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(54) **METHOD AND APPARATUS FOR COOLING DOWN A CRYOGENIC HEAT EXCHANGER AND METHOD OF LIQUEFYING A HYDROCARBON STREAM**

(76) Inventors: **Clive Beeby**, Bangalore (IN); **Maria Isabel Parra-Calvache**, Amsterdam (NL)

Correspondence Address:
SHELL OIL COMPANY
P O BOX 2463
HOUSTON, TX 772522463

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(57) **ABSTRACT**

Method and apparatus for cooling down a cryogenic heat exchanger, employing a programmable controller that receives input signals representing sensor signals of one or more controlled variables in a selected process, and produces control signals to control one or more manipulated variables in the selected process. The programmable controller can execute a computer program that comprises a network of at least three modules. The modules in the network are interconnected such a trigger signal received by a second and a third module of the at least three modules corresponds to a communication signal that is generated when the first module of the at least three modules has reached a pre-determined target for that module.

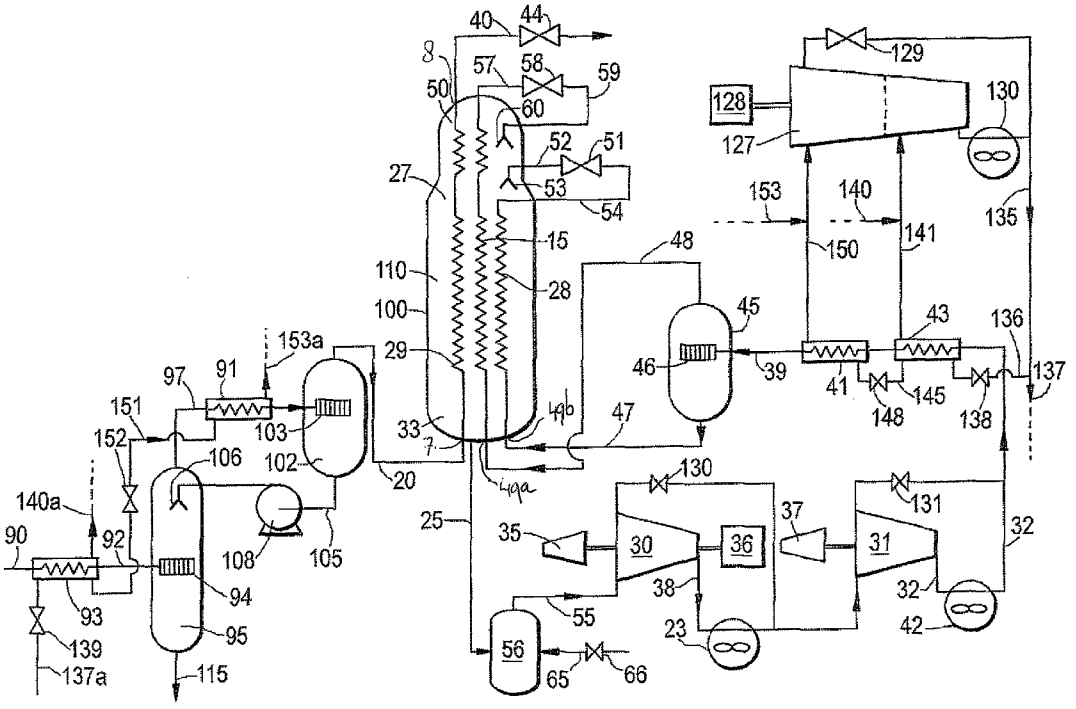


Fig.1

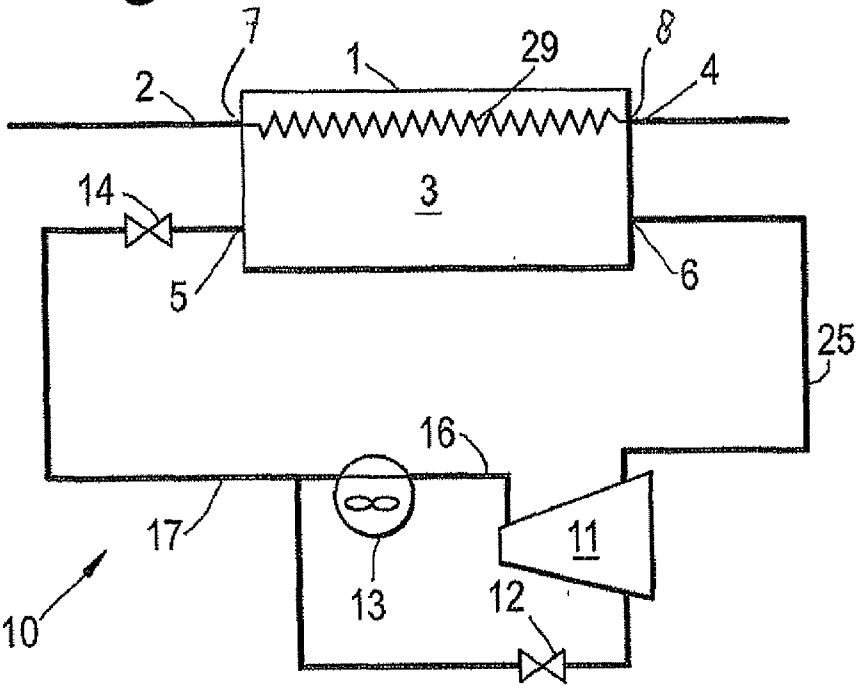

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Fig.2

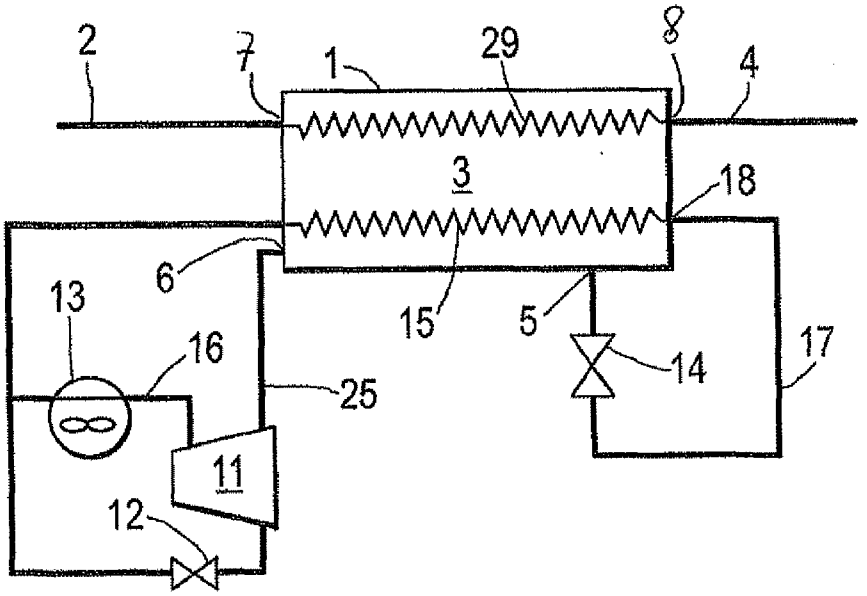
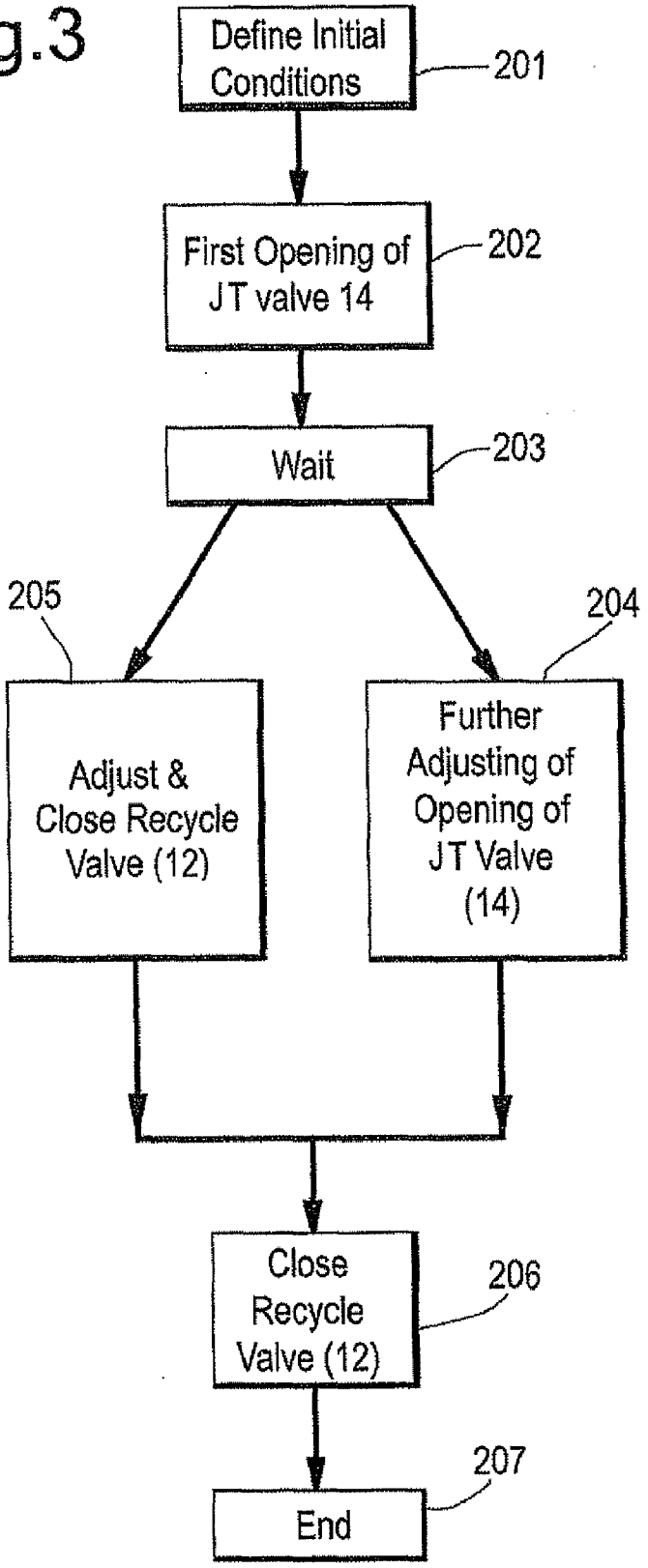

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11
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Fig.3


Define Initial Conditions
201
First Opening of JT valve 14
202
Wait
203
205
204
Adjust & Close Recycle Valve (12)
Further Adjusting of Opening of JT Valve (14)
Close Recycle Valve (12)
206
End
207

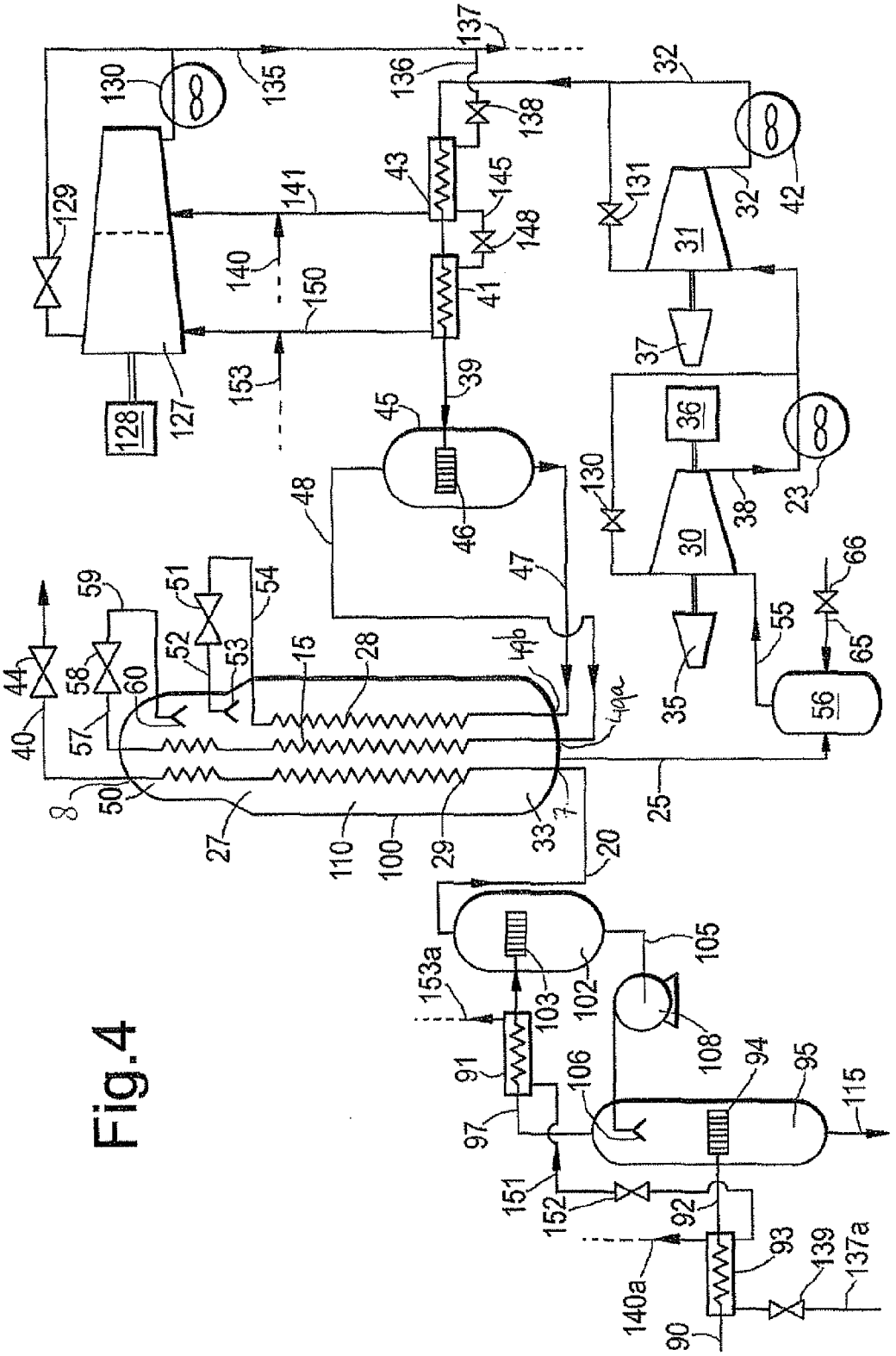

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27
110
100
29
33
20
105
153a
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137a
140a
90

Fig.4

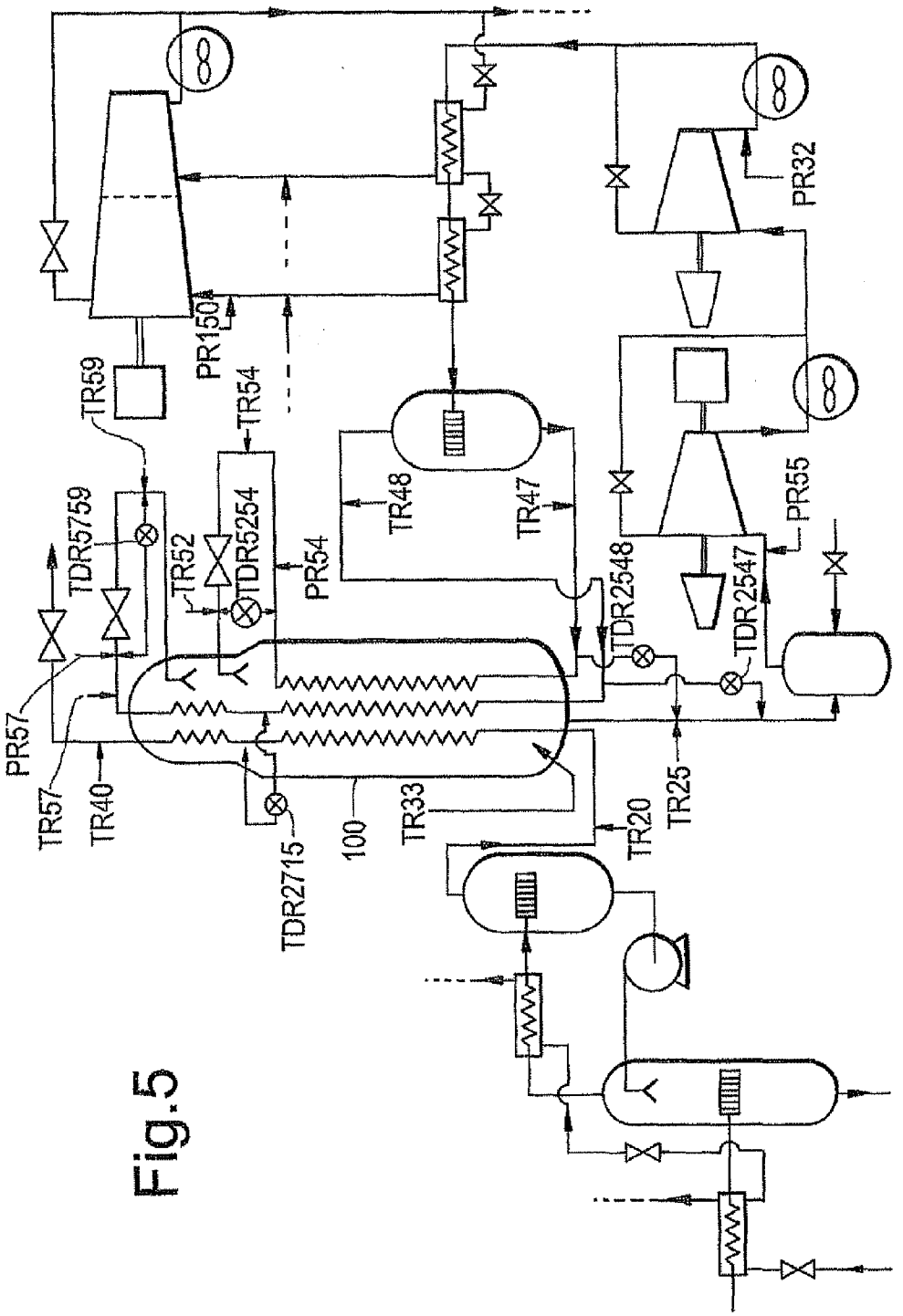

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Fig.5

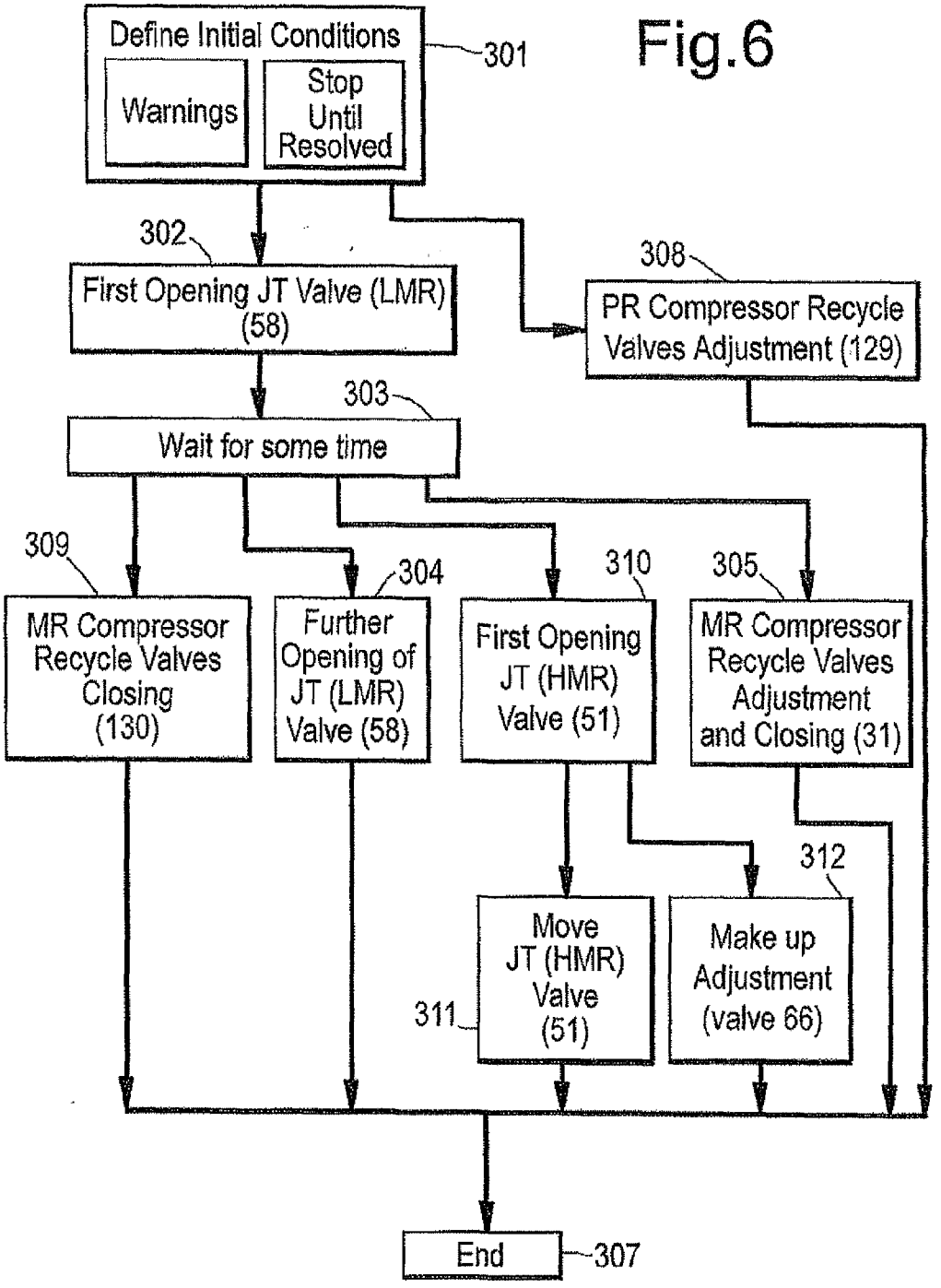
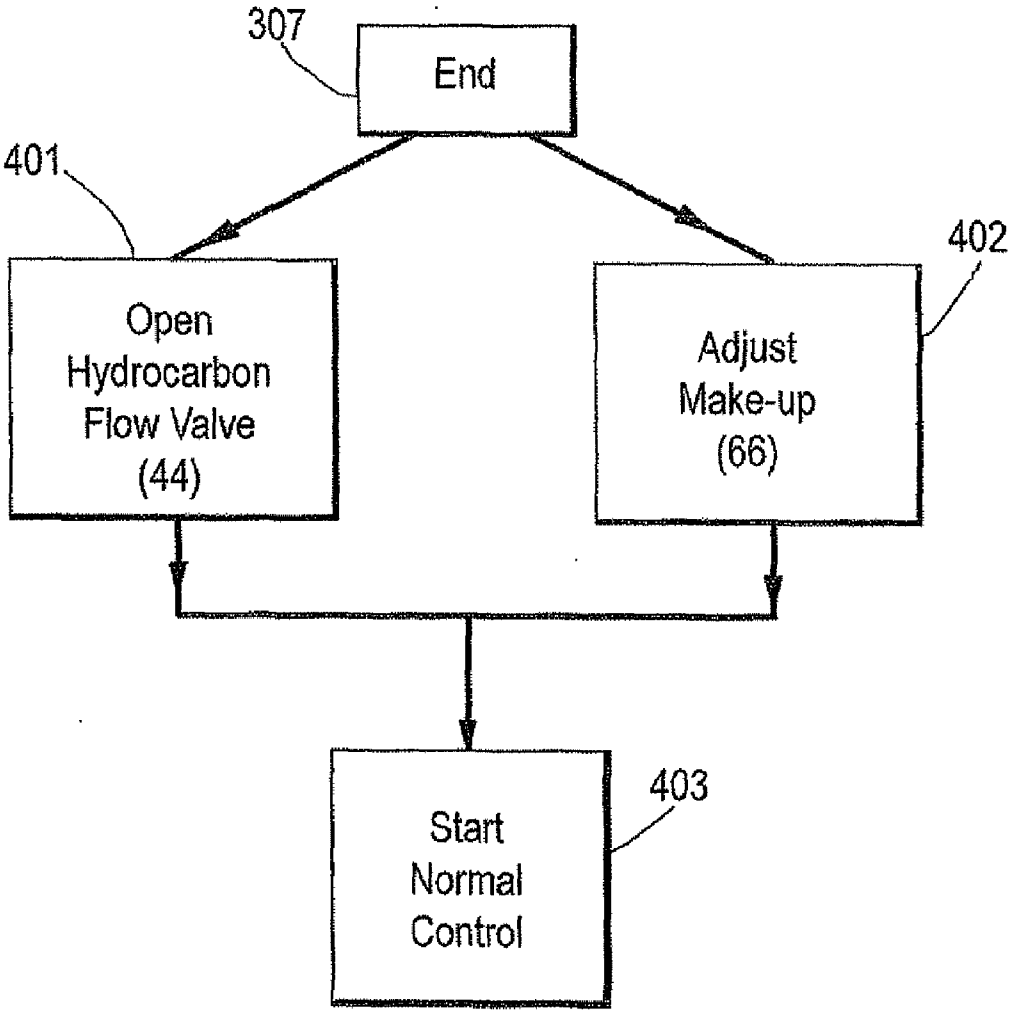

Define Initial Conditions
Warnings
Stop Until Resolved
301
302
First Opening JT Valve (LMR) (58)
308
PR Compressor Recycle Valves Adjustment (129)
303
Wait for some time
309
MR Compressor Recycle Valves Closing (130)
304
Further Opening of JT (LMR) Valve (58)
310
First Opening JT (HMR) Valve (51)
305
MR Compressor Recycle Valves Adjustment and Closing (31)
312
Move JT (HMR) Valve (51)
311
Make up Adjustment (valve 66)
End
307

Fig.6

Fig.7


307
End
401
402
Open
Hydrocarbon
Flow Valve
(44)
Adjust
Make-up
(66)
403
Start
Normal
Control

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

[0001] The present invention relates to a method and apparatus for cooling down a cryogenic heat exchanger.

[0002] In various embodiments specifically disclosed herein, the cryogenic heat exchanger is adapted to liquefy a hydrocarbon stream, such as a natural gas stream.

[0003] In another aspect, the present invention relates to a method of liquefying such a hydrocarbon stream.

[0004] 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.

[0005] 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.

[0006] 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.

[0007] 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.

[0008] 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.

[0009] U.S. Pat. No. 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.

[0010] 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.

[0011] The process controller system of U.S. 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 U.S. 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.

[0012] 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

[0013] 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;

[0014] a programmable controller arranged to

[0015] (i) receive input signals representing sensor signals of one or more controlled variables;

[0016] (ii) produce control signals to control one or more manipulated variables; and

[0017] (iii) execute a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein the at least three modules are each arranged to:

[0018] (a) wait until a trigger signal is received; and

[0019] (b) start executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and which modules in the network are interconnected such that the trigger signal received by a second and a third module of the at least three modules corresponds to a communication signal that is generated upon the first module of the at least three modules reaching the pre-determined target for that module.

[0020] 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

[0021] 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,

[0022] 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;

[0023] activating a programmable controller which

[0024] (i) receives input signals representing sensor signals of one or more controlled variables;

[0025] (ii) produces control signals to control one or more manipulated variables; and

[0026] (iii) executes a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein each of the at least three modules

[0027] (a) waits until a trigger signal is received; and

[0028] (b) starts executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and wherein a communication signal is generated upon the first module of the at least three modules reaching the predetermined target for that module, which communication signal is passed on to a second and a third module of the three or more modules where the communication signal acts as the trigger signal for the second and third modules.

[0029] 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.

[0030] 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:

[0031] FIG. **1** schematically shows a cryogenic heat exchanger arrangement according to one embodiment;

[0032] FIG. **2** schematically shows a cryogenic heat exchanger arrangement according to another embodiment; FIG. **3** schematically shows a block diagram of modules for automatically cooling down the cryogenic heat exchanger of FIG. **1** or FIG. **2**

[0033] FIG. **4** schematically shows a main cryogenic heat exchanger arrangement according to another embodiment of the invention as used in a test;

[0034] FIG. **5** schematically shows the line-up of FIG. **4** illustrating monitored temperatures and pressures;

[0035] FIG. **6** shows a block diagram of the modules as used in the test in conjunction with the line-up of FIG. **4**; and

[0036] FIG. **7** schematically shows an alternative module structure that may be incorporated into the block diagram of FIG. **6**.

[0037] 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).

[0038] Described are methods and apparatuses employing a programmable controller that receives input signals representing sensor signals of one or more controlled variables in a selected process, and produces control signals to control one or more manipulated variables in the selected process. The programmable controller can execute a computer program that comprises a network of at least three modules.

[0039] Such a division into modules facilitates better flexibility and ease of management of the cool down process, and maintenance of the programmable controller. Various modules may manipulate one or more valves and has at least one clearly defined module target. The modules may operate independently from each other, but there may be common variables monitored by several modules that can be affected by the action of more than one module. This type of modular approach employing independently executable modules, makes the invention suitable for automating the cooling down of any type of heat exchanger, including those of the so-called coil-wound type and of the plate-fin type.

[0040] One or more of the at least three modules receive a representation of one or more of the input signals and produce representations of one or more of the control signals. The at least three modules are each arranged to

[0041] (a) wait until a trigger signal is received; and

[0042] (b) start executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is achieved.

[0043] A communication signal is generated that marks the module has reached or achieved the predetermined module target. The communication signal may be generated by the module itself, elsewhere in the programmable controller, or it may comprise for instance a sensor signal that indicates that a predetermined condition in or around the cryogenic heat exchanger has been reached. The predetermined module target may be an intermediate result for the module in which case the module may continue to execute more computer readable instructions, e.g. to reach an additional module target. Alternatively, the communication signal may be marking the completion of the execution of the module.

[0044] The modules in the network are interconnected such the trigger signal received by a second and a third module of the at least three modules corresponds to a communication signal that is generated when the first module of the at least three modules has reached the pre-determined target for that module.

[0045] This way of interconnecting the modules allows for control of a sequential process wherein at least a specified task need to be completed before commencing one or more other tasks, and wherein at least two tasks need to be carried out one after another, while other tasks need to be carried out simultaneously.

[0046] There is no need for managing priority of the various tasks, because each module waits until it receives a trigger signal before it may start to carry out its task, and it generates a communication signal upon completion of its task. The completion of the task may be represented by the communication signal that marks the achieving of a predetermined target associated with the task for that module.

[0047] Any signal marking the completion of the predetermined module target may be passed on to and/or be received by one or more next module(s) that can then work on one or more next tasks in the sequential process. When the communication signal is received by two or more next modules, the two or more next modules are ready to start executing their computer readable instructions in parallel with each other.

[0048] For the purpose of interpreting the present claims and specification, the communication signal may be generated after reaching the target or it may be any signal from which can be inferred that the module has reached the predetermined target.

[0049] It will be understood that second and/or third communication signals may be generated when the second and/or third modules have achieved their respective module targets, which second and third communications signals may act as trigger signal(s) for one or more subsequent modules or be used in another way in the procedure.

[0050] The task in a selected module may have to be carried out while being bound by some constraint on one or more of the controlled variables while these one or more controlled

variables are not controlled by the selected module in question, but for instance by a simultaneously active other module. In such a case, the execution of the task of the selected module will automatically experience a delay if further executing of its task would lead to a violation of said constraint. This delay could end when the other module, that does influence the controlled variable, has advanced in executing its task such that the constraint is lifted or shifted giving space for the selected module in question to further advance in executing its task.

[0051] Thus, an effect of the proposed network structure of the modules involving independent modules operating in parallel with each other whereby a control action of one of the modules is constrained by a variable that is influenced by the manipulating one or more manipulated variables by another module, is that the module tasks are quasi-sequentially performed when needed and simultaneously if possible. This makes this type of module network excellently suitable for an operation such as cooling down of a cryogenic heat exchanger within certain constraints.

[0052] An additional option for the interconnection of at least two of the modules is that a content signal is generated in one module that is received by another module and causes a change in the operation of the other module other than the starting up of that module. For example, the content signal may trigger a parameter change in the other module when a certain condition is reached in the first module that causes the content signal to be generated.

[0053] The network of modules can be such that the trigger signal that marks the start of executing the predetermined instructions for a particular module, may be the n^{th} trigger signal received by that module, whereby n can be any natural number. E.g., a selected module may need to wait for, for instance, three other modules to achieve their targets upon which communication signal are generated, before it may start executing its sequence of computer readable instructions. In such a case, it may have to wait until it has received three communication signals acting as trigger signals, and thus the relevant trigger signal, which marks the start of executing the predetermined sequence of instructions for a particular module, is in this example preceded by two earlier trigger signals.

[0054] The programmable controller may be embedded in a distributed control system (DCS), wherein for instance the 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 of the manipulated variables (such as selected valves) without waiting for the programmable controller to transfer control as may be desired during emergencies or the like.

[0055] The inventors associated with the present patent application have contemplated that the presently disclosed type of programmable controller is ideally suited for automation of cooling down of a cryogenic heat exchanger adapted to liquefy a hydrocarbon stream, such as a natural gas stream.

[0056] 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.

[0057] Moreover, experience has revealed that in about 30% of the time the specified maximum rate of temperature change is exceeded unintentionally because of the complexity of the operation. Thanks to the automation as herein described, this percentage is expected to be reduced significantly. The inventors estimate that the exceeding of the maximum rate of temperature change could be reduced to about 12% of the time, or at least less than 15% of the time.

[0058] 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).

[0059] 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.

[0060] The methods and apparatuses disclosed herein make use of so-called manipulated variables and controlled variables. In addition, there are optionally also one or more monitored variables.

[0061] In the specification and in the claims the term 'manipulated variable' is used to refer to variables that are subject to control actions by the programmable controller, and the term 'controlled variables' is used to refer to variables that have to be kept by the programmable controller at a predetermined value (hereinafter referred to as "set point") or within a predetermined range ("set range"). The set point or set range does not have to be a fixed entity. In fact, it will often be subject to changes (either calculated during the cooling down, or as a predetermined sequence over time). Like a controlled variable, a 'monitored variable' is measured and optionally logged, but in contrast to a controlled variable, it does not have to be kept by the programmable controller at a set point or within a set range. However, monitored variables may serve as input for the programmable controller to enable it to take decisions based on these monitored variables, or to generate communications signals, or for instance give rise to the programmable controller to issue a warning signal or to pause and/or abort the automatic procedure.

[0062] Preferably, the one or more controlled variables comprise a rate of change in temperature over time of one or more of: temperature of the refrigerant at the suction side of the first JT valve; temperature of the refrigerant at the discharge side of the first JT valve; temperature of the hydrocarbon stream at a point inside the cryogenic heat exchanger; and temperature of the hydrocarbon stream downstream of the cryogenic heat exchanger. This provides a direct indication that further facilitates cooling down of the cryogenic heat exchanger without exceeding the specified maximum rate of temperature change.

[0063] Instead of, or in combination with the rate of change in temperature, the one or more controlled variables may comprise a selected spatial temperature gradient in or around the cryogenic heat exchanger. This facilitates cooling down of the cryogenic heat exchanger without exceeding a specified maximum spatial temperature gradient. A suitable spatial

temperature gradient to keep within a pre-determined maximum is the temperature gradient between a refrigerant tube and the shell wall.

[0064] 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.

[0065] 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.

[0066] 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.

[0067] 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.

[0068] 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.

[0069] 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 opening 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 opening 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.

[0070] 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.

[0071] 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.

[0072] 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.

[0073] 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.

[0074] 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.

[0075] 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.

[0076] 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**.

[0077] 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.

[0078] 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.

[0079] 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.

[0080] 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**.

[0081] 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**.

[0082] 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**.

[0083] 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.

[0084] 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.

[0085] The inventors have discovered that the sequence of steps and tasks by which a cryogenic heat exchanger is best cooled down can ideally be automated using a programmable controller as herein described, wherein one or more of:

[0086] a rate of change in temperature of the refrigerant at the suction side of the first JT valve;

[0087] a rate of change in temperature of the refrigerant at the discharge side of the first JT valve;

[0088] a rate of change in temperature of the hydrocarbon stream at a point inside the cryogenic heat exchanger;

[0089] a rate of change in temperature of the hydrocarbon stream downstream of the cryogenic heat exchanger;

[0090] a first temperature differential in the refrigerant stream across the first JT valve (difference in temperature of the refrigerant on the suction side of the first JT valve and the refrigerant on the discharge side of the first JT valve);

[0091] a temperature gradient reflecting the temperature differential between the spent refrigerant (in or close to outlet **6** or conduit **25**) and the refrigerant at the inlet **5** of the cryogenic heat exchanger **1**;

[0092] a temperature gradient reflecting the temperature differential between a shell side of the cryogenic heat exchanger **3** and a refrigerant containing tube side (such as tube side **15**);

[0093] a suction pressure in the refrigerant stream at a suction side of the compressor;

are used as controlled variable(s), while:

[0094] the first JT valve setting, e.g. representing a measure of amount of opening of the first JT valve (X_{14}) or of the flow through the first JT valve; and/or

[0095] a compressor recycle valve setting, e.g. representing a measure of amount of opening of the compressor recycle valve (X_{12}) or of the flow through the recycle valve; are used as manipulated variable(s). When a make-up system is provided, the make-up valves of the refrigerant components may also be used as manipulated variables.

[0096] In addition, one or more of:

[0097] one or more absolute temperatures in one or more locations in or around the cryogenic heat exchanger; and

[0098] compressor discharge pressure;

may be used as monitored variable.

[0099] FIG. **3** shows a schematic block diagram containing an example module structure of the computer program in the programmable controller for the automatic cool down method and apparatus. A first module **201** defines initial conditions. Module **201** may contain a graphic interface with a summary of warnings and information modes. It may contain information on critical and non-critical initial conditions. In case of occurrence of a critical condition, the module ends the computer programme thereby stopping the procedure. The procedure may be resumed and/or restarted after the critical condition has been resolved, either manually by an operator or by running an automated control procedure to restore the initial condition. In case of a non-critical initial condition, the module **201** issues a warning. This module may further initiate the monitoring of critical variables. The module target is reached when all critical variables are within predetermined ranges. The end trigger can then be generated.

[0100] Examples of critical initial conditions are:

[0101] first JV valve **14** is not sufficiently closed (e.g. more than 0.1% open or other suitable number);

[0102] pressure in the refrigerant circuit is lower than the compressor **11** discharge;

[0103] 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;

[0104] refrigerant pressure is too high (e.g. above 20 barg, or other suitable figure);

[0105] compressor inlet guide vane (IGV) is open.

[0106] Examples of non-critical initial conditions are:

[0107] 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;

[0108] compressor recycle valves are not fully open (e.g. less than 99% open or any other suitable value); and

[0109] 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.

[0110] Clearly, module **201** may be preceded by one or more other modules, e.g. modules related to cooling down to an intermediate temperature level or such, and it may start upon receipt of one or more trigger signals.

[0111] Once the communication signal is generated, it may be emitted and received by the module **202**, which has a module target first opening of the first JT valve **14**. This may involve an algorithm that takes into account any non-linear behaviour of the JT valve. Once a cooling trend is detected, the valve will be closed partially to avoid a too high cooling rate.

[0112] The communication signal of module **202** (or a corresponding signal) triggers module **203**, which then starts by simply waiting some time. The purpose is to wait for the apparatus to stabilize after the first critical action of module **202**. The waiting time may depend on the final condition of the module **202**.

[0113] A signal corresponding to the communication signal of module **203** is received by two modules (**204**, **205**), which are consequently triggered simultaneously.

[0114] Module **204** further opens the first JT valve **14**. 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 in 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. This is the module target.

[0115] 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° C.

[0116] 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**.

[0117] In preferred embodiments, the module cannot close the JT valve **14** further than a minimum opening corresponding to the opening at the start of this module.

[0118] 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 module **205** is module **205** is executing its instructions at the same time as module **204**. Module **205** manipulates 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.

[0119] 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.

[0120] Since the closing of recycle valve **12** affects the compressor suction pressure, this pressure is preferably monitored by the module **205** 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.

[0121] When the temperature of the cryogenic heat exchanger **1** has met its operating temperature, a communication signal is generated in modules **204** and **205**, which is received by module **206**. For a heat exchanger that is used to cool methane sufficiently to be liquefied, an operating temperature could be −160° C. In this case, since both of the modules preceding end module **206** generate their communication signal in response of the same condition (i.e. the temperature of the cryogenic heat exchanger has reached a predetermined operating temperature), a corresponding single trigger signal that marks said condition and is passed on to the module in question is considered to be a signal corresponding to the communication signals of both the modules the module in question.

[0122] Module **206** fully closes 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.

[0123] 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.

[0124] In some cases, module **206** may be superfluous and therefore omitted, thereby relying fully on module **205**.

[0125] Once the recycle valve is fully closed or closed sufficiently, a communication signal is generated and, as depicted in FIG. **3** for the present example, received by module **207**.

[0126] Module **207** may be an end module which may be programmed to hand over control to 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. However, module **207** may also be a start module for a subsequent control procedure, e.g. normal operating control such as advanced process control as described in e.g. U.S. Pat. No. 7,266,975 and/or U.S. Pat. No. 6,272,882, or any other type of module.

[0127] On top of the above-described sequential control for cooling down the heat exchanger, there may be built in some overriding boundaries for one or more of the monitored and/or controlled variables. Crossing of one of these boundaries 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.

[0128] Typical examples of such overriding boundaries are:

[0129] a pre-determined maximum temperature rate of change 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 conduit **4**; the spent refrigerant temperature; the refrigerant temperature at the discharge side of the first JT valve **14** or the suction side thereof (particularly after auto-cooling); any shell side temperature in the heat exchanger **1**;

[0130] a pre-determined maximum spatial temperature gradient, reflecting a specified temperature difference between two spatially separated points in or around the heat exchanger, suitably the temperature difference between the refrigerant in inlet **5** and/or downstream of the first JT valve **14** and the spent refrigerant in or around outlet **6** or in conduit **25**; and the temperature difference between the refrigerant or hydrocarbon stream in a tube side and a local temperature in the shell side of the heat exchanger.

[0131] 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.

[0132] 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. 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.

[0133] 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.

[0134] 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.

[0135] 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.

[0136] 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.

[0137] 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 (C_3-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 C_3-MR-N_2 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.

[0138] 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., typically between −80 and −30° C., and the second stage, which may be referred to as a main cryogenic stage, cools to below −100° C. to liquefy the hydrocarbon stream.

[0139] Depending on the source, the natural gas may contain varying amounts of hydrocarbons heavier than methane such as ethane, propane, butanes and pentanes as well as some aromatic hydrocarbons. The natural gas stream may also contain non-hydrocarbons such as H_2O, N_2, CO_2, H_2S and other sulphur compounds, and the like.

[0140] If desired, the hydrocarbon streams may be pre-treated before using them in the present invention. This pre-treatment may comprise removal of any undesired components present such as CO_2 and H_2S, or other steps such as pre-cooling, pre-pressurizing or the like. As these steps are well known to the person skilled in the art, they are not further discussed here.

[0141] Furthermore, the person skilled in the art will readily understand that after liquefaction, the liquefied natural gas may be further processed, if desired. As an example, the obtained LNG may be depressurized by means of a Joule-Thomson valve or by means of a cryogenic turbo-expander.

[0142] 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.

[0143] FIG. **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".

[0144] 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:

[0145] 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**;

[0146] a second tube side **28** extending from the warm end **33**, preferably from a gaseous refrigerant inlet **49***a* at the warm end **33**, to the mid-point **27**; and

[0147] a third tube side **15** extending from the warm end **33**, preferably from a liquid refrigerant inlet **49***b* at the warm end **33**, to the cold end **50**.

[0148] 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.

[0149] 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.

[0150] 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**.

[0151] 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.

[0152] 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**.

[0153] 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**.

[0154] 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.

[0155] 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.

[0156] 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 hereinbelow. The pre-cool heat exchangers **41**,**31** may be operating at mutually different pressures and/or be using different refrigerant compositions.

[0157] 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.

[0158] 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.

[0159] 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**.

[0160] 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**.

[0161] 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 then 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 U.S. Pat. No. 6,272,882 for a more detailed description of such an option.

[0162] 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.

[0163] 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**.

[0164] 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.

[0165] 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.

[0166] 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**.

[0167] 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 **137***a*. 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 **140***a* 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 **153***a* and **153**.

[0168] 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**.

[0169] 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**.

[0170] 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 C_5+ 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**.

[0171] 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 pump **108**.

[0172] 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**.

[0173] The liquid, C_3+-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.

[0174] 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.

[0175] 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. FIG. **5** shows the points in and around the main cryogenic heat exchanger **100** where in a test the temperature sensors (TR**20**; TR**25**; TR**33**; TR**40**; TR**47**; TR**48**; TR**52**; TR**54**; TR**57**; TR**59**) and differential temperature sensors (TDR**2547**; TDR**2548**; TDR**2715**; TDR**5254**; TDR**5759**) 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.

[0176] 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.

[0177] 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 TR**57** and TR**59**. The difference between these temperatures was also monitored, which may be used to determine the actual JT effect over the first JT valve.

[0178] 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 (TDR**2715**). In addition, the shell temperature near the warm end **33** was measured using TR**33**, as well as the temperature of the spent refrigerant drawn from the heat exchanger in conduit **25** (TR**25**).

[0179] The inlet temperature of the heavy liquid refrigerant fraction may be measured using TR**47**, inlet temperature of the hydrocarbon stream immediately upstream of the main cryogenic heat exchanger **100** may be measured using TR**20**, and the temperature of the hydrocarbon rundown stream immediately downstream of the main cryogenic heat exchanger **100** may be measured using TR**40**.

[0180] 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.

[0181] The temperature that indicates the end of the cool down is the hydrocarbon product rundown line temperature TR**40**. 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 TR**59** downstream of the first JT valve **58**, may be monitored instead. However at the end of cool down the reference temperature will be TR**40**.

[0182] 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 (PR**32**; PR**54**; PR**55**; PR**57**; PR**150**) are indicated in FIG. **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 PR**150** in conduit **150**, the mixed refrigerant compressor **30** suction pressure (PR**55**) in conduit **55**; and the mixed refrigerant compressor discharge pressure PR**32** in conduit **32**.

[0183] 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.

[0184] 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, PR**57** and PR**54** (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).

[0185] 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 (PR**57** and PR**54**, respectively) and the suction pressure (PR**55**) of the refrigerant circuit before going to the compressors may be used.

[0186] 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.

[0187] 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:

[0188] 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);

[0189] temperature control of stream **20**;

[0190] depressurisation of the refrigerant circuit, notably tube-sides **15**, **28**;

[0191] 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.

[0192] 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".

[0193] FIG. **6** schematically shows the module structure as was used in the test. Module **301** defines initial conditions much in the same way as described above for module **201**. Examples of critical initial conditions are:

[0194] 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 C_5+ is tolerated);

[0195] first and second JT valves (**58**, **51**) not sufficiently closed (in the test a value of more than 1% open was used);

[0196] pressure in refrigeration circuit (LMR and HMR) is lower than the compressor **31** discharge;

[0197] 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);

[0198] suction and discharge valves on these compressors are not open;

[0199] refrigerant pressure at the compressor **31** discharge is too high (the test used a maximum of 20 barg);

[0200] pre-cooling refrigerant compressor **127** suction pressure outside of a predetermined pressure window (suitably a window around approximately 0.5 barg);

[0201] any IGV valve present is not sufficiently closed.

[0202] Examples of non-critical initial conditions are:

[0203] TDR**5759** too small (a typical minimum value recommended in case of a coil wound heat exchanger from Air Products & Chemicals Inc is 25° C.);

[0204] one or more of refrigerant compressor recycle valves (e.g. **130**, **131**) are not sufficiently open (the test used less than 99% open);

[0205] discharge pressure of compressor **31** below a predetermined minimum value (the test used 18 barg).

[0206] A signal corresponding to the communication signal of module **301** triggers **308**. Module **302** is also triggered by the same signal that corresponds to the communication signal of module **301**.

[0207] Module **302** marks the first module in a sub-network of modules, here being modules **303**, **304**, **305**, and **309** to **312**. Hence, the entire sub-network of modules described below will operate in parallel with and concurrently to module **308**.

[0208] Module **302** in itself first opens the first JT valve **58** much in the same way as that module **202** first opens JT valve **14**.

[0209] Module **303** is triggered by module **302**, and it waits some time, much in the same way as described above for module **203**. Modules **305**, **305**, **309**, and **310** trigger on a signal that corresponds to the communication signal of module **303**.

[0210] Module **304** further opens the first JT valve **58** much in the way as described for JT valve **14** in module **204**.

[0211] Module **305** adjusts the compressor recycle valve (or valves) **131** much in the same way as described above for module **205** which adjusts recycle valve **12**.

[0212] However, in addition, there is a module **309**, operating at the same level in the network as module **305**, which closes the compressor recycle valve **130**, preferably in response to when a pre-determined temperature indicative of the main cryogenic heat exchanger temperature has reached a predetermined value. The closing of the compressor recycle valve **130** is constrained by the surge deviation, which is in part influenced by modules **304** and **310** to **312**. Thus, in effect, module **309** maximizes the refrigerant pressure as far as possible while maintaining an allowable surge deviation.

[0213] Preferably, the pre-determined temperature is the temperature TR**57** and the pre-determined value is such that it is certain that the auto-cooled LMR and HMR fractions flowing in conduits **57** and **52** are fully condensed such that the closing of the recycle valve(s) does not cause unexpected effects on the cooling rate. For example, the predetermined temperature value may be −135° C. but it depends on the constituents of the multiple component refrigerant used. Of course, a too low surge deviation forms a constraint on closing of the recycle valve(s). A message may be generated for the operator that an IGV move may be necessary instead.

[0214] In addition, module **309** may contain computer executable instruction to close the recycle valve **130** before the temperature has reached the pre-determined value but triggered by other urgent conditions. Such another urgent condition may, for instance, occur if the surge deviation of the compressor **30** has a value above a pre-determined maximum value (typically 0.3). Excessive surge deviation may be the cause of physical vibration of the compressor and therefore the recycle valve(s) **130** are closed even if the pre-determined temperature has not yet been reached.

[0215] Module **310** controls the first opening of the second JT valve **51**. It is opened enough so that a cooling trend is established that is faster than with only the first JT valve (**58**) movements. The first opening of the second JT valve **51** involves an algorithm that takes into account non-linear behaviour of the valve by first opening. The module attempts to keep the initial cooling rate below the maximum limit, in this cooling less fast than 28° C./h. However, because of the non-linear behaviour of the JT valves at initial opening (described above), this may not be possible. In this case the procedure continues with the minimum-cooling rate possible which corresponds to the cooling rate achieved at the minimum observable opening of the JT valve. Conditions for the beginning of this module is the presence of a clear temperature profile, which may be understood as a profile where the temperature rate of change of TR**54** is normalized and cooling down. Therefore this module is activated simultaneously with module **304**. Taken together with module **311** (which is triggered by module **310** as described below), this combination of modules operates at the same level in the network as module **304**.

[0216] To establish an increased cooling trend, the module **310** opens the second JT valve at pre-determined time intervals, e.g. every minute, until a cooling temperature change is detected (in the test, until a cooling rate faster than 0.1° C./h was detected). It then closes the valve **51** by a small amount. Then there is a further check in the cooling to make sure that the second JT valve **51** is not closed again or that the cooling is not too fast. If it is too fast, further closing of the second JT valve will take place. If the cooling trend stopped then open the valve until a cooling trend is established again. The communication signal is generated upon reaching a stable cooling trend within a pre-determined range.

[0217] The communication signal from module **310** is received by module **311** and it also triggers module **312**. Module **311** further moves the second JT valve **51**. Three cases are taken into account:

[0218] i) above condensation range, control is done on the second JT valve position;

[0219] ii) just before condensation occurs in the heavy refrigerant in conduit **54**, any JT valve movements are slowed slow down;

[0220] iii) when condensation is detected the second JT valve **51** is closed a little bit, too avoid a high cooling rate caused by condensed flow. After condensation of the heavy refrigerant in the conduit **54** is detected, the flow of the heavy refrigerant will be controlled on a remote set point setting using a flow controller. The temperature rate of change TR**54** and the temperature on TR**25** will determine the step on the flow controller set point. The final temperature target for both TR**54** and TR **25** will stop the valve actions.

[0221] Module **311** is finished when top temperature, e.g. at TR**57** or at TR**40**, has reached its target value. Any contribution from the heavy refrigerant to the cooling duty will from then on reduce, unless the refrigerant make-up is adjusted.

[0222] The make up adjustment is controlled by module **312**, which as stated above, is triggered to start simultaneously with module **311** based on the communication signal generated in module **310**. The module manipulates the make-up to:

[0223] Increase the compressor **31** discharge pressure along a ramp towards a target operating pressure (in the test, 30 barg);

[0224] 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.

[0225] 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 TR**57** goes below a predetermined value of −135° C. or −140° C.

[0226] During the test, nitrogen was a special part of the make up. Nitrogen make up is preferably done only when there is an opportunity, for instance then when the MR compressor **30** suction pressure is low (e.g. below 2.0 barg). This is because the nitrogen supply pressure during the text was only about 2 barg.

[0227] The module **312** was provided with some robustness in the case of failure in obtaining a reliable measurement on the methane inventory in the MR stream (e.g. due to communication failure between instrument and DCS, or due to sensor failure), which has been found to be quite common. In such a case, instead of being directly measured, the methane composition was estimated from the compositions of C_2 (ethane), C_3 (propane) and N_2 by assuming that the balance was methane.

[0228] The entire sub-network as described above (containing modules **303**, **304**, **305**, and **309** to **312**) as a whole is executed in parallel to the module 308 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.

[0229] 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.

[0230] 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.

[0231] Typical examples of such overriding boundaries are:

[0232] 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**;

[0233] 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 TDR**2547** between the light refrigerant upstream of main cryogenic heat exchanger **100** and the spent refrigerant (also possible: TDR**3347**, not shown); the temperature difference TDR**2548** between the heavy refrigerant upstream of main cryogenic heat exchanger **100** and the spent refrigerant (also possible: TDR**3348**, not shown); TDR**2715**; and TDR**5759**;

[0234] 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**;

[0235] suction and discharge valves on the refrigerant compressors closed;

[0236] a maximum specified top shell pressure (5 barg) at the cold end of the main cryogenic heat exchanger;

[0237] detection of a trip;

[0238] existence of communication errors in the control system.

[0239] Clearly, other overriding boundaries may be used, e.g. in case of other types of cryogenic heat exchangers being used.

[0240] Table I below shows all the variables used in the test as manipulated variable, while Table II below shows all the variables used in the test as controlled variables or monitored variables for decision making.

TABLE I

manipulated variables

Description of variable	Reference symbol	Optional remarks
HMR flow set point		e.g. flow through second JT valve 51
Second JT valve (51) position	X_{51}	Controls cooling rate
Methane make-up valve opening	X_{66}	Controls refrigerant pressure and MR composition
N_2 make-up valve opening		
Ethane make-up valve opening		
Propane make-up valve opening		
Recycle valve (130) position of compressor 30	X_{130}	
First stage recycle valve of compressor 31	X_{131}	Used to control MR discharge pressure
Second stage recycle valve of compressor 31		
First stage recycle valve (129) of pre-cool compressor 127	X_{129}	Used to control pre-cool refrigerant suction pressure
First JT valve (58) opening	X_{58}	

TABLE II

Controlled and monitored variables

Description of variable	Reference symbol	Optional remarks
HMR flow		e.g. flow through second JT valve 51; used to determine whether condensation occurring
LMR flow		e.g. flow through second JT valve 58; used to determine whether condensation occurring
LMR circuit tube pressure	PR57	Used to calculate LMR flow
HMR circuit tube pressure	PR54	Used to calculate HMR flow
MR discharge pressure	PR32	Process variable; monitored to reach target MR composition.
PR suction pressure	PR150	Process variable
MR suction pressure	PR55	Process variable
N_2 inventory (%)		Monitored to reach target composition of MR
Methane inventory		
Ethane inventory		
Propane inventory		
Temperature downstream of first JT valve 58	TR59	Used as back-up variable to determine end of the cool down process
Temperature upstream of the first JT valve 58	TR57	Process variable
Cryogenic heat exchanger bottom temperature	TR33	Process variable for monitoring cooling rate
Hydrocarbon stream temperature upstream of cryogenic heat exchanger	TR20	Process variable
Temperature upstream of the second JT valve 51	TR54	Process variable for monitoring cooling rate
Cryogenic heat exchanger top temperature	TR40	Process variable, indicates end of the cool down process
Surge deviation parameter compressor 30		Process variables
Surge deviation parameter first stage of compressor 31		
Surge deviation parameter second stage of compressor 31		

[0241] The automated procedure for final cool down of the main cryogenic heat exchanger as described above gradually reduced the main cryogenic heat exchanger overall temperature by manipulating the mixed refrigerant flow, composition and first and second JT valves which in part determine the compression ratio flashing across these JT valves.

[0242] Although not implemented in the test, it has been contemplated to further embed the module structure of FIG. **6** (or a similar one for another line-up or heat exchanger) in a larger module network comprising other, preceding modules, or subsequent modules, or both. An example of embedding in subsequent modules is shown in FIG. **7**.

[0243] FIG. **7** shows a module structure 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**.

[0244] Other manipulated variables relevant at this stage include all the manipulated variables of the cool-down stage as described above plus possibly the IGV and any pre-cooling refrigerant compressor recycle valves that were not included as manipulated variable in the cool-down automation.

[0245] Preferably, the LMR and HMR manipulation is done based on flow control rather than valve opening.

[0246] In addition, any reflux stream on an in-line NGL extraction could be included as manipulated variable. However, it is expected that normal level control can take over after the hydrocarbon feed rate has reached its normal operating range.

[0247] 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.

[0248] 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.

[0249] 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.

1. An apparatus for cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon 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:

(i) receive input signals representing sensor signals of one or more controlled variables;

(ii) produce control signals to control one or more manipulated variables; and

(iii) execute a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein the at least three modules are each arranged to:

(a) wait until a trigger signal is received; and

(b) start executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and which modules in the network are interconnected such that the trigger signal received by a second and a third module of the at least three modules corresponds to a communication signal that is generated upon the first module of the at least three modules reaching the pre-determined target for that module.

2. The apparatus of claim **1**, wherein the second and third modules are operating in parallel with each other, whereby a control action of one of these modules is constrained by a variable that is influenced by manipulating of one or more manipulated variables by at least the other one of the second and third modules.

3. The apparatus of claim **1**, wherein the one or more controlled variables comprise a rate of change in temperature over time.

4. The apparatus of claim **3**, wherein the rate of change of temperature over time comprises one or more of: temperature of the refrigerant at the suction side of the first JT valve; temperature of the refrigerant at the discharge side of the first JT valve; temperature of the hydrocarbon stream at a point inside the cryogenic heat exchanger; temperature of the hydrocarbon stream downstream of the cryogenic heat exchanger.

5. The apparatus of claim **1**, wherein the one or more controlled variables comprises a selected spatial temperature gradient in or around the cryogenic heat exchanger.

6. The apparatus of claim **5**, wherein the selected spatial temperature gradient reflects one or more of the following temperature differentials: the temperature differential between the spent refrigerant and the refrigerant at a refrigerant inlet of the cryogenic heat exchanger; the temperature differential between the refrigerant at the suction side and the refrigerant at the discharge side of the first JT valve.

7. The apparatus of claim **1**, wherein the cryogenic heat exchanger comprises a shell side for evaporating refrigerant and a tube side for auto-cooling the refrigerant.

8. The apparatus of claim **7**, wherein the selected spatial temperature gradient reflects the temperature differential between a shell side of the cryogenic heat exchanger and a refrigerant containing tube side.

9. The apparatus of claim **1**, 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.

10. The apparatus of claim **9**, wherein the selected spatial temperature gradient reflects one or more of: the temperature differential between the temperature differential between the spent refrigerant and the refrigerant between the gas outlet and a gaseous refrigerant inlet of the cryogenic heat exchanger; and the temperature differential between spent refrigerant and the refrigerant between the liquid outlet and a liquid refrigerant inlet of the cryogenic heat exchanger.

11. The apparatus of claim **1**, wherein the one or more controlled variables comprise one or both of: a first temperature difference in the refrigerant stream across the first JT valve; and a suction pressure in the refrigerant stream at a suction side of the compressor.

12. The apparatus of claim **1**, wherein the one or more manipulated variables at least comprise one or both of: a first JT valve setting representing a measure of amount of opening of the first JT valve; and any pressure setting that controls refrigerant pressure upstream of the first JT valve.

13. The apparatus of claim **12**, wherein the pressure setting comprises a compressor recycle valve setting representing a measure of amount of opening of the compressor recycle valve.

14. The apparatus of claim **1**, wherein the cryogenic heat exchanger comprises a hydrocarbon stream inlet and a hydrocarbon stream outlet for the hydrocarbon stream, and one or more separate refrigerant inlets and a refrigerant outlet for the refrigerant and spent refrigerant, respectively.

15. A method of cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon 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;

activating a programmable controller which

(i) receives input signals representing sensor signals of one or more controlled variables;

(ii) produces control signals to control one or more manipulated variables; and

(iii) executes a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein each of the at least three modules

(a) waits until a trigger signal is received; and

(b) starts executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and wherein a communication signal is generated upon the first module of the at least three modules reaching the predetermined target for that module, which communication signal is passed on to a second and a third module of the three or more modules where the communication signal acts as the trigger signal for the second and third modules.

16. A method of liquefying a hydrocarbon stream, the method comprising steps of:

cooling down a cryogenic heat exchanger adapted to liquefy the hydrocarbon stream;

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

wherein said cooling down of the said cryogenic heat exchanger comprises 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;

activating a programmable controller which

(i) receives input signals representing sensor signals of one or more controlled variables;

(ii) produces control signals to control one or more manipulated variables; and

(iii) executes a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein each of the at least three modules

(a) waits until a trigger signal is received; and

(b) starts executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and wherein a communication signal is generated upon the first module of the at least three modules reaching the predetermined target for that module, which communication signal is passed on to a second and a third module of the three or more modules where the communication signal acts as the trigger signal for the second and third modules.

17. A method of liquefying a hydrocarbon stream, comprising the steps of:

cooling down a cryogenic heat exchanger adapted to liquefy the hydrocarbon stream;

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

wherein said cooling down of the said cryogenic heat exchanger comprises using an apparatus for cooling down a cryogenic heat exchanger adapted to liquefy a hydrocarbon 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:

(i) receive input signals representing sensor signals of one or more controlled variables;

(ii) produce control signals to control one or more manipulated variables; and

(iii) execute a computer program, the computer program comprising a network of at least three modules, wherein one or more of the at least three modules receive a representations of one or more of the input signals and produce representations of one or more of the control signals;

and wherein the at least three modules are each arranged to:

(a) wait until a trigger signal is received; and

(b) start executing a predetermined sequence of one or more computer readable instructions upon receipt of the trigger signal at least until a predetermined module target for that module is reached;

and which modules in the network are interconnected such that the trigger signal received by a second and a third module of the at least three modules corresponds to a communication signal that is generated upon the first module of the at least three modules reaching the pre-determined target for that module.

18. The method of claim **17**, wherein the hydrocarbon stream is a natural gas stream.

19. The method of claim **17**, wherein the second and third modules are operating in parallel with each other, whereby a control action of one of these modules is constrained by a variable that is influenced by manipulating of one or more manipulated variables by at least the other one of the second and third modules.

20. The method of claim **17**, wherein the one or more controlled variables comprise a rate of change in temperature over time.

21. The method of claim **20**, wherein the rate of change of temperature over time comprises one or more of: temperature of the refrigerant at the suction side of the first JT valve; temperature of the refrigerant at the discharge side of the first JT valve; temperature of the hydrocarbon stream at a point inside the cryogenic heat exchanger; temperature of the hydrocarbon stream downstream of the cryogenic heat exchanger.

22. The method of claim **17**, wherein the one or more controlled variables comprises a selected spatial temperature gradient in or around the cryogenic heat exchanger.

23. The method of claim **22**, wherein the selected spatial temperature gradient reflects one or more of the following temperature differentials: the temperature differential between the spent refrigerant and the refrigerant at a refrigerant inlet of the cryogenic heat exchanger; the temperature differential between the refrigerant at the suction side and the refrigerant at the discharge side of the first JT valve.

24. The method of claim **17**, wherein the cryogenic heat exchanger comprises a shell side for evaporating refrigerant and a tube side for auto-cooling the refrigerant.

25. The method of claim **24**, wherein the selected spatial temperature gradient reflects the temperature differential between a shell side of the cryogenic heat exchanger and a refrigerant containing tube side.

26. The method of claim **17**, 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.

27. The method of claim **26**, wherein the one of these fractions is the light refrigerant fraction.

28. The method of claim **26**, wherein the selected spatial temperature gradient reflects one or more of: the temperature differential between the temperature differential between the spent refrigerant and the refrigerant between the gas outlet and a gaseous refrigerant inlet of the cryogenic heat exchanger; and the temperature differential between spent refrigerant and the refrigerant between the liquid outlet and a liquid refrigerant inlet of the cryogenic heat exchanger.

29. The method of claim **17**, wherein the one or more controlled variables comprise one or both of: a first temperature difference in the refrigerant stream across the first JT valve; and a suction pressure in the refrigerant stream at a suction side of the compressor.

30. The method of claim **17**, wherein the one or more manipulated variables at least comprise one or both of: a first JT valve setting representing a measure of amount of opening of the first JT valve; and any pressure setting that controls refrigerant pressure upstream of the first JT valve.

31. The method of claim **30**, wherein the pressure setting comprises a compressor recycle valve setting representing a measure of amount of opening of the compressor recycle valve.

32. The method of claim **17**, wherein the cryogenic heat exchanger comprises a hydrocarbon stream inlet and a hydrocarbon stream outlet for the hydrocarbon stream, and one or more separate refrigerant inlets and a refrigerant outlet for the refrigerant and spent refrigerant, respectively.

33. The method of claim **16**, wherein the hydrocarbon stream is a natural gas stream.

34. The method of claim **16**, wherein the second and third modules are operating in parallel with each other, whereby a control action of one of these modules is constrained by a variable that is influenced by manipulating of one or more manipulated variables by at least the other one of the second and third modules.

35. The method of claim **16**, wherein the one or more controlled variables comprise a rate of change in temperature over time.

36. The method of claim **35**, wherein the rate of change of temperature over time comprises one or more of: temperature of the refrigerant at the suction side of the first JT valve; temperature of the refrigerant at the discharge side of the first JT valve; temperature of the hydrocarbon stream at a point inside the cryogenic heat exchanger; temperature of the hydrocarbon stream downstream of the cryogenic heat exchanger.

37. The method of claim **16**, wherein the one or more controlled variables comprises a selected spatial temperature gradient in or around the cryogenic heat exchanger.

38. The method of claim **37**, wherein the selected spatial temperature gradient reflects one or more of the following temperature differentials: the temperature differential between the spent refrigerant and the refrigerant at a refrigerant inlet of the cryogenic heat exchanger; the temperature differential between the refrigerant at the suction side and the refrigerant at the discharge side of the first JT valve.

39. The method of claim **16**, wherein the cryogenic heat exchanger comprises a shell side for evaporating refrigerant and a tube side for auto-cooling the refrigerant.

40. The method of claim **39**, wherein the selected spatial temperature gradient reflects the temperature differential between a shell side of the cryogenic heat exchanger and a refrigerant containing tube side.

41. The method of claim **16**, 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.

42. The method of claim **41**, wherein the one of these fractions is the light refrigerant fraction.

43. The method of claim **41**, wherein the selected spatial temperature gradient reflects one or more of: the temperature differential between the temperature differential between the spent refrigerant and the refrigerant between the gas outlet and a gaseous refrigerant inlet of the cryogenic heat exchanger; and the temperature differential between spent refrigerant and the refrigerant between the liquid outlet and a liquid refrigerant inlet of the cryogenic heat exchanger.

44. The method of claim **16**, wherein the one or more controlled variables comprise one or both of: a first temperature difference in the refrigerant stream across the first JT valve; and a suction pressure in the refrigerant stream at a suction side of the compressor.

45. The method of claim **16**, wherein the one or more manipulated variables at least comprise one or both of: a first JT valve setting representing a measure of amount of opening of the first JT valve; and any pressure setting that controls refrigerant pressure upstream of the first JT valve.

46. The method of claim **45**, wherein the pressure setting comprises a compressor recycle valve setting representing a measure of amount of opening of the compressor recycle valve.

47. The method of claim **16**, wherein the cryogenic heat exchanger comprises a hydrocarbon stream inlet and a hydrocarbon stream outlet for the hydrocarbon stream, and one or more separate refrigerant inlets and a refrigerant outlet for the refrigerant and spent refrigerant, respectively.

48. The method of claim **9**, wherein the one of these fractions is the light refrigerant fraction.

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