Abstract: A gas liquefaction process, especially for producing LNG, maintains product flow rate and temperature by controlling the refrigeration so that variation to reduce any difference between actual and required product temperatures is initiated before variation of the product flow rate to reduce any difference between actual and required flow rates. In preferred embodiments, the flow rate of one of a first refrigerant used to liquefy natural gas and a second refrigerant used to subcool the liquefied gas is controlled by a difference between actual and predetermined liquefied product flow rate and the flow rates of the other refrigerant and of the product are controlled by respective process temperature differences between actual and predetermined values.
CONTROLLING LIQUEFACTION OF NATURAL GAS

TECHNICAL FIELD

This invention relates to the field of control systems for production of liquefied gas (LG), and more specifically, to a process and system which controls LG production and LG temperature. It has particular but not exclusive application to liquefying natural gas (NG) to produce liquefied natural gas (LNG).

BACKGROUND ART

Systems for the liquefaction of natural gas (NG) by refrigeration in heat exchange means, especially using a multicomponent refrigerant, are in use throughout the world. Control of the LNG production process is important to operate a plant efficiently, especially when attempting to meet demands for incremental production for downstream processing or when attempting to adjust to external process disturbances. Essentially simultaneous and independent control of both the LNG production flow rate and temperature is important for LNG plant operation. By fixing and maintaining the LNG production rate, plant operators can adequately plan and achieve desired production levels as required by the product shipping schedule. Maintaining the temperature of the LNG within a specified range is important for downstream processing and the prevention of downstream equipment problems. Once regulatory control is achieved for the key variables, optimization strategies can be properly implemented. However, if regulatory control is not adequate, even standard day to day operation is adversely affected.

In typical NG liquefaction processes, natural gas is fed to the warm end of heat exchange means, having a liquefying section in which the natural gas is liquefied and a subcooling section in which the liquefied natural gas is subcooled, and the LNG outlet stream is withdrawn from the cold end of the heat exchange means. Some refrigeration duty in the liquefying section is provided by flashing a first refrigerant ("MRL"), provided by cooling in the heat exchange means the liquid portion of a phase separation of a multicomponent refrigerant (MR) and refrigeration duty in the subcooling section is provided by flashing a second refrigerant ("MRV"), provided by condensing in the heat exchange means the vapor portion of the MR phase separation. The remainder of the refrigeration duty in the liquefying section is provided by spent MRV from the liquefaction section. The refrigerants exiting the warm end of the heat exchanger means are combined, if not already mixed in the liquefaction section, compressed and precooled before return to the MR phase separation for recycle to the heat exchange means. A
process having the aforementioned features is referred to herein as "a typical NG liquefaction process".

U.S. Patent 5,791,160 (Mandler et al. corresponding to EP-A-0893665) describes a natural gas liquefaction control scheme where LNG product flow rate and temperature are simultaneously and independently controlled by adjusting the amount of refrigeration. In the exemplified embodiments, the control variables (the ones having a set point that can be changed by the operator) of a typical NG liquefaction process include LNG product flow rate and temperature as well as the MRL/MRV ratio. Manipulated variables (the ones that are automatically controlled in response to operator setting of one or more of the control variables) include MR compressor speed and MR/LNG ratio. In this scheme the amount of refrigeration is adjusted after the actual LNG product flow rate has been changed in response to a change in the LNG product flow rate set point.

U.S. Patent 6,725,688 (Eiion et al.; corresponding to WO-A-0 1/81845) describes a modification of Mandler et al./ with the object of maximizing power utilization. LNG product temperature and MRL/MRV ratio are retained as controlled variables and the manipulated variable is LNG/MRL ratio but LNG product flow rate cannot be independently set.

U.S. Patent Application Publication 2004/0255615 (Hupkes et al.; corresponding to WO-A-2004/068049 & EP-A-1595101) describes the use of an advanced process controller based on model-predictive control to control a typical NG liquefaction process. The controller determines simultaneous control actions for a set of manipulated variables in order to optimize at least one of a set of parameters including the production of liquefied product whilst controlling at least one of a set of controlled variables. The set of manipulated variables includes MRL flow rate, MRV flow rate, MR composition, MR removal, MR compressor capacity and NG feed flow rate. The set of controlled variables includes the temperature difference at the warm end of the main heat exchanger, an adjustable relating to the LNG temperature, the composition of the refrigerant entering the MR phase separator, the pressure in the shell of the main heat exchanger, and the pressure and liquid level in MR phase separator.

There is a need to develop a simple and robust control scheme that allows control of LNG product temperature and flow rate without subjecting the heat exchange means to thermal stresses and without the need to manipulate the MR compressor and it is an object of the present invention to meet that need.
DISCLOSURE OF THE INVENTION

The present invention relates to the control of liquefaction of gas, especially natural gas, in a manner that maintains the LG product at a required flow rate and temperature with limited thermal stress on the heat exchange means even when the LG flow rate and/or temperature requirements have been changed. The invention resides in the manner in which refrigeration is changed by manipulated variables.

A control system for typical NG liquefaction processes has been devised in which the thermal stress on the heat exchange means is limited and the need to manipulate the MR compressor can be avoided by controlling the refrigeration so that variation to reduce any difference between actual and required LNG temperature is initiated before variation of the LNG product flow rate to reduce any difference between actual and required LNG flow rate. Accordingly, refrigeration leads LG production. The invention has particular, but not exclusive, application to a typical NG liquefaction process in which the controlled variables are LNG temperature, LNG flow rate and either heat exchanger warm end temperature difference ("WETD") or heat exchanger mid-point temperature ("MPT") and the manipulated variables are MRL and MRV flow rates. However, the invention is not restricted to the control of NG liquefaction processes but is more generally applicable to gas liquefaction, e.g. of hydrocarbon mixtures.

In a broad aspect, the invention provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied gas ("LG") outlet stream of a gas liquefaction in which a gas feed is liquefied by refrigeration in heat exchange means, comprising the steps of:

- comparing said predetermined LG flow rate value with the actual LG flow rate;
- comparing said predetermined LG temperature value with the actual LG temperature; and
- varying the refrigeration provided by said heat exchange means in response to said LG flow rate and LG temperature comparisons to reduce any differences,

characterized in that variation of the refrigeration to reduce any LG temperature difference is initiated before variation of the LNG flow rate to reduce any LG flow rate difference.

In a corresponding apparatus aspect, the invention also provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied gas ("LG") outlet stream of a gas liquefaction in which a gas feed is liquefied by refrigeration in heat exchange means, comprising:
means for comparing said predetermined LG flow rate value with the actual LG flow rate;
means for comparing said predetermined LG temperature value with the actual LG temperature; and
means for varying the actual LG product flow rate;
means for varying the refrigeration provided by said heat exchange means in response to said LG flow rate and LG temperature comparisons to reduce any differences,
characterized in that adjustment of the means for varying the LNG flow rate is not initiated until the refrigeration has been varied to reduce any LG temperature difference.

Said predetermined values can be adjustable and the method further comprise the steps of setting the predetermined flow rate value for the LG outlet stream and setting the predetermined temperature value for the LG outlet stream.

The actual LG flow rate can be adjusted in response to changes in the actual LG temperature; in response to changes in the temperature difference between a stream entering the warm end of the heat exchange means and a stream leaving that end of the heat exchanger; or in response to changes in the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means.

The invention has particular application to typical NG liquefaction processes and in a preferred embodiment provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

comparing said predetermined LNG flow rate value with the actual LNG flow rate;
comparing said predetermined LNG temperature value with the actual LNG temperature;
comparing a predetermined value of (i) the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") and/or (ii) the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with respectively (i) the actual warm end temperature difference or (ii) the actual mid-point temperature;

varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, one of the MRL and MRV flow rates;

varying the other of the MRV and MRL flow rates to maintain an MRL/MRV ratio, which ratio is determined by one of (a) the difference between the actual and predetermined LNG temperatures and (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures; and

varying, by an amount corresponding to the other of (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures and (a) the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

In a corresponding apparatus embodiment, the invention provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising:

means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;

means for comparing said predetermined LNG temperature value with the actual LNG temperature;

means for comparing a predetermined value of (i) the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed
("warm end temperature difference") or (ii) the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with respectively (i) the actual warm end temperature difference or (ii) the actual mid-point temperature;

means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, one of the MRL and MRV flow rates;

means for varying the other of the MRV and MRL flow rates to maintain an MRL/MRV ratio, which ratio is determined by one of (a) the difference between the actual and predetermined LNG temperatures and (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures; and

means for varying, by an amount corresponding to the other of (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures and (a) the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

In accordance with an embodiment illustrated in Figure 1, the invention provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

- comparing said predetermined LNG flow rate value with the actual LNG flow rate;
- comparing said predetermined LNG temperature value with the actual LNG temperature;
- comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
- varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined warm end temperature differences; and

varying, by an amount corresponding to the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

In a corresponding apparatus embodiment, the invention provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising:

means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;

means for comparing said predetermined LNG temperature value with the actual LNG temperature;

means for comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;

means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;

means for varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined warm end temperature differences; and

means for varying, by an amount corresponding to the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

Said predetermined values can be adjustable and the method further comprise the steps of:

setting the predetermined flow rate value for the LNG outlet stream;
setting the predetermined temperature value for the LNG outlet stream; and
setting the predetermined value of the warm end temperature difference value.

In accordance with an embodiment illustrated in Figure 2, the invention provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

comparing said predetermined LNG flow rate value with the actual LNG flow rate;
comparing said predetermined LNG temperature value with the actual LNG temperature;
comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio determined by the difference between the actual and predetermined LNG temperatures; and
varying, by an amount corresponding to the difference between the actual and predetermined warm end temperature differences, the actual LNG flow rate.

In accordance with a corresponding apparatus embodiment, the invention provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second
refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising:

- means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;
- means for comparing said predetermined LNG temperature value with the actual LNG temperature;
- means for comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
- means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
- means for varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio determined by the difference between the actual and predetermined LNG temperatures;

and

means for varying, by an amount corresponding to the difference between the actual and predetermined warm end temperature differences, the actual LNG flow rate.

Said predetermined values can be adjustable and the method further comprise the steps of:

- setting the predetermined flow rate value for the LNG outlet stream;
- setting the predetermined temperature value for the LNG outlet stream; and
- setting the predetermined value of the warm end temperature difference value.

In accordance with an embodiment illustrated in Figure 3, the invention provides a method of maintaining at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

- comparing said predetermined LNG flow rate value with the actual LNG flow rate;
comparing said predetermined LNG temperature value with the actual LNG temperature;
comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
varies, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
varies the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined LNG temperatures;

In accordance with a corresponding apparatus embodiment, the invention provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising:

means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;
means for comparing said predetermined LNG temperature value with the actual LNG temperature;
means for comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
means for varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined LNG temperatures; and

means for varying, by an amount corresponding to the difference between the actual and predetermined warm end temperature differences multiplied by a value dependent on the actual MRL flow rate, the actual LNG flow rate.

Said predetermined values can be adjustable and the method further comprise the steps of:

setting the predetermined flow rate value for the LNG outlet stream;

setting the predetermined temperature value for the LNG outlet stream; and

setting the predetermined value of the warm end temperature difference value.

In accordance with an embodiment illustrated in Figure 4, the invention provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

comparing said predetermined LNG flow rate value with the actual LNG flow rate;

comparing said predetermined LNG temperature value with the actual LNG temperature;

comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;

comparing a predetermined value of temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with the actual mid-point temperature;

varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates and also, when the difference between actual and
predetermined warm end temperature differences exceeds a threshold value, to said
difference between warm end temperature differences, the MRL flow rate;
5 varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is
determined by the difference between the actual and predetermined mid-point

temperatures; and

varying, by an amount corresponding to the difference between the actual and
predetermined LNG temperatures, the actual LNG flow rate.

In accordance with a corresponding apparatus embodiment, the invention
provides a control system for maintaining at a predetermined flow rate value and at a
predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a
natural gas liquefaction using heat exchange means, having a warm end to which the
natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooioing
section in which the liquefied natural gas is subcooled and a cold end from which said
LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying
section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied
for refrigeration duty at an MRL flow rate and in the subcooioing section by a second
refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration
duty at an MRV flow rate, comprising:

means for comparing said predetermined LNG flow rate value with the actual
LNG flow rate;

means for comparing said predetermined LNG temperature value with the actual
LNG temperature;

means for comparing a predetermined value of the temperature difference
between spent refrigerant leaving the warm end of the heat exchange means and a
stream entering said warm end selected from MRL, MRV and the natural gas feed
("warm end temperature difference") with the actual warm end temperature difference;

means for comparing a predetermined value of temperature ("mid-point
temperature") of a stream at a location between the liquefying and subcooioing sections of
the heat exchanger means with the actual mid-point temperature;

means for varying, by an amount corresponding to the difference between the
actual and predetermined LNG flow rates and also, when the difference between actual
and predetermined warm end temperature differences exceeds a threshold value, to said
difference between warm end temperature differences, the MRL flow rate;
means for varying the MRV flow rate to maintain an MRUMRV ratio, which ratio is determined by the difference between the actual and predetermined mid-point temperatures; and
means for varying, by an amount corresponding to the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.
Said predetermined values can be adjustable and the method further comprise the steps of:
setting the predetermined flow rate value for the LNG outlet stream;
setting the predetermined temperature value for the LNG outlet stream; and
setting the predetermined warm end temperature difference value.
In accordance with an embodiment illustrated in Figure 5, the invention provides a method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:
comparing said predetermined LNG flow rate value with the actual LNG flow rate;
comparing said predetermined LNG temperature value with the actual LNG temperature;
comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
comparing the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with a calculated temperature value, which is determined by the difference between the actual and predetermined actual warm end temperature differences;
varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and calculated mid-point temperatures; and

varying, by an amount corresponding to the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

In accordance with a corresponding apparatus embodiment, the invention provides a control system for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising:

- means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;
- means for comparing said predetermined LNG temperature value with the actual LNG temperature;
- means for comparing a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference;
- means for varying, by an amount corresponding to the difference between the actual and predetermined actual warm end temperature differences;
- means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, the MRL flow rate;
- means for varying the MRV flow rate to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and calculated mid-point temperatures; and
- means for varying, by an amount corresponding to the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.
Said predetermined values can be adjustable and the method further comprise
the steps of:

setting the predetermined flow rate value for the LNG outlet stream;
setting the predetermined temperature value for the LNG outlet stream; and
setting the predetermined value of the warm end temperature difference value.

**BRIEF DESCRIPTION OF THE DRAWINGS**

Fig 1 is a schematic flow diagram of a mixed refrigerant LNG plant process of a
first exemplary embodiment of the present invention.

Fig 2 is a schematic flow diagram of a mixed refrigerant LNG plant process of a
second exemplary embodiment of the present invention.

Fig 3 is a schematic flow diagram of a mixed refrigerant LNG plant process of a
third exemplary embodiment of the present invention.

Fig 4 is a schematic flow diagram of a mixed refrigerant LNG plant process of a
fourth exemplary embodiment of the present invention.

Fig 5 is a schematic flow diagram of a mixed refrigerant LNG plant process of a
fifth exemplary embodiment of the present invention.

Fig 6 is a schematic flow diagram of a modification of the mixed refrigerant LNG
plant process of Figure 3.

Fig 7 is a schematic flow diagram of a comparative mixed refrigerant LNG plant
process.

**MODES FOR CARRYING OUT THE INVENTION**

Referring to Figure 1, natural gas is introduced via line 100 into the warm end of
a first tube side of a heat exchanger 112 in which is it liquefied and then subcooled
before leaving the heat exchanger at the cold end. Refrigeration duty in the heat
exchange is provided by a multi component refrigerant ("MR") circulating in a closed
loop. Spent refrigerant from the heat exchanger is fed via line 144 to a compressor 102
and the compressed refrigerant is partially condensed in a cooler 104 before separation
in a phase separator 106. The liquid phase ("MRL") is fed via line 124 to a second tube
side of the heat exchanger in which it is cooled before being throttled in valve 132 and
introduced into the shell side of the heat exchanger 112 below the cold bundle. The
vapor phase ("MRV") is fed via line 134 to a third tube side of the heat exchanger 112 in
which it is cooled and then liquefied before being throttled in valve 138 and introduced
into the shell side of the heat exchanger at the cold end. The liquid and condensed vapor portions vaporize in the heat exchanger and combine to provide the refrigerant feed to line 144.

The flow of LNG product is controlled by a valve 120 and the flows of the refrigerant portions to the heat exchanger are controlled by valves 132 and 138 respectively.

The temperature of the LNG product is compared in temperature indicator controller ("TIC") 114 against the required product temperature determined by an operator set point (SP). A signal proportionate to the difference in actual and required temperature is sent from the TIC 114 to a flow indicator controller ("FIC") 116, which in turn adjusts the position of the product valve 120 to maintain the required temperature. At constant refrigeration, an increase in product flow will increase the actual product temperature and a decrease in product flow will reduce the actual product temperature. The product flow rate is monitored by the FIC 116 and a signal proportionate to the actual value ("PV") of the flow is sent from the FIC 116 to a FIC 122 for comparison with a set point value determined by the operator.

A signal proportionate to the difference between the actual and required product flow rates is sent to FIC 126, which compares the actual flow rate of the MRL with a required value set by that signal. The MRL control valve 132 is adjusted in response to differences between the actual and required flow rates in order to adjust the refrigeration in heat exchanger 112.

A signal proportionate to the difference between actual and required MRL flow rates is sent to a flow ratio indicator controller ("FRIC") 140 where it is compared with a signal from flow indicator ("FI") 136 measuring actual MRV flow rate in order to determine the actual MRV/MRL flow ratio. The actual MRV/MRL flow rate is compared with a set point value determined by a signal received from the temperature differential indicator controller ("TDIC") 142. A signal proportionate to the difference between the actual and required MRV/MRL flow ratios adjusts flow valve 138 and the corresponding refrigeration provided to the heat exchanger 112.

The TDIC 142 compares the actual temperature difference between the spent refrigerant in line 144 and the MRL in line 124 with a set point value determined by the operator. The set point signal provided by the TDIC 142 to the FRIC 140 is proportionate to that difference in temperature.
The TDIC 142 could measure temperature difference between the spent refrigerant and either the MRV in line 134 or the natural gas feed in line 100 instead of the difference with the MRL as shown in Figure 1.

FL 136 could be located upstream instead of downstream of the heat exchanger 112. Similarly, the FIC 126 also could be located upstream instead of downstream of the heat exchanger 112.

It will be apparent that following operator change to the required LNG product flow rate, required LNG product temperature and/or warm end temperature difference ("WETD"), there will be resultant changes to valves 132 and 138 determined by the extent to which the flow rate, temperature and/or WETD have been changed. This will change the amount of refrigeration provided to the heat exchanger 112 and thereby change the difference between the actual and set LNG product temperature values. That change will adjust the valve 120 and hence the actual product flow rate. The change of the actual product flow rate will result in further adjustment valves 132 and 138 controlling the refrigeration supplied to the heat exchanger 112 and provide a corresponding change in the actual LNG product temperature.

Essentially simultaneously with actual change in product temperature, there will be a corresponding change in the WETD detected by TDIC 142 that will result in a corresponding change in the required MRV/MRL flow ratio of FRIC 140. Further, also essentially simultaneously with the change in actual product flow rate, there will be a corresponding change in product temperature that will cause, via the change in difference between actual and required product flow rates, change in refrigeration. Thus, the differences between actual and required product temperatures, actual and required LNG product flow rates and actual and required WETDs will automatically incrementally change in order to achieve the required combination of LNG product flow rate, LNG product temperature and WETD. Further, the control system will automatically change the refrigeration provided to the heat exchanger to maintain the set values if there is any change in LNG product flow rate, LNG product temperature or WETD arising from changes to any of those parameters not occasioned by changes to their required values, such as changes in NG composition, NG flow rate, partial condensation refrigeration duty for 104, ambient air temperature, cooling water temperature, or atmospheric pressure.

The control system of Figure 2 differs from that of Figure 1 in that the LNG product valve 120 is adjusted in response to changes in the WETD and the required MRV/MRL flow ratio is determined by the difference between the actual and required
LNG product temperatures. In particular, the TDIC 142 sends a signal to FIC 116 instead of to FRIC 140 and TIC 114 sends a signal to FRIC 140 instead of FIC 116.

The control system of Figure 3 differs from that of Figure 2 in that the signal from TDIC 142 to FIC 116 is dependent upon the difference between the actual and required MRL flow rates. In particular, a signal proportionate to that difference is sent to a multiplier 300 to modify the signal from TDIC 142.

The control system of Figure 4 differs from that of Figure 1 in that the required MRV/MRL flow ratio is determined by the difference between actual and required temperatures at a mid-point of the heat exchanger 112 located between the liquefying and subcooling sections of the heat exchanger, typically between the cold and warm or middle bundles of the heat exchanger. A TIC 400 has a set point determined by the operator and compares that set point with the actual mid-point temperature. The mid-point temperature can be that on the shell side of the heat exchanger 112 as shown in Figure 4 or could be the temperature of the LNG or MRL or MRV at an appropriate location in the relevant tube section. In this embodiment adjustment of the MRL flow rate by valve 132 in response to the difference between the actual and required MRV flow rates is overridden by a FIC 326 responsive to the WETD if the actual difference differs from the required difference by a predetermined amount.

The control system of Figure 5 differs from that of Figure 4 in that the required mid-point temperature is not operator set but is determined by the difference between actual and required WETDs. In particular, a signal from TDIC 142 no longer provides an override to the FIC 126 control of valve 132 but provides a set point for TIC 400.

The control system of Figure 6 differs from that of Figure 3 in that a constraint controller 146 limits the opening of the MRV valve 138 to, for example 90%, by adjusting a "Production Factor" that is multiplied by multiplier 148 to produce an LNG Master Flow Controller set point. When the system is in control and the valve 138 is open less than the set 90% (or other predetermined maximum) amount the controller 146 provides a Production Factor of 1 and does not limit production. However, if the valve position exceeds 90% (or other predetermined maximum) amount, then the controller would begin to reduce the Production Factor until the system was in control with the required maximum valve position.

It is a common feature of all of the exemplified embodiments that there is no change in LNG product flow rate except in response to changes in refrigeration duty for the heat exchanger 112.
Each of the embodiments of Figures 2 to 5 and the comparative process of Figure 7 was subject to the following disturbances:

- Increase LNG rundown temperature from \(-247^\circ\text{F}\) \((-155^\circ\text{C})\) to \(-245^\circ\text{F}\) \((-153.9^\circ\text{C})\) in 24 minutes;
- Decrease production by 5% while simultaneously decreasing turbine speed by 1% in 24 minutes; and
- Increase production by 2.8% in 24 minutes.

The process of Figure 7 differs from that of Figure 1 in that the LNG product flow rate is directly adjusted to the required value and FIC 126 is controlled by the difference between actual and desired LNG product temperature difference.

**Response to increase LNG rundown temperature**

The process of Figure 1 had some oscillations in its response to the increased rundown temperature with both the LNG flow rate and the LNG temperature oscillating somewhat as they reached the new steady state. It is believed that this was more a result of conflict between the two controllers rather than a tuning issue. The process of Figure 7 did not oscillate but did take a long time to reach the new steady state, which is believed to have been a function of tuning rather than controller interaction. The process of Figure 2 exhibited much tighter control of the temperature with little disturbance to the rest of the system. The process of Figure 3 showed similar ability to that of Figure 2 in tracking the LNG temperature set point and slightly less disturbances to the rest of the system. Both of the processes of Figure 2 and 3 showed the best response to this disturbance.

**Decrease LNG Production with simultaneous turbine speed reduction**

The process of Figure 1 had difficulty in following the LNG production set point taking 2 hours to return to steady state. During that time, the LNG temperature had deviations as large as \(20^\circ\text{F}(1.1^\circ\text{C})\) warmer before finally reaching steady state over 2 hours after the disturbance began. The process of Figure 7, with its direct control over LNG flow rate had excellent tracking of the LNG production set point, but also saw large temperature swings before finally reaching steady state almost 3 hours after the disturbance. The process of Figure 2 lagged in the tracking of the LNG production set point taking two hours to reach steady state, but maintained tight LNG temperature control throughout the disturbance. The process of Figure 3 tracked the set point of the
LNG production very well reaching steady state within an hour of the beginning of the disturbance and maintaining tight temperature control throughout.

**LNG Production increase**

The process of Figure 1 took 2 hours to reach the desired set point as well as allowing the LNG temperature to drift cold by 1°F (0.55°C) before returning to its set point. The process of Figure 3 experienced a more than 1°F (0.55°C) warming of the LNG before returning to steady state in close to 3 hours. The process of Figure 2 took 3 hours to reach the new production set point, but maintained excellent temperature control throughout. The process of Figure 3 showed excellent response to the production change and maintained tight temperature control.

**Unattainable production**

Although the increased production disturbance was easily achieved by the exemplified embodiments of the invention, there still remained a question as to how the systems would respond to a truly unattainable production disturbance. Accordingly, the process of Figure 3 was subjected to a disturbance where the production set point was raised to 7% higher than the current steady state. The simulation was also set up to simulate bog down of the MR turbine 102 and additional parameters were monitored to determine the systems responsiveness.

The system tracked the LNG production to the new set point, however, the LNG temperature continued to rise driving the MRV valve 138 fully open. The LNG temperature finally settled out approximately 4°F (2.2°C) warmer than the desired LNG temperature. The mid point temperature between the middle and cold bundles of the heat exchanger 112 warmed up by close to 20°F (11°C). The increased MRV flow almost doubled the cold bundle pressure drop. The gas turbine reached full power and then bogged down reducing its speed by approximately 1%. The results showed that the control system had no checks to prevent it from reaching an unacceptable new operating point.

The process of Figure 6 overcomes this problem by providing a check to prevent the control system from reaching an undesirable operating point. With the controller 146 set to limit the valve opening to 90%, the 7% production increase limited production to a 4.8% increase and maintained control of the LNG temperature throughout and did not bog down the MR turbine 102.
Other embodiments and benefits of the invention will be apparent to those skilled in the art from a consideration of the specification and from practice of the invention disclosed herein. It is intended that this specification be considered as exemplary only with modifications and variations being within the scope and spirit of the invention as defined by the following claim. In particular, any of the exemplified embodiments could be used for liquefaction of gases other than natural gas and the tube and shell heat exchanger 112 could be replaced by two or more individual heat exchanges arranged in series and/or by any of the heat exchanger types known in the art.

**INDUSTRIAL APPLICABILITY**

The invention is applicable to the liquefaction of gases, especially natural gas (NG) to produce liquefied natural gas (LNG).
CLAIMS

1. A method of maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied gas ("LG") outlet stream of a gas liquefaction in which a gas feed is liquefied by refrigeration in heat exchange means, comprising the steps of:
   comparing said predetermined LG flow rate value with the actual LG flow rate;
   comparing said predetermined LG temperature value with the actual LG temperature; and
   varying the refrigeration provided by said heat exchange means in response to said LG flow rate and LG temperature comparisons to reduce any differences, characterized in that variation of the refrigeration to reduce any LG temperature difference is initiated before variation of the LG flow rate to reduce any LG flow rate difference.

2. A method of Claim 1 wherein said predetermined values are adjustable and the method further comprises the steps of:
   setting the predetermined flow rate value for the LG outlet stream and
   setting the predetermined temperature value for the LG outlet stream.

3. A method of Claim 1 or Claim 2, wherein the gas feed is natural gas.

4. A method of any one of Claims 1 to 3, wherein the actual LG flow rate is adjusted in response to changes in the actual LG temperature.

5. A method of any one of Claims 1 to 3, wherein the actual LG flow rate is adjusted in response to changes in the temperature difference between a stream entering the warm end of the heat exchange means and a stream leaving that end of the heat exchanger.

6. A method of any one of Claim 1 to 3, wherein the actual LG flow rate is adjusted in response to changes in the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means.

7. A method of Claim 1 for maintaining at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream
of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, comprising the steps of:

- comparing said predetermined LNG flow rate value with the actual LNG flow rate;
- comparing said predetermined LNG temperature value with the actual LNG temperature;
- comparing (i) a predetermined value of the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") with the actual warm end temperature difference and/or (ii) a predetermined value of the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with the or the actual mid-point temperature;
- varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, one of the MRL and MRV flow rates;
- varying the other of the MRV and MRL flow rates to maintain an MRL/MRV ratio, which ratio is determined by one of (a) the difference between the actual and predetermined LNG temperatures and (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures; and
- varying, by an amount corresponding to the other of (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures and (a) the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.

A method of Claim 7, wherein said predetermined values are adjustable and the method further comprises the steps of:

- setting the predetermined flow rate value for the LNG outlet;
- setting the predetermined temperature value for the LNG outlet stream; and
- setting the predetermined value of (i) the warm end temperature difference or (ii) the mid-point temperature.
9. A method of Claim 8, wherein the MRL flow rate varies by an amount corresponding to the difference between the actual and predetermined LNG flow rates.

10. A method of Claim 8, wherein the MRL flow rate varies by an amount corresponding to the difference between the actual and predetermined warm end temperature differences.

11. A method of Claim 8, wherein the MRL flow rate varies by an amount corresponding to the difference between the actual and predetermined mid-point temperatures.

12. A method of Claim 9, wherein the MRL/MRV ratio is determined by the difference between the actual and predetermined LNG temperatures.

13. A method of Claim 10, wherein the MRL/MRV ratio is determined by the difference between the actual and predetermined warm end temperature differences.

14. A method of Claim 11, wherein the MRL/MRV ratio is determined by the difference between actual and predetermined mid-point temperatures.

15. A method of Claim 7 or Claim 8, wherein:
   the predetermined warm end temperature difference is compared with the actual warm end temperature difference;
   the MRL flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG flow rates;
   the MRV flow rate is varied to maintain an MRL/MRV ratio, which ratio is determined by difference between the actual and predetermined warm end temperature differences; and
   the actual LNG flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG temperatures.

16. A method of Claim 7 or Claim 8, wherein:
   the predetermined warm end temperature difference is compared with the actual warm end temperature difference;
   the MRL flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG flow rates;
the MRV flow rate is varied to maintain an MRI/MRV ratio, which ratio is determined by the difference between the actual and predetermined LNG temperatures; and

the actual LNG flow rate is varied by an amount corresponding to the difference between the actual and predetermined warm end temperature differences.

17. A method of Claim 7 or Claim 8, wherein:

the predetermined warm end temperature difference is compared with the actual warm end temperature difference;

the MRL flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG flow rates;

the MRV flow rate is varied to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined LNG temperatures; and

the actual LNG flow rate is varied by an amount corresponding to the difference between the actual and predetermined warm end temperature differences.

18. A method of Claim 7 or Claim 8, wherein:

the predetermined warm end temperature difference is compared with the actual warm end temperature difference;

the predetermined mid-point temperature is compared with the actual mid-point temperature;

the MRL flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG flow rates and also, when the difference between actual and predetermined warm end temperature differences exceeds a threshold value, to said difference between warm end temperature differences;

the MRV flow rate is varied to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and predetermined mid-point temperatures; and

the actual LNG flow rate by an amount corresponding to the difference between the actual and predetermined LNG temperatures.

19. A method of Claim 7 or Claim 8, wherein:

the predetermined warm end temperature difference is compared with the actual warm end temperature difference;
the actual mid-point temperature is compared with a calculated temperature value, which is determined by the difference between the actual and predetermined actual warm end temperature differences;  
the MRL flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG flow rates;  
the MRV flow rate is varied to maintain an MRL/MRV ratio, which ratio is determined by the difference between the actual and calculated mid-point temperatures; and  
the actual LNG flow rate is varied by an amount corresponding to the difference between the actual and predetermined LNG temperatures.

20. A control system for maintaining, by a method of Claim 1, at a predetermined flow rate value and at a predetermined temperature value the liquefied gas ("LNG") outlet stream of a gas liquefaction in which a gas feed is liquefied by refrigeration in heat exchange means, said system comprising:  
means for comparing the predetermined flow rate value for the LG outlet stream with the actual LG flow rate;  
means for varying the actual LG product flow rate;  
means for comparing the predetermined temperature value for the LG outlet stream with the actual LG temperature; and  
means for varying the refrigeration provided by said heat exchange means in response to said LG flow rate and LG temperature comparisons to reduce any differences, characterized in that adjustment of the means for varying the actual LG product flow rate is not initiated until the refrigeration has been adjusted to reduce any LG temperature difference.

21. A control system of Claim 20 for maintaining, by a method of Claim 7, at a predetermined flow rate value and at a predetermined temperature value the liquefied natural gas ("LNG") outlet stream of a natural gas liquefaction using heat exchange means, having a warm end to which the natural gas is fed, a liquefying section in which the natural gas is liquefied, a subcooling section in which the liquefied natural gas is subcooled and a cold end from which said LNG outlet stream is withdrawn, in which refrigeration duty is provided in the liquefying section by a first refrigerant ("MRL") cooled in said heat exchange means and supplied for refrigeration duty at an MRL flow rate and
in the subcooling section by a second refrigerant ("MRV") cooled in said heat exchange means and supplied for refrigeration duty at an MRV flow rate, said system comprising:

means for comparing said predetermined LNG flow rate value with the actual LNG flow rate;

means for comparing said predetermined LNG temperature value with the actual LNG temperature;

means for comparing a predetermined value of (i) the temperature difference between spent refrigerant leaving the warm end of the heat exchange means and a stream entering said warm end selected from MRL, MRV and the natural gas feed ("warm end temperature difference") or (ii) the temperature ("mid-point temperature") of a stream at a location between the liquefying and subcooling sections of the heat exchanger means with respectively (i) the actual warm end temperature difference or (ii) the actual mid-point temperature;

means for varying, by an amount corresponding to the difference between the actual and predetermined LNG flow rates, one of the MRL and MRV flow rates;

means for varying the other of the MRV and MRL flow rates to maintain an MRL/MRV ratio, which ratio is determined by one of (a) the difference between the actual and predetermined LNG temperatures and (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures; and

means for varying, by an amount corresponding to the other of (b) the difference between the actual and predetermined warm end temperature differences or mid-point temperatures and (a) the difference between the actual and predetermined LNG temperatures, the actual LNG flow rate.