in a recycle line that connects the compressor discharge, downstream of the respective coolers, to the low pressure suction inlet.

[0121] The first refrigerant compressor 30 is driven by a suitable motor, for example a gas turbine 35, which is provided with a helper motor 36 for start-up, and the second refrigerant compressor 31 is driven by a suitable motor, for example a gas turbine 37 provided with a helper motor (not shown). Alternatively, the compressors 30 and 31 may be driven on a single shaft on a shared motor.

[0122] During normal operation after the main cryogenic heat exchanger has been cooled down, a gaseous, preferably methane-rich hydrocarbon feed stream is supplied at elevated pressure through supply conduit 20 to the first tube side 29 of the main cryogenic heat exchanger 100 at its warm end 33. The hydrocarbon feed stream passes through the first tube side 29 where it is cooled, liquefied and optionally sub-cooled, against a mixed refrigerant (MR) evaporating in the shell side 110 forming spent refrigerant. The resulting liquefied hydrocarbon stream is removed from the main cryogenic heat exchanger 100 at its cold end 50 through conduit 40. The flow of the hydrocarbon stream through the system may be controlled, e.g. using rundown valve 44 provided in conduit 40.

[0123] Stream 40 may optionally be passed through a suitable end flash system, wherein the pressure is brought down to storage and/or transportation pressure. Finally, liquefied hydrocarbon stream is passed as the product stream to storage where it is stored as liquefied product, or optionally directly to transportation.

[0124] During normal operation, and during cooling down of the main cryogenic heat exchanger, spent refrigerant is removed from the shell side 110 of the main cryogenic heat exchanger 100 at its warm end 33 through conduit 25 and passed to knock-out drum 56.

[0125] A refrigerant make-up adjustment conduit 65 also feeds into knock-out drum 56 to optionally add refrigerant inventory to the spent refrigerant stream. The adding of the various refrigerant components is controlled by one or more valves, typically one valve per component. Here, these valves are schematically represented as valve 66.

[0126] The evaporated fraction 55 of the spent refrigerant, which exits from the top of the knock out drum 56, is compressed, in refrigerant compressors 30 and 31, to obtain a compressed refrigerant stream, which is removed through conduit 32. Other refrigerant compressor arrangements are possible.

[0127] In between the two refrigerant compressors 30 and 31, heat of compression is removed from the fluid passing through conduit 38 in ambient cooler 23, which may comprise an air cooler and/or a water cooler and/or any other type of ambient cooler. Likewise, an intercooler (not shown) may be provided between two successive compressor stages of a compressor.

[0128] The compressed refrigerant stream in conduit 32 is cooled in air cooler 42 and partly condensed in one or more pre-cool heat exchangers (shown are 43 and 41) against a pre-cool refrigerant cycle that will be described in more detail later herein below. The pre-cool heat exchangers 41, 43 may be operating at mutually different pressures and/or be using different refrigerant compositions.

[0129] The partly condensed refrigerant stream 39 is then passed to and let into a liquid/vapour separator via an inlet device, here depicted as separator vessel 45 and inlet device 46. In the separator vessel 45, the partly-condensed refrigerant stream is separated into a, at this point liquid, heavy refrigerant fraction (HMR) and a, at this point gaseous, light refrigerant fraction (LMR). These streams may each be individually controlled by means of a JT valve or the like, the first JT valve 58 for controlling the vapour (light) refrigerant stream and a second JT valve 51 for controlling the liquid (heavy) refrigerant stream.

[0130] The liquid heavy refrigerant fraction is removed from the separator vessel 45 through conduit 47, and the gaseous light refrigerant fraction is removed through conduit 48. The heavy refrigerant fraction is sub-cooled in the second tube side 28 of the main cryogenic heat exchanger 100 to get a sub-cooled heavy refrigerant stream 54. The sub-cooled heavy refrigerant stream is removed from the main cryogenic heat exchanger 100 through conduit 54, and allowed to expand over an expansion device comprising second JT valve 51. The expansion device may further comprise a dynamic expander (not shown) in series with the second JT valve 51, which does not have to be operated during any cool down procedure of the main cryogenic heat exchanger.

[0131] The sub-cooled heavy refrigerant stream is, at reduced pressure, introduced through conduit 52 and nozzle 53 into the shell side 110 of the main cryogenic heat exchanger 100 at its mid-point 27. The heavy refrigerant stream is allowed to evaporate in the shell side 110 at reduced pressure, thereby cooling the fluids in the tube sides 29, 28 and 15.

[0132] The gaseous light refrigerant fraction removed from separator vessel 45 through conduit 48 is passed to the third tube side 15 in the main cryogenic heat exchanger 100 where it is cooled, liquefied and sub-cooled to get a sub-cooled light refrigerant stream 57. The sub-cooled light refrigerant stream is removed from the main cryogenic heat exchanger 100 through conduit 57, and allowed to expand over an expansion device comprising first JT valve 58. At reduced pressure it is introduced through conduit 59 and nozzle 60 into the shell side 110 of the main cryogenic heat exchanger 100 at its cold end 50. The light refrigerant stream is allowed to evaporate in the shell side 110 at reduced pressure, thereby cooling the fluids in the tube sides 29, 28 and 15.

[0133] Optionally (not shown), an optional side stream may be drawn from the gaseous light refrigerant stream 48, which may be cooled, liquefied and sub-cooled against one or more other cold streams in one or more other heat exchangers other than the main cryogenic heat exchanger 100. For instance, it may be cooled, liquefied and sub-cooled against cold flash vapour generated from stream 40 in an optional end flash system. The optional sub-cooled side stream may be recombined with the light refrigerant stream in conduit 57 or 59 in which case it needs an auxiliary expander means such as an auxiliary first JT valve. Reference is made to US Pat. 6,272,882 for a more detailed description of such an option.

[0134] Pre-cool heat exchangers 41,43 are operated using a pre-cooling refrigerant, which may be a mixed component refrigerant or a single component refrigerant. For this example, propane has been used. Evaporated propane is compressed in pre-cool compressor 127 driven by a suitable motor, such as a gas turbine 128. A pre-cooling refrigerant compressor recycling valve 129 is provided as well, here symbolically shown in a line connecting the first stage compressor low pressure suction inlet with the intermediate pressure level. However, a recycling line may optionally be provided across all of or a selection of compression stages.

[0135] Compressed propane is then condensed in air cooler 130, and the condensed compressed propane, at elevated pressure, is then passed through conduits 135 and 136 to heat exchangers 43 and 41 which are arranged in series with each other. The condensed propane is allowed to expand to an intermediate pressure over expansion valve 138, before entering into heat exchanger 43. There, the propane partly evaporates against the heat from the multi-component refrigerant in conduit 32, and the resulting evaporated gaseous fraction is passed through conduit 141 to an intermediate pressure inlet of the propane compressor 127. The liquid fraction is passed through conduit 145 to the heat exchanger 41. Before entering into the heat exchanger 41, the propane is allowed to expand to a low pressure over expansion valve 148. The evaporated propane is passed through conduit 150 to a suction inlet of the propane compressor 127.

[0136] As the person skilled in the art knows, knock-out drums or the like may be provided in any conduit connecting to a compressor suction to avoid feeding a non-gaseous phase to the compressor. An economizer may also be provided.

[0137] In the present example, two pre-cooling heat exchangers have been shown operating at two pressure levels. However, any number of heat pre-cooling heat exchangers and corresponding pressure levels may be employed.

[0138] The pre-cooling refrigerant cycle may also be used to obtain hydrocarbon stream 20, for instance as follows. A hydrocarbon feed, in the present example a natural gas feed, is passed at elevated pressure through supply conduit 90. The natural gas feed, which typically is a multi-component mixture of methane and heavier constituents, is partially condensed in at least one heat exchanger 93.

[0139] In the present example, this heat exchanger operates at approximately the same pressure level as pre-cooling heat exchanger 43, using a side stream 137 of the pre-cooling refrigerant drawn from conduit 135. Although not drawn in Fig. 4, conduit 137 connects to conduit 137a. Prior to entering into the heat exchanger 93, the pre-cooling refrigerant is allowed to expand over valve 139 to approximately intermediate pressure. The resulting evaporated gaseous fraction is passed through conduits 140a and 140 to conduit 141 where it is recombined with the gaseous fraction drawn from pre-cooling heat exchanger 43. The liquid fraction of the pre-cooling refrigerant is drawn from the heat exchanger 93 in conduit 151 and fed into heat exchanger 91 after expansion over valve 152 to approximately the low pressure. The evaporated pre-cooling refrigerant is then led to conduit 150 via conduits 153a and 153.

[0140] It is remarked that heat exchangers 43 and 93 and/or heat exchangers 41 and 91 may be provided in the form of combined heat exchangers comprising separate sides for the natural gas and for the refrigerant in conduit 32.

[0141] The partly condensed feed 92 is introduced, e.g. via an inlet device 94, into a gas/liquid separator 95 which may be provided e.g. in the form of a scrub column or similar. In the scrub column 95, the partly condensed feed is separated to get a methane-enriched gaseous overhead stream 97 and a liquid, methane-depleted bottom stream 115.

[0142] The gaseous overhead stream 97 is passed through conduit 97 via heat exchanger 91 to an overhead separator 102. In the heat exchanger 100, the gaseous overhead stream is partly condensed against the pre-cooling refrigerant in conduit 151, and the partly condensed overhead stream is introduced into the overhead separator 102 via inlet device 103. In the overhead separator 102, the partly condensed overhead stream is separated into a gaseous, stream 20 (which is substantially depleted from C5+ components and/or relatively rich in methane when compared to the feed stream) and a liquid bottom stream 105. The gaseous stream 20 forms the hydrocarbon feed at elevated pressure in conduit 20.

[0143] At least part of the liquid bottom stream 105 may be introduced through conduit 105 and nozzle 106 into the scrub column 95 as reflux. The conduit 105 is provided with a flow control valve (not shown) and/or a pump 108.

[0144] If there is less reflux required than there is liquid in the partly condensed gaseous overhead stream 105, the surplus may be passed on to conduit 20 over a bypass conduit (not shown) and a flow control valve (not shown). In case too little reflux is available, an external reflux medium, suitably butane, may be added from an external source (not shown), suitably into conduit 105.

[0145] The liquid, C3+-enriched bottom stream is removed from the scrub column 95 via conduit 115. Here it may be withdrawn from the process, sent to a fractionation train and/or storage/transport and/or a reboiler in any fashion known to the person skilled in the art.

[0146] Prior to its normal operation as described above, the main cryogenic heat exchanger has to be cooled down to operating temperature. The presently disclosed methods and apparatuses achieve an automated cooling down of the main cryogenic heat exchanger. This has been demonstrated in accordance with the following.

[0147] Several temperatures, temperature rates of change, and temperature differentials at various points in and around the main cryogenic heat exchanger may be monitored by the programmable controller during the cool down process. This enables the programmable controller to determine the evolution of the temperature profile over time. Figure 5 shows the points in and around the main cryogenic heat exchanger 100 where in a test the temperature sensors (TR20; TR25; TR33; TR40; TR47; TR48; TR52; TR54; TR57; TR59) and differential temperature sensors (TDR2547; TDR2548; TDR2715; TDR5254; TDR5759) were provided in addition to other temperature and temperature differential sensors that will not be further discussed here as they were considered of less relevance for the described automation.

[0148] The line-up in Fig. 5 corresponds to the line-up of Fig. 4, but the reference numbers have been omitted in the interest of highlighting the reference numbers corresponding to the various sensors that are shown. Temperature sensors are marked by “TR” followed by a number that corresponds to the reference number assigned to the component, stream or line (conduit) where the sensor is provided. For temperature differential sensors, the code TDR is used followed by two two-digit numbers corresponding to the reference numbers assigned to the components, streams or lines (conduits) between which the differential sensor is provided. The temperature sensors and differential temperature sensors generate sensor signals that may be received by and monitored by the programmable controller which may use one or more of these as controlled variables.

[0149] At the top of the main cryogenic heat exchanger 100, temperatures in conduits 57 and 59, upstream and downstream of the first JT valve 58, were monitored using temperature sensors TR57 and TR59. The difference between these temperatures was also monitored, which may be used to determine the actual JT effect over the first JT valve.

[0150] The difference between the shell temperature at mid-point 27 was measured and the temperature in tube side 15 at mid-point 27 was determined (TDR2715). In addition, the shell temperature near the warm end 33 was measured using TR33, as well as the temperature of the spent refrigerant drawn from the heat exchanger in conduit 25 (TR25).

[0151] The inlet temperature of the heavy liquid refrigerant fraction may be measured using TR47, inlet temperature of the hydrocarbon stream immediately upstream of the main cryogenic heat exchanger 100 may be measured using TR20, and the temperature of the hydrocarbon rundown stream immediately downstream of the main cryogenic heat exchanger 100 may be measured using TR40.

[0152] All temperature measurements stabilize and are reliable when there is forward flow. Thus, the measurements can be unreliable at times, for instance when stagnant gas goes back to the temperature sensor at the beginning of cool down. The monitoring depends on the initial conditions, pressure conditions for example. The temperature that indicates the end of the cool down is the hydrocarbon product rundown line temperature TR40. However, this measurement may not be reliable at the beginning of cool down when the hydrocarbon flow is extremely low. Therefore, at the beginning of cool down another temperature, suitably the LMR temperature TR59 downstream of the first JT valve 58, may be monitored instead. However at the end of cool down the reference temperature will be TR40.

[0153] Several pressures and pressure differentials, in various points in the line-up, may be monitored by the programmable controller during the cool down process. The most relevant pressure sensors (PR32; PR54; PR55; PR57; PR150) are indicated in Figure 5, using PR followed by a number that corresponds to the reference number assigned to the component or line (conduit) where the sensor is provided. The most important pressures to be monitored include the pre-cool compressor suction pressure PR150 in conduit 150, the mixed refrigerant compressor 30 suction pressure (PR55) in conduit 55; and the mixed refrigerant compressor discharge pressure PR32 in conduit 32.

[0154] These pressure sensors generate sensor signals that may be received by and monitored by the programmable controller which may use one or more of these as controlled variables.

[0155] The pressure in the line-up after a long shut down can affect the cooling procedure, especially if the line-up has been in full recycle for days. Small changes, while having a high pressure, may have big consequences in the overall cooling of the main cryogenic heat exchanger 100. Additionally, PR57 and PR54 (LMR and HMR tube pressure upstream of the first (58) and second (51) JT valves, respectively) may be monitored before cool down. Any valve manipulation may have faster dynamics if these pressures are too high, so as initial condition the system should have a pressure level that is lower than a predetermined initial maximum pressure value (in the test we used 20 barg).

[0156] Flow rates may be calculated for the LMR and HMR streams, in order to be used as a controlled variable or at least a variable to be monitored. Such calculations may be based on the differential in pressure and the nominal valve opening of the first (58) or second (51) JT valve, respectively. For this, measurements of the pressures before the first and second JT valves on both LMR and HMR circuits (PR57 and PR54, respectively) and the suction pressure (PR55) of the refrigerant circuit before going to the compressors may be used.

[0157] The standard deviation of flow measurements for small JT valve openings may be quite large, which could lead to errors if used as monitored variable. A linear model of the LMR and HMR flows has been calculated as the Least Squares Linear model from all measurements with high valve openings. Based on this model, the estimated flows will be given by:

$$F_{LMR} = K_{LMR} \cdot X_{58} \cdot \sqrt{}(PR57 - PR55); \text{ and}$$

$$F_{HMR} = K_{HMR} \cdot X_{51} \cdot \sqrt{}(PR54 - PR55)$$

wherein F_{LMR} (F_{HMR}) represents the flow rate in the LMR conduit 48 (HMR conduit 47); X_{58} (X_{51}) represents the amount of opening of the first (second) JT valve 58, resp. 51; and K_{LMR} (K_{HMR}) represents the least squares linear model constant corresponding to the slope. A linear least squares model has been found to satisfy the desired accuracy. However, other types of functions may be employed instead. In particular, a quadratic function could be estimated for the HMR, while for the LMR flow a characteristic shape resembling a square root function has been found.

[0158] Immediately prior to executing the automated cooling down, the main cryogenic heat exchanger 100 was first pre-cooled, under manual control, to a temperature between about –25 °C and about –35 °C. Other tasks that have been completed at this stage, for the time being manually but these could also be automated and incorporated in the module structure as presently disclosed, include:

- level control in any in-line NGL (natural gas liquid, typically consisting of molecules having mass comparable to propane and higher) extraction column (e.g. scrub column);
- temperature control of stream 20;

- depressurisation of the refrigerant circuit, notably tube-sides 15, 28;
- defrosting of gas/cold gas mixture controls, used to cool the refrigerant circuit tubes to the temperature of between about –25 °C and about –35 °C.

[0159] Further cooling down of the main cryogenic heat exchanger to the operating temperature of below about -155 °C, here to an operating temperature of about -160 °C, was achieved using the automated cooling down method and apparatus. The further cooling down may hereinafter be referred to as the “final cool down”.

[0160] So, step (i) as described above may comprise obtaining one or more refrigerant temperature indications comprising at least one of a refrigerant temperature indication of the liquid, heavy refrigerant fraction (HMR) and/or the gaseous, light refrigerant fraction (LMR)

- at a suction side of the JT valve 14;
- at a discharge side of the JT valve 14;
- at an entry side of the cryogenic heat exchanger 1;
- at a point inside the cryogenic heat exchanger 1;
- at a discharge side of the cryogenic heat exchanger 1.

[0161] So, in view of the embodiment described above with reference to Fig.’s 4 and 5, according to an embodiment the refrigerant recirculation circuit to recirculate spent refrigerant back to the cryogenic heat exchanger comprises a plurality of compression stages with each compression stage comprising a compressor recycle valve (130, 131) and the adjustment step (507) comprises adjusting and closing the plurality of recycle valves (509a, 509b).

[0162] So, in view of the embodiment described above with reference to Fig.’s 4 - 6, according to an embodiment downstream of the cooler 42 and upstream of the first JT valve a liquid/vapour separator 45 is provided in the refrigerant recirculation circuit, to receive a partly condensed refrigerant and separate the partly-condensed refrigerant stream into a liquid heavy refrigerant fraction (HMR) and a gaseous light refrigerant fraction (LMR) and to discharge the liquid heavy refrigerant fraction via a liquid outlet and the gaseous light refrigerant fraction via a gas outlet, which fractions are passed to the cryogenic heat exchanger, wherein the first JT valve is arranged to control passage of one of these fractions, preferably the light refrigerant fraction and wherein a second JT valve is arrange to control passage of the other of these fractions, preferably the heavy refrigerant fraction.

[0163] Next, with reference to Fig. 6 a block diagram for automatically cooling down the cryogenic heat exchanger of Fig. 4 or Fig. 5 will be described.

[0164] Similar to the embodiment described above with reference to Fig. 3, after a start signal is generated in step 501, a comparison step 502 is performed which comprises:

(i) receiving one or more refrigerant temperature indications, providing an indication of the temperature of the refrigerant,

(ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and

(iii) based on the outcome of the comparison under (ii), selecting one of an automated warm cooling down procedure 503 of the cryogenic heat exchanger or an automated cold cooling down procedure 504 of the cryogenic heat exchanger.

[0165] The warm cooling down procedure 503 will not be described in more detail here. Reference is made to WO2009/098278 in which a detailed description of the warm cooling down procedure is provided.

[0166] The cold cooling down procedure 504 starts with defining the initial conditions in action 505 much in the same way as described above. Examples of critical initial conditions are:

- presence of an excess of heavy components in the hydrocarbon feed (e.g. in line 20) if the hydrocarbon flow is manipulated (generally a maximum of 0.08 mol% of C5+ is tolerated);
- first and second JT valves (58, 51) not sufficiently closed (in the test a value of more than 1 % open was used);
- pressure in refrigeration circuit (LMR and HMR) is lower than the compressor 31 discharge;
- one or more of refrigerant compressors 30, 31, and pre-cool refrigerant compressor 127 is not on-line and running (as e.g. monitored by compressor speed);
- suction and discharge valves on these compressors are not open;
- refrigerant pressure at the compressor 31 discharge is too high (the test used a maximum of 20 barg);
- pre-cooling refrigerant compressor 127 suction pressure outside of a predetermined pressure window (suitably a window around approximately 0.5 barg);
- any IGV valve present is not sufficiently closed.

[0167] Examples of non-critical initial conditions are:

- TDR5759 too small (a typical minimum value recommended in case of a coil wound heat exchanger from Air Products & Chemicals Inc is 25 °C);
- one or more of refrigerant compressor recycle valves (e.g. 130, 131) are not sufficiently open (the test used less than 99 % open);
- discharge pressure of compressor 31 below a pre-determined minimum value (the test used 18 barg).

[0168] When the initial conditions are defined and possible warnings are resolved, actions 506 and 511 are triggered.

[0169] In initial opening action 506 the first JT valve 58 for controlling the vapour (light) refrigerant stream and a second JT valve 51 for controlling the liquid (heavy) refrigerant stream are set at an initial opening (506a), wherein the initial opening according to the automated warm cooling down procedure 503 differs from the initial opening step of the first JT valve 14 according to the automated cold cooling down procedure 504. Preferably, the initial openings of the JT valves are greater in the automated warm cooling down procedure 503 than in the automated cold cooling down procedure 504.

[0170] Action 506b, following action 506a initiates a waiting time as described above.

[0171] The initial opening step may comprise imposing an initial opening of the first and second JT valve, wherein the initial opening step of the first and second JT valves (51, 58) according to the automated warm cooling down procedure differs from the initial opening step of the first and second JT valves (51, 58) according to the automated cold cooling down procedure.

[0172] In particular, the initial opening of the first and second JT valves is greater in the automated warm cooling down procedure than in the automated cold cooling down procedure.

[0173] The initial opening step may further comprise performing a TROC step comprising adjusting the opening of the first and second JT valves 51, 58 based on a determined temperature rate of change (TROC) of the refrigerant over the first and second JT valves 51, 58 in accordance with an adjustment scheme, wherein the automated warm cooling down procedure 503 and the automated cold cooling down procedure 504 comprise different adjustment schemes.

[0174] In particular, the adjustment scheme of the cold cooling down procedure may comprise waiting a predetermined time interval between imposing an initial opening of the first and second JT valves 51, 58 and initiating adjusting the opening of the first and second JT valves 51, 58 based on a monitored temperature rate of change (TROC) of the refrigerant over the first and second JT valves 51, 58.

[0175] Next, after action 506 has been completed the automated cold cooling down procedure comprises performing an adjustment step (507) comprising simultaneously

- adjusting and closing recycle valve (509) and
- further adjusting the first and second JT valves (508a, 508b).

[0176] As described above, there may be a plurality of compression stages with each compression stage comprising a compressor recycle valve (130, 131) and action 509 may thus comprise adjusting and closing a plurality of recycle valves 130, 131.

[0177] The make-up adjustment is controlled in action 512 which is performed parallel to action 507 and manipulates the make-up to:

- Increase the compressor 31 discharge pressure along a ramp towards a target operating pressure (in the test, 30 barg);

- Move the refrigerant composition towards a target composition, which may be an end target for normal operation of the main cryogenic heat exchanger 100 or an intermediate target.

[0178] The refrigerant target composition may change during the cool down procedure. It may change gradually or step wise upon a controlled variable reaching a predetermined value. For instance, it may change once the temperature TR57 goes below a predetermined value of – 135°C or -140°C.

[0179] Parallel to actions 506 and 507, action 511 is executed which adjusts one or more of the pre-cool refrigerant compressor recycle valve(s), here in the form of the first stage recycle valve 129 that controls recycle stream through the first compression stage of compressor 127. The module objective is to maintain a suction pressure on the pre-cool refrigerant suction pressure (in conduit 150 of Fig. 4) within a pre-determined range, e.g. 0.25 – 0.50 barg, but without reducing the surge deviation too close to the control line. The low pressure will assure that the temperature of the hydrocarbon feed gas going into the main cryogenic heat exchanger 100 (e.g. via conduit 20) has a reasonable value. Therefore, the temperature in conduit 20 itself does not need to be monitored or used as condition for control in this module.

[0180] Additionally, the pre-cooling refrigerant compressor 127 discharge temperature (in conduit 135) was not monitored, since the automated cool down procedure as used in the test did not offer a capability to manipulate any variable that could be used to improve the situation of a high discharge temperature of the pre-cooling refrigerant compressor 127. However, this may be implemented without departing from the scope of the invention.

[0181] There may be built in some overriding boundaries, for one or more of the monitored variables. Crossing of one of these boundaries (i.e. exceeding a pre-determined maximum and/or minimum value) by one or more of the monitored variables may result in issuance of a warning signal to alert an operator, or pausing the cooling down, or abortion of the cooling down, or a combination of these.

[0182] Typical examples of such overriding boundaries are:

- a pre-determined maximum temperature rate of change (e.g. 28 °C/hour as specified for an Air Products cryogenic heat exchanger) on any selected temperature, suitably one or more of a temperature of the hydrocarbon product at a location in tube side 29 and/or in the discharge conduit 40; the spent refrigerant temperature (e.g. in bottom warm end of the shell side 33 or in conduit 25); the refrigerant temperature at the discharge side of the first JT valve 58 or the second JT valve 51, or at the suction side thereof; any shell side temperature in the heat exchanger 1;
- a pre-determined maximum spatial temperature gradient, reflecting a specified maximum temperature difference between two spatially separated points in or around the heat exchanger (e.g. a maximum temperature difference of 28 °C), suitably the temperature difference TDR2547 between the light refrigerant upstream of main cryogenic heat exchanger 100 and the spent refrigerant (also possible: TDR3347, not shown); the temperature difference TDR2548 between the heavy refrigerant upstream of main cryogenic heat exchanger 100 and the spent refrigerant (also possible: TDR3348, not shown); TDR2715; and TDR5759;

- a predetermined maximum content (0.08 mol%) of heavy components in the hydrocarbon feed stream that would freeze in the main cryogenic heat exchanger 100;
- suction and discharge valves on the refrigerant compressors closed;
- a maximum specified top shell pressure (5 barg) at the cold end of the main cryogenic heat exchanger;
- detection of a trip;
- existence of communication errors in the control system.

[0183] Clearly, other overriding boundaries may be used, e.g. in case of other types of cryogenic heat exchangers being used.

[0184] Although not implemented in the test, it has been contemplated to further embed the above block diagrams (Fig. 6 or a similar one for another line-up or heat exchanger) in a larger structure comprising other, preceding or subsequent actions, or both. An example is shown in Fig. 7.

[0185] Fig. 7 shows an example with some post cool-down tasks. These may, for instance, be intermediate tasks that need to be completed before an automatic process control system for normal operation can take over the control. For instance, module 401 manipulates the run down valve 44, with the goal to ramp up the flow through conduit 20 and 40 and the hydrocarbon tube side 29.

[0186] Other modules could therefore be in parallel to module 401. As an example, module 402 has been depicted, but also included could be a module for ramping up any fractionation section that may be provided downstream of any NLG extraction column to receive and further fractionate the extracted NLG liquids. The person of skill in the art would be able to work out which manipulated and controlled variables could be used, depending on the type of line-up and equipment used.

[0187] The apparatuses and methods described herein may be applied to cryogenic heat exchangers whenever a cryogenic heat exchanger needs to be cooled down before operation. This could for instance be initial cooling down, or cooling down after a maintenance operation or after a trip: the reason why the heat exchanger was warmer than operation temperature is not material to the application of the subject matter described herein.

[0188] The person skilled in the art will understand that the present invention can be carried out in many various ways without departing from the scope of the appended claims. The invention has been described with particularity, including providing target values for certain controlled variables. However, it will be apparent to the person skilled in the art that these values were chosen in connection to the specific line up and equipment used for the test. Such details may need to be optimized when the invention is to be carried out on another line-up using other equipment, and therefore should not be considered as limiting the scope of the present invention.

CLAIMS:

1. A method of cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, the method comprising the steps of:

receiving, by the cryogenic heat exchanger, the hydrocarbon stream to be liquefied and a refrigerant, to exchange heat between the hydrocarbon stream and the refrigerant, thereby at least partially liquefying the hydrocarbon stream, and to discharge the at least partially liquefied hydrocarbon stream and a spent refrigerant that has passed through the cryogenic heat exchanger,

recirculating, by a refrigerant recirculation circuit, the spent refrigerant back to the cryogenic heat exchanger, wherein the refrigerant recirculation circuit comprises at least a compressor, a compressor recycle valve, a cooler, and a first Joule Thomson (JT) valve;

performing a comparison step by a programmable controller, said comparison step comprising:

(i) receiving one or more refrigerant temperature indications, and providing an indication of a temperature of the refrigerant,

(ii) comparing the one or more refrigerant temperature indications with one or more associated predetermined threshold values, and

(iii) based on an outcome of the comparison under (ii) selecting one of an automated warm cooling down procedure of the cryogenic heat exchanger and an automated cold cooling down procedure of the cryogenic heat exchanger;

wherein the automated cold cooling down procedure is adapted to reduce a temperature of the cryogenic heat exchanger from a cold condition down to LNG production point and is allowed to start with an opened first JT valve,

wherein the automated warm cooling down procedure and the automated cold cooling down procedure comprise an initial opening step, the initial opening step comprises imposing an initial opening of the first JT valve, wherein the initial opening step of the first JT valve according to the automated warm cooling down procedure differs in size of the initial opening from the initial opening step of the first JT valve according to the automated cold cooling down procedure; and

wherein as part of the initial opening step, performing, by the programmable controller, a TROC step comprising adjusting the opening of the first JT valve based on a determined temperature rate of change (TROC) of the refrigerant over the first JT valve in accordance with an adjustment scheme, wherein the automated warm cooling down procedure and the automated cold cooling down procedure comprise a plurality of different adjustment schemes.

2. The method of claim 1 further comprising the step of:

- subsequently liquefying the hydrocarbon stream in one or more steps including at least heat exchanging the hydrocarbon stream in the cryogenic heat exchanger.

3. The method according to claim 1, wherein the one or more refrigerant temperature indications comprise at least one of a refrigerant temperature indication of the refrigerant

- at a suction side of the first JT valve;
- at a discharge side of the first JT valve;
- at an entry of the cryogenic heat exchanger;
- at a point inside the cryogenic heat exchanger;
- at a discharge side of the cryogenic heat exchanger.

4.. The method according to claim 1, wherein the initial opening of the first JT valve is greater in the automated warm cooling down procedure than in the automated cold cooling down procedure.

5. The method according to claim 1,

wherein the initial opening step of the first JT valve in the automated warm cooling down procedure comprises imposing a predetermined initial opening of the first JT valve, and

wherein the initial opening step of the first JT valve in the automated cold cooling down procedure comprises determining a current opening of the first JT valve and imposing the determined current opening of the first JT valve.

6. The method according to claim 1, wherein the initial opening step of the cold cooling down procedure further comprises opening the compressor recycle valve.

7. The method according to claim 1,

wherein determining the temperature rate of change (TROC) of the refrigerant over the first JT valve is done by comparing two refrigerant temperature indications obtained at a respective first and second moment in time, the first and second moment in time being separated by a predetermined time interval, wherein the predetermined time interval according to the cold cooling down procedure is shorter than the predetermined time interval according to the warm cooling down procedure.

8. The method according to claim 1, wherein the adjustment scheme of the cold cooling down procedure comprises waiting a predetermined time interval between imposing the initial opening of the first JT valve and initiating adjusting the opening of the first JT valve based on the monitored temperature rate of change (TROC) of the refrigerant over the first JT valve.

9. The method according to claim 1, wherein the automated cold cooling down procedure comprises performing an adjustment step comprising simultaneously

(i) adjusting and closing the compressor recycle valve; and
(ii) further adjusting of the first JT valve.

10. The method according to claim 9, wherein the refrigerant recirculation circuit to recirculate the spent refrigerant back to the cryogenic heat exchanger comprises a plurality of compression stages with each compression stage comprising a compressor recycle valve and the adjustment step comprises adjusting and closing the plurality of compressor recycle valves.

11. The method according to claim 1,

wherein downstream of the cooler and upstream of the first JT valve a liquid/vapor separator is provided in the refrigerant recirculation circuit, to receive a partly condensed refrigerant stream and separate the partly-condensed refrigerant stream into a liquid heavy refrigerant fraction (HMR) and a gaseous light refrigerant fraction (LMR) and to discharge the liquid heavy refrigerant fraction via a liquid outlet and the gaseous light refrigerant fraction via a gas outlet,

the method comprising the steps of the first JT valve controlling passage of the light refrigerant fraction and a second JT valve controlling passage of the heavy refrigerant fraction.

12. The method according to claim 11, wherein an initial opening step comprises imposing an initial opening of the first and second JT valve, wherein the initial opening step of the first and second JT valves according to the automated warm cooling down procedure differs in size from the initial opening step of the first and second JT valves according to the automated cold cooling down procedure.

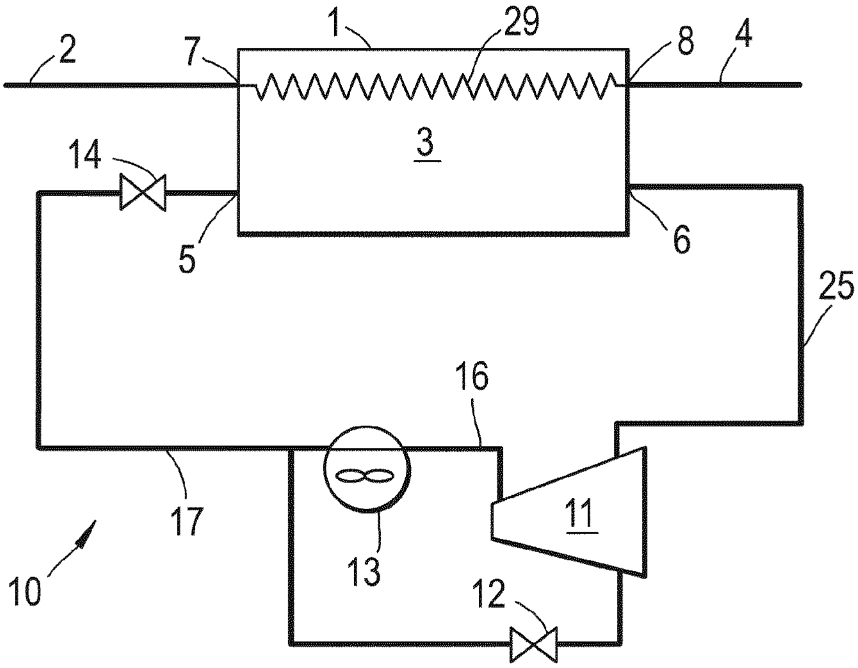
13. The method according to claim 12, wherein the automated cold cooling down procedure comprises performing an adjustment step comprising simultaneously

(i) adjusting and closing the compressor recycle valve; and

(ii) further adjusting the first and second JT valves.

Shell Internationale Research Maatschappij B.V.
Patent Attorneys for the Applicant/Nominated Person
SPRUSON & FERGUSON

Fig.1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10

Fig.2

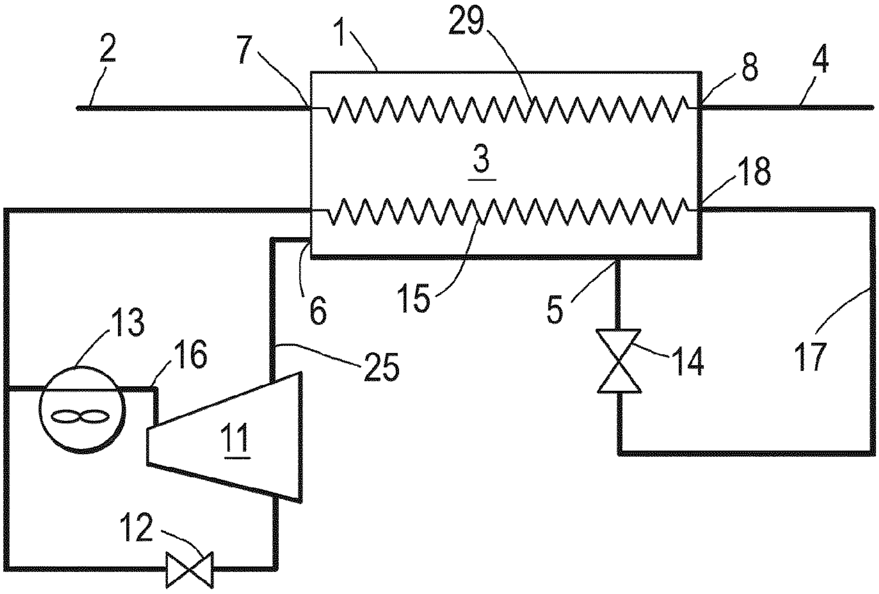
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Fig.3

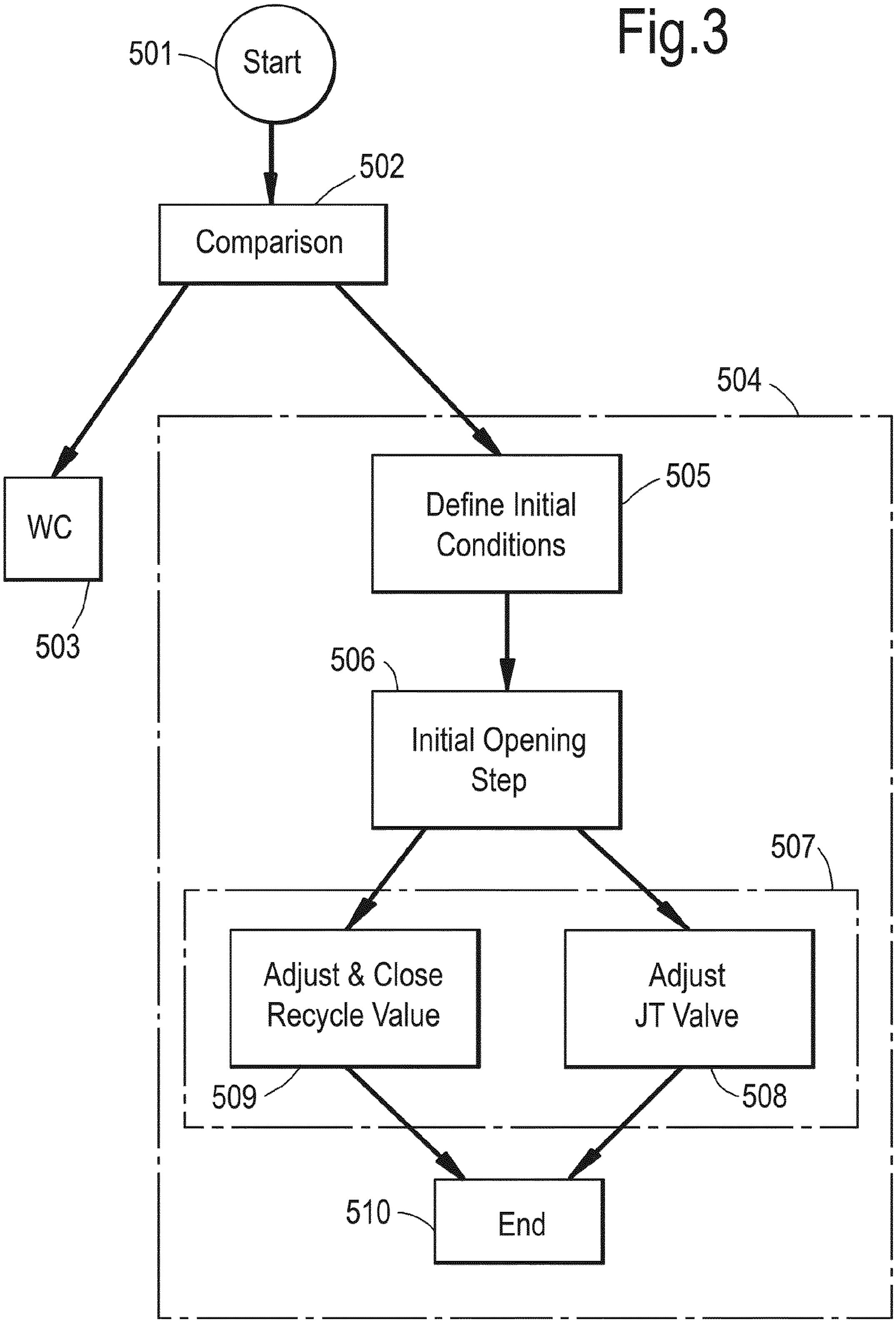
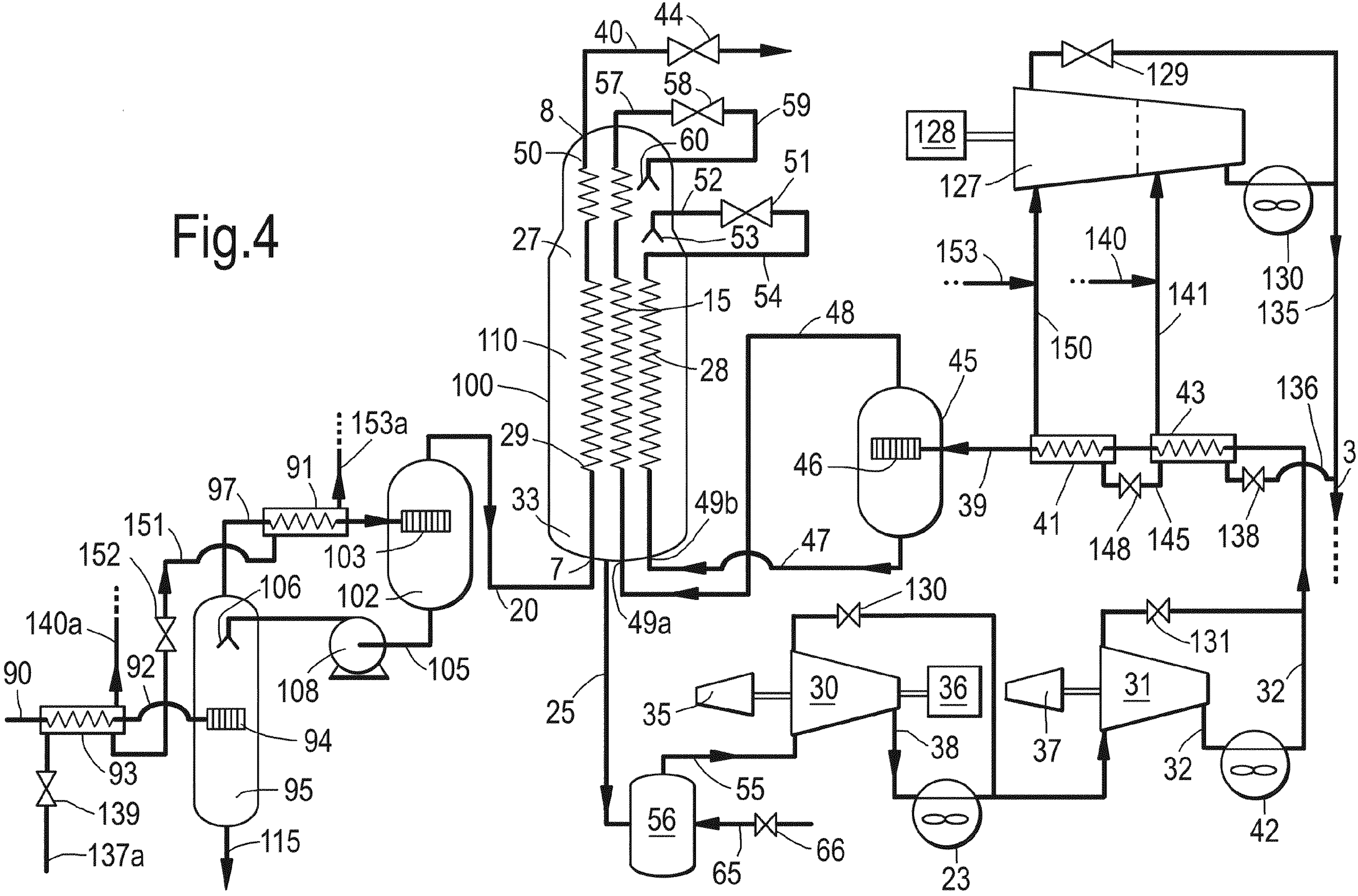

501
Start
502
Comparison
WC
503
504
505
Define Initial Conditions
506
Initial Opening Step
507
Adjust & Close Recycle Value
509
Adjust JT Valve
508
510
End

Fig.4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44
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59
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50
51
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53
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54
15
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28
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49b
7
49a
20
25
153a
91
97
151
152
103
102
106
140a
92
90
93
139
137a
94
95
115
108
105
48
45
46
47
35
30
36
38
55
56
65
66
23
130
128
127
129
153
140
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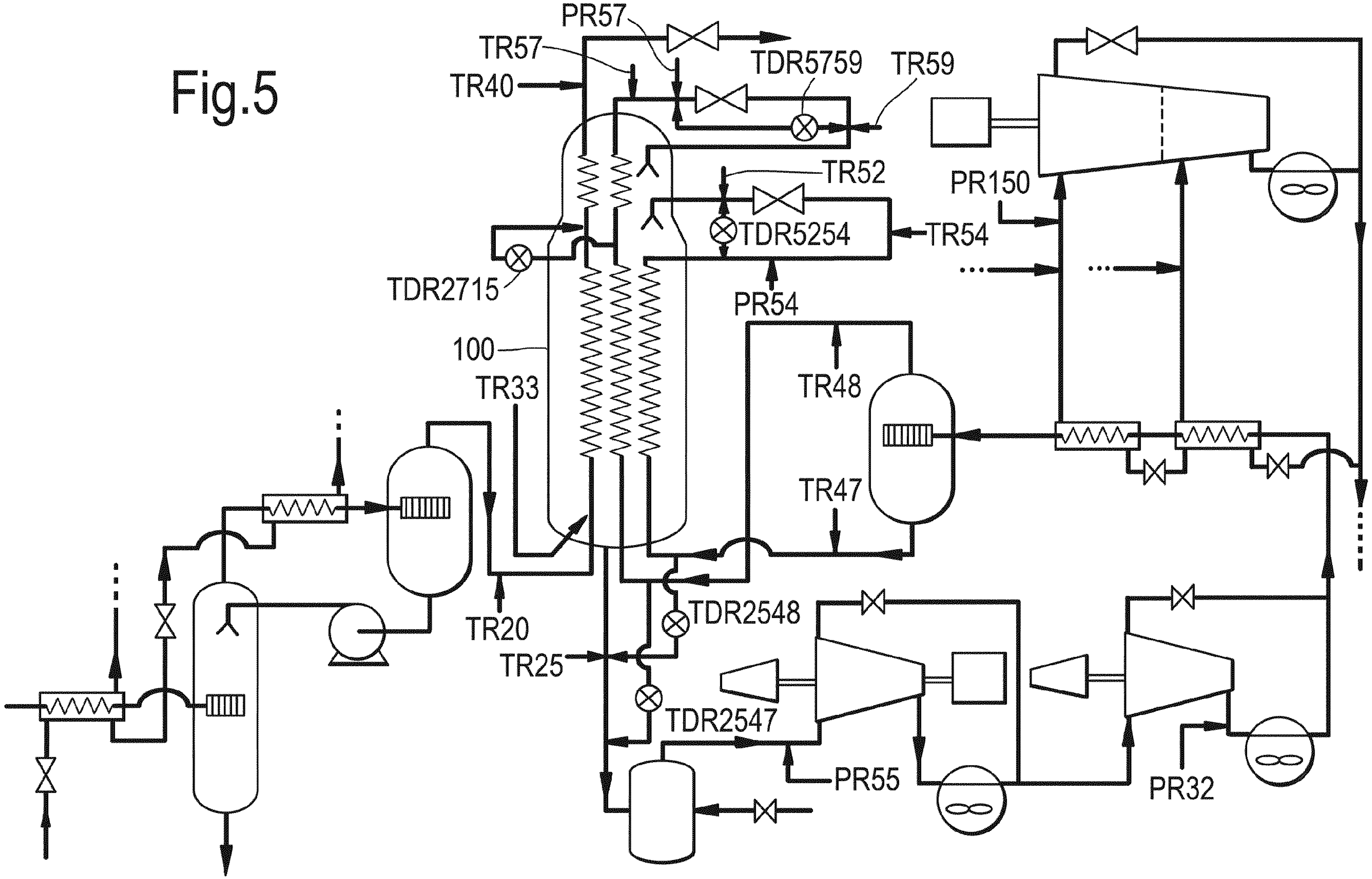
131
31
37
32
32
42

Fig.5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TR57
TR40
TDR5759
TR59
TR52
PR150
TDR5254
TR54
TDR2715
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TR33
TR47
TR20
TDR2548
TR25
TDR2547
PR55
PR32

Fig.6

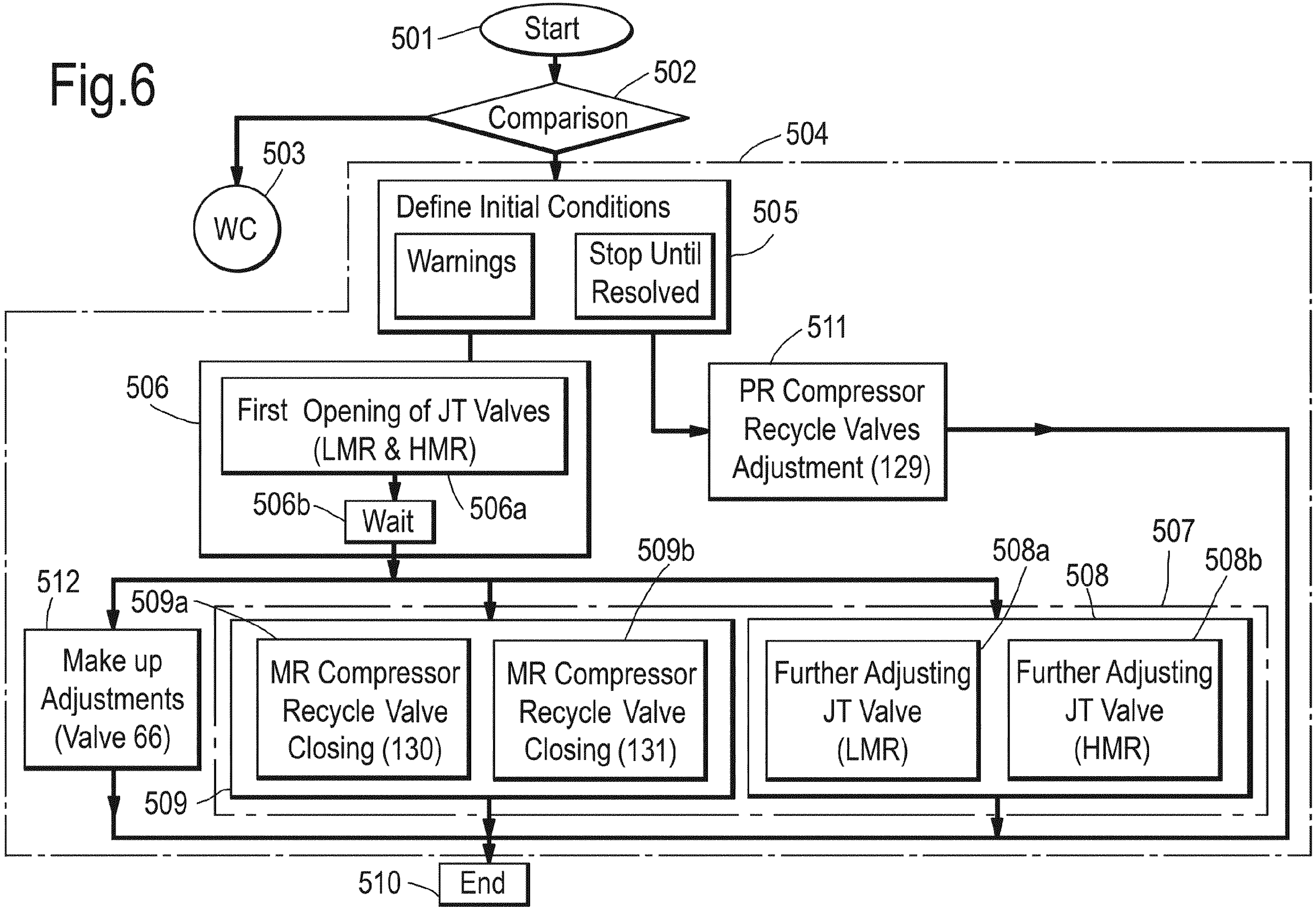
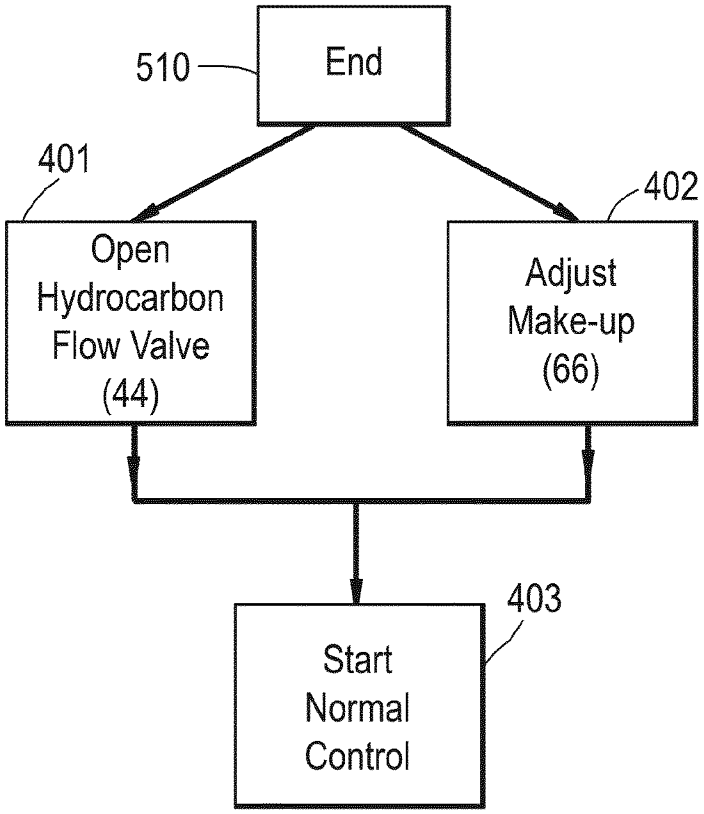

501
Start
502
Comparison
503
WC
504
Define Initial Conditions
Warnings
Stop Until Resolved
505
511
PR Compressor Recycle Valves Adjustment (129)
506
First Opening of JT Valves (LMR & HMR)
506b
Wait
506a
509b
508a
507
508
508b
512
509a
Make up Adjustments (Valve 66)
MR Compressor Recycle Valve Closing (130)
MR Compressor Recycle Valve Closing (131)
Further Adjusting JT Valve (LMR)
Further Adjusting JT Valve (HMR)
509
510
End

Fig.7


510
End
401
Open Hydrocarbon Flow Valve (44)
402
Adjust Make-up (66)
403
Start Normal Control