

US 20070107465A1

(19) **United States**(12) **Patent Application Publication**
Turner et al.(10) **Pub. No.: US 2007/0107465 A1**(43) **Pub. Date: May 17, 2007**(54) **APPARATUS FOR THE LIQUEFACTION OF GAS AND METHODS RELATING TO SAME**(75) Inventors: **Terry D. Turner**, Idaho Falls, ID (US);
Bruce M. Wilding, Idaho Falls, ID (US); **Dennis N. Bingham**, Idaho Falls, ID (US); **Michael G. McKellar**, Idaho Falls, ID (US); **Lisa R. Hoffman**, Vestal, NY (US)

Correspondence Address:

BATTELLE ENERGY ALLIANCE, LLC
P.O. BOX 1625
IDAHO FALLS, ID 83415-3899 (US)(73) Assignee: **BATTELLE ENERGY ALLIANCE, LLC**, Idaho Falls, ID (US)(21) Appl. No.: **11/560,682**(22) Filed: **Nov. 16, 2006****Related U.S. Application Data**

(60) Continuation-in-part of application No. 11/124,589, filed on May 5, 2005, which is a continuation of application No. 10/414,991, filed on Apr. 14, 2003, now Pat. No. 6,962,061, which is a division of application No. 10/086,066, filed on Feb. 27, 2002, now Pat. No. 6,581,409.

Continuation-in-part of application No. 11/381,904, filed on May 5, 2006, which is a continuation-in-part of application No. 11/124,589, filed on May 5, 2005. Continuation-in-part of application No. 11/383,411, filed on May 15, 2006, which is a continuation-in-part

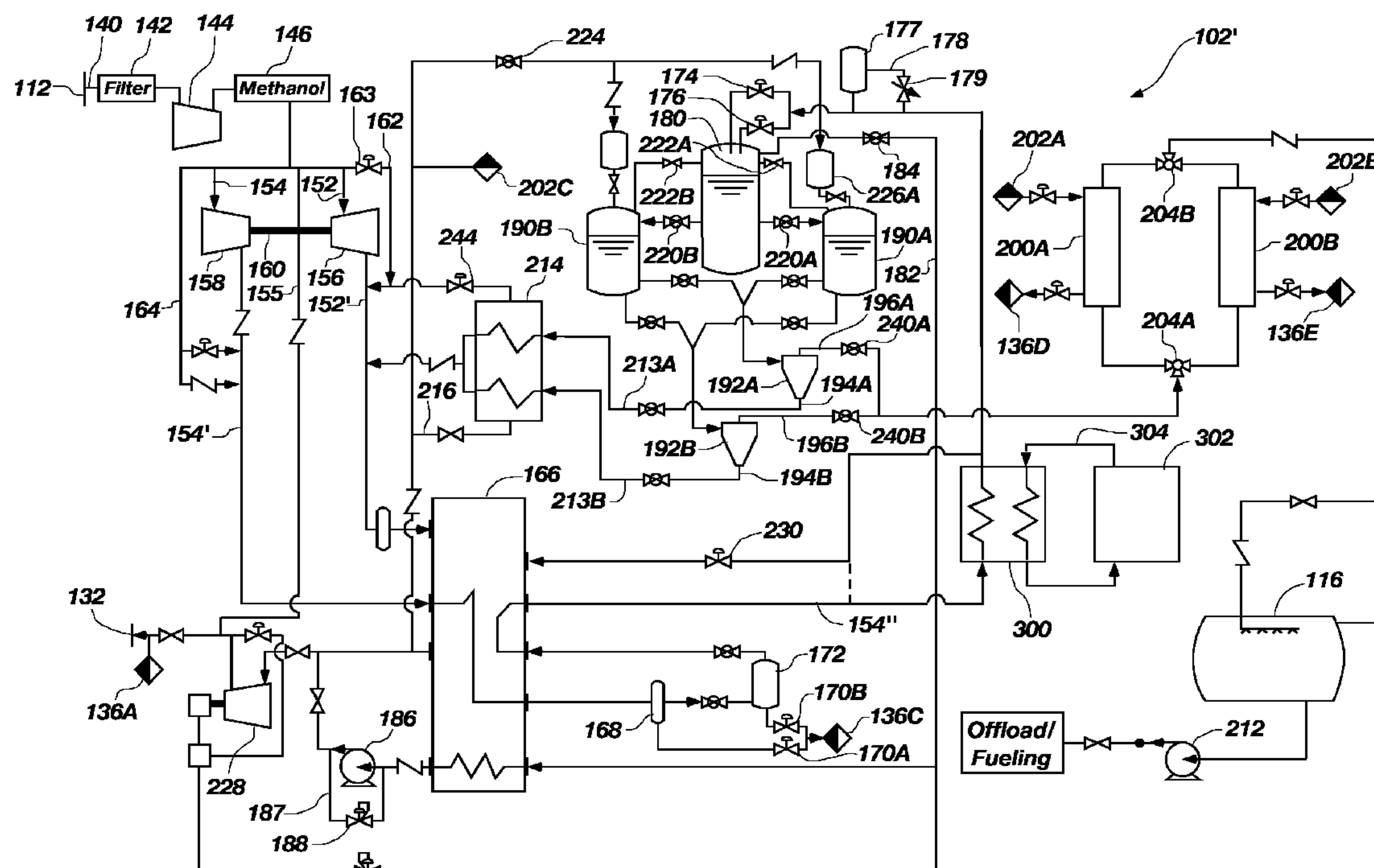
of application No. 11/124,589, filed on May 5, 2005, and which is a continuation-in-part of application No. 11/381,904, filed on May 5, 2006.

Continuation-in-part of application No. 11/536,477, filed on Sep. 28, 2006, which is a continuation-in-part of application No. 11/124,589, filed on May 5, 2005, and which is a continuation-in-part of application No. 11/381,904, filed on May 5, 2006.

(60) Provisional application No. 60/288,985, filed on May 4, 2001.

Publication Classification(51) **Int. Cl.**
F25J 1/00 (2006.01)(52) **U.S. Cl.** **62/613**(57) **ABSTRACT**

An apparatus, a system and a method for producing liquefied gas are provided. A liquefaction plant may be coupled to a source of, for example, unpurified natural gas, such as a natural gas pipeline at a pressure letdown station. A portion of the gas is drawn off and split into a process stream and a cooling stream. The cooling stream may pass through an expansion device. The compressed process stream is cooled, such as by a heat exchange process utilizing the expanded cooling stream, by a heat exchanger utilizing a separate, independent refrigerant, or by both. The cooled, compressed process stream is expanded to liquefy the natural gas. A gas-liquid separator separates the vapor from the liquid natural gas. A portion of the liquid gas may be used for additional cooling or substantially all of the liquid gas may be collected as product.



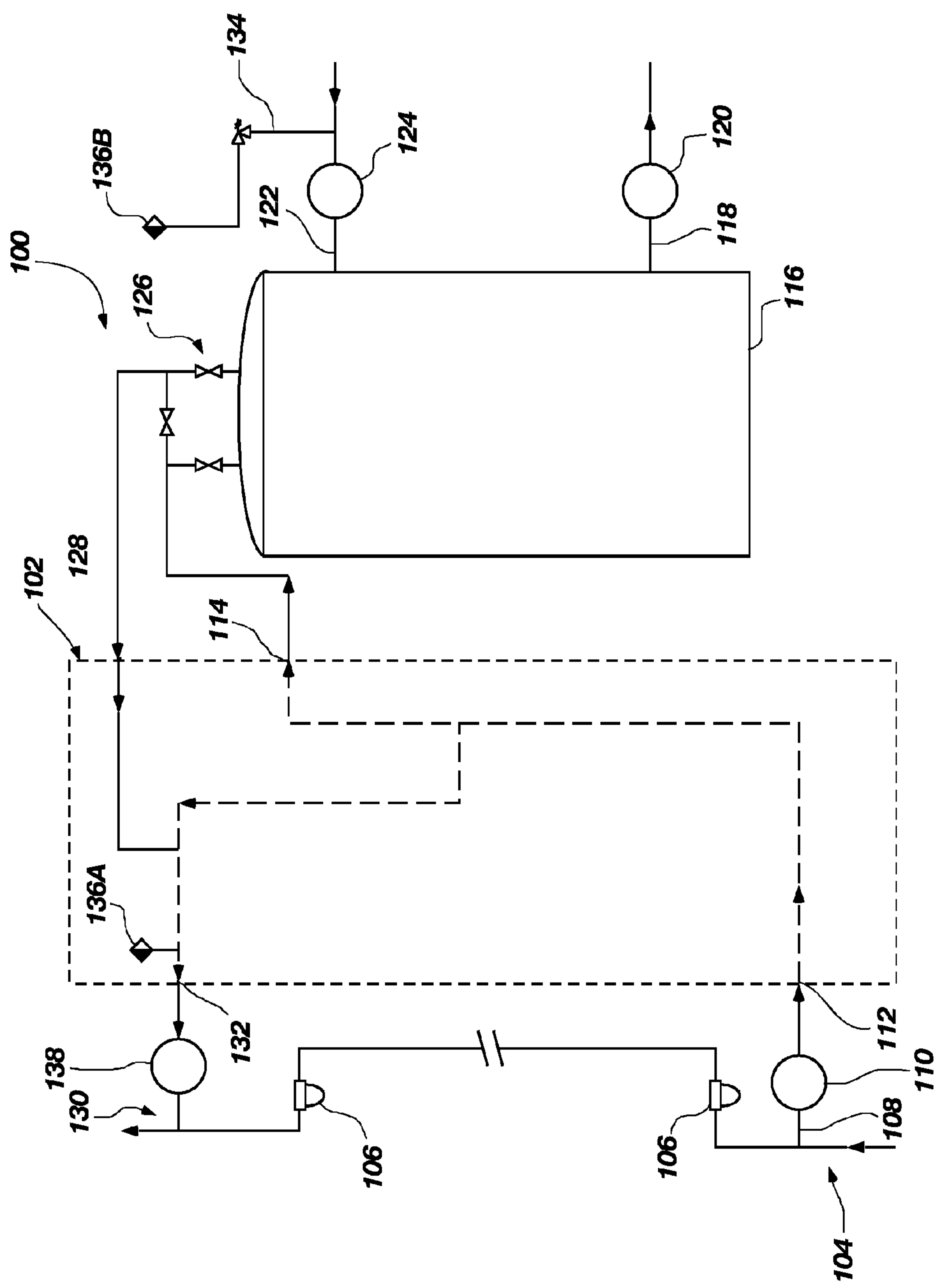
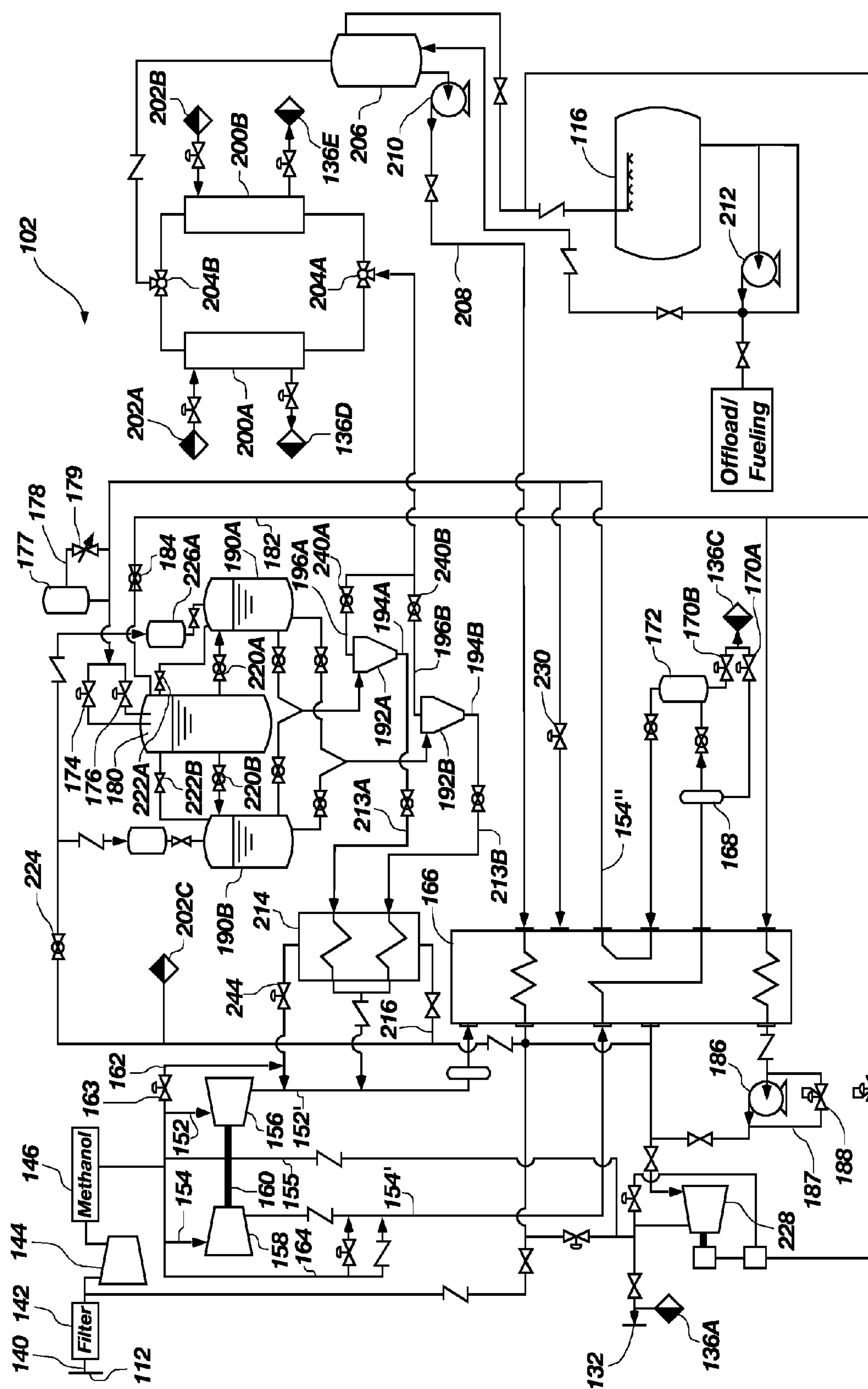


FIG. 1



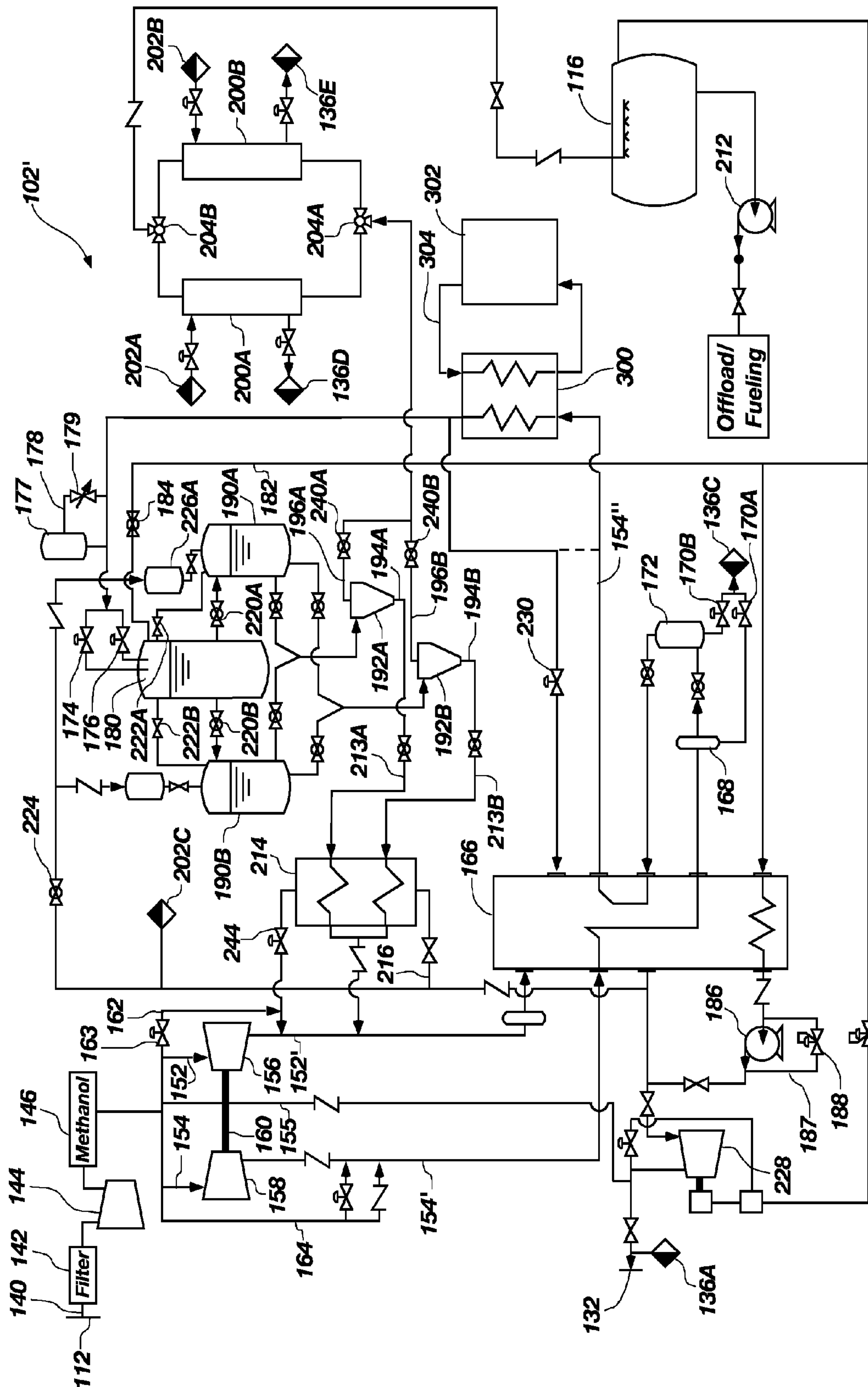


FIG. 3

APPARATUS FOR THE LIQUEFACTION OF GAS AND METHODS RELATING TO SAME

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part of U.S. patent application Ser. No. 11/124,589 filed on May 5, 2005, which is a continuation of U.S. patent application Ser. No. 10/414,991 filed on Apr. 14, 2003, now U.S. Pat. No. 6,962,061 issued on Nov. 8, 2005, which is a divisional of U.S. patent application Ser. No. 10/086,066 filed on Feb. 27, 2002, now U.S. Pat. No. 6,581,409 issued on Jun. 24, 2003 and which claims the benefit of U.S. Provisional Patent Application Ser. No. 60/288,985, filed May 4, 2001. This application is also a continuation in part of U.S. patent application Ser. No. 11/381,904 filed on May 5, 2006, entitled APPARATUS FOR THE LIQUEFACTION OF NATURAL GAS AND METHODS RELATING TO SAME which is also a continuation-in-part of the above-referenced U.S. patent application Ser. No. 11/124,589 filed on May 5, 2005. Further, this application is a continuation-in-part of U.S. patent application Ser. No. 11/383,411, filed on May 15, 2006, entitled APPARATUS FOR THE LIQUEFACTION OF NATURAL GAS AND METHODS RELATING TO SAME which is also a continuation-in-part of the above-referenced U.S. patent application Ser. No. 11/124,589 filed on May 5, 2005, and U.S. patent application Ser. No. 11/381,904 filed on May 5, 2006. Additionally, this application is a continuation in part of U.S. application Ser. No. 11/536,477 filed on Sep. 28, 2006, entitled APPARATUS FOR THE LIQUEFACTION OF NATURAL GAS AND METHODS RELATING TO SAME which is also a continuation-in-part of the above-referenced U.S. patent application Ser. No. 11/124,589 filed on May 5, 2005, and U.S. patent application Ser. No. 11/381,904 filed on May 5, 2006. The disclosures of the above-referenced priority patents and patent applications are each incorporated by reference herein in their entireties.

GOVERNMENT RIGHTS

[0002] The United States Government has certain rights in this invention pursuant to Contract No. DE-AC07-05ID14517 between the United States Department of Energy and Battelle Energy Alliance, LLC.

BACKGROUND OF THE INVENTION

[0003] 1. Field of the Invention

[0004] The present invention relates generally to the compression and liquefaction of gases, and more particularly to the liquefaction of a gas, such as natural gas, on a small scale by utilizing a combined refrigerant and expansion process.

[0005] 2. State of the Art

[0006] Natural gas is a known alternative to combustion fuels such as gasoline and diesel. Much effort has gone into the development of natural gas as an alternative combustion fuel in order to combat various drawbacks of gasoline and diesel including production costs and the subsequent emissions created by the use thereof. As is known in the art, natural gas is a cleaner burning fuel than other combustion fuels. Additionally, natural gas is considered to be safer than gasoline or diesel as natural gas will rise in the air and dissipate, rather than settling or accumulating.

[0007] To be used as an alternative combustion fuel, natural gas (also termed "feed gas" herein) is conventionally converted into compressed natural gas (CNG) or liquified (or liquid) natural gas (LNG) for purposes of storing and transporting the fuel prior to its use. Conventionally, two of the known, basic processes used for the liquefaction of natural gases are referred to as the "cascade cycle" and the "expansion cycle."

[0008] Briefly, the cascade cycle consists of subjecting the feed gas to a series of heat exchanges, each exchange being at successively lower temperatures until the desired liquefaction is accomplished. The levels of refrigeration are obtained with different refrigerants or with the same refrigerant at different evaporating pressures. The cascade cycle is considered to be relatively efficient at producing LNG as operating costs are relatively low. However, the efficiency in operation is often seen to be offset by the relatively high investment costs associated with the expensive heat exchange equipment and the compression equipment associated with the refrigerant system. Additionally, a liquefaction plant incorporating such a system may be impractical where physical space is limited, as the physical components used in cascading systems are relatively large.

[0009] In an expansion cycle, gas is conventionally compressed to a selected pressure, cooled, then allowed to expand through an expansion turbine, thereby producing work as well as reducing the temperature of the feed gas. The low temperature feed gas is then heat exchanged to effect liquefaction of the feed gas. Conventionally, such a cycle has been seen as being impracticable in the liquefaction of natural gas since there is no provision for handling some of the components present in natural gas which freeze at the temperatures encountered in the heat exchangers, for example, water and carbon dioxide. It is noted that the need for expensive pre-clean-up or prepurification is also an issue associated with the cascade cycle.

[0010] Additionally, to make the operation of conventional systems cost effective, such systems are conventionally built on a large scale for the processing of large volumes of natural gas. As a result, fewer facilities are built, making it more difficult to provide the raw gas to the liquefaction plant or facility as well as making distribution of the liquefied product an issue. Another major issue with large scale facilities is the capital and operating expenses associated therewith. For example, a conventional large scale liquefaction plant, i.e., producing on the order of 70,000 gallons of LNG per day, may cost \$2 million to \$15 million, or more, in capital expenses. Also, such a plant may require thousands of horsepower to drive the compressors associated with the refrigerant cycles, making operation of the plants expensive.

[0011] An additional problem with large facilities is the cost associated with storing large amounts of fuel in anticipation of future use and/or transportation. Not only is there a cost associated with building large storage facilities, but there is also an efficiency issue related therewith as stored LNG will tend to warm and vaporize over time, creating a loss of the LNG fuel product. Further, safety may become an issue when larger amounts of LNG fuel product are stored.

[0012] In addition to such technical issues, it is noted that significant issues may be associated with siting and licensing

of large scale LNG and CNG facilities including obtaining the necessary real estate and approval from numerous levels of government agencies.

[0013] In confronting the foregoing issues, various systems have been devised which attempt to produce LNG or CNG from feed gas on a smaller scale, in an effort to eliminate long-term storage issues and to reduce the capital and operating expenses associated with the liquefaction and/or compression of natural gas. However, such systems and techniques have all suffered from one or more drawbacks.

[0014] U.S. Pat. No. 5,505,232 to Barclay, issued Apr. 9, 1996 is directed to a system for producing LNG and/or CNG. The disclosed system is stated to operate on a small scale producing approximately 1,000 gallons a day of liquefied or compressed fuel product. However, the liquefaction portion of the system itself requires the flow of a “clean” or “purified” gas, meaning that various constituents in the gas such as carbon dioxide, water, or heavy hydrocarbons must be removed before the actual liquefaction process can begin.

[0015] Similarly, U.S. Pat. Nos. 6,085,546 and 6,085,547 both issued Jul. 11, 2000 to Johnston, describe methods and systems of producing LNG. The Johnston patents are both directed to small scale production of LNG, but again, both require “prepurification” of the gas in order to implement the actual liquefaction cycle. The need to provide “clean” or “prepurified” gas to the liquefaction cycle is based on the fact that certain gas components might freeze and plug the system during the liquefaction process because of their relatively higher freezing points as compared to methane which makes up the larger portion of natural gas.

[0016] Since many sources of natural gas including, for example, pipelines and well gas, whether being provided to residential or industrial end customers, are considered to be relatively “dirty,” the requirement of providing “clean” or “prepurified” gas is actually a requirement of implementing expensive and often complex filtration and purification systems prior to the liquefaction process. This requirement simply adds expense and complexity to the construction and operation of such liquefaction plants or facilities.

[0017] In view of the shortcomings in the art, it would be advantageous to provide a process, and a system or a plant for carrying out such a process, of efficiently producing liquefied natural gas on a small scale. Additionally, it would be advantageous to provide a system for producing liquefied natural gas from a source of relatively “dirty” or “unpurified” natural gas without the need for “prepurification.” Such a system or process may include various clean-up cycles which are integrated with the liquefaction cycle for purposes of efficiency.

[0018] It would be additionally advantageous to provide a plant or a system for the liquefaction of natural gas which is relatively inexpensive to build and operate, and which desirably requires little or no operator oversight.

[0019] It would be additionally advantageous to provide such a plant or a system which is easily transportable and which may be located and operated at existing sources of natural gas which are within or near populated communities, thus providing easy access for consumers of LNG fuel.

BRIEF SUMMARY OF THE INVENTION

[0020] The present invention provides apparatuses, systems and methods for the liquefaction of gas including, for example, the liquefaction of natural gas. In accordance with one embodiment of the present invention, a method of producing liquid natural gas is provided. The method includes providing a source of unpurified natural gas and flowing a portion of the natural gas from the source. The portion of natural gas is divided into at least a process stream and a cooling stream. The process stream is flowed sequentially through a compressor and a first side of at least one heat exchanger. At least a portion of the process stream is flowed from the at least one heat exchanger through an expansion device and into a liquid-gas separator. The cooling stream is flowed sequentially through an expander and a second side of the at least one heat exchanger. A refrigerant is flowed in a heat exchange relationship with the process stream, the refrigerant being maintained separate from the process stream and the cooling stream.

[0021] The method may further include forming a slurry within the separator, the slurry comprising at least liquid natural gas and solid carbon dioxide. Forming the slurry may be accomplished by expanding the gas, such as through one or more Joule-Thomson valves. The slurry may be flowed into one or more hydrocyclones by way of one or more pressurized transfer tanks. The transfer tanks may be used alternately or sequentially so as to provide a continuous transfer of slurry to the hydrocyclones. The hydrocyclones substantially separate the solid carbon dioxide and the liquid natural gas. A thickened slush may exit an underflow of the hydrocyclone wherein the thickened slush may include the solid carbon dioxide and a portion of the liquid natural gas. The remaining portion of liquid natural gas is flowed through an overflow of the hydrocyclone.

[0022] In accordance with another embodiment of the present invention, a liquefaction apparatus, which may also be termed a “plant,” is provided. The liquefaction plant includes a compressor, a first expansion device, a first heat exchanger, at least a second expansion device and a gas-liquid separator. The liquefaction plant further includes a first flow path configured for sequential delivery of a first stream of gas through the compressor and a first side of the first heat exchanger. A second flow path is defined and configured for sequential delivery of a second stream of gas through the first expansion device and a second side of the first heat exchanger. At least one additional flow path is defined and configured for delivery of at least a portion of the first stream of gas from the first exchanger through the second expansion device and into the gas-liquid separator. A refrigerant loop is defined and configured to flow a refrigerant stream in a heat exchange relationship with the first stream, wherein the refrigerant stream remains separate from the first stream and the second stream.

[0023] The liquefaction plant may include additional components including a plurality of transfer tanks configured to sequentially or alternately fill with slurry and transfer the slurry to one or more hydrocyclones. The hydrocyclones may be used to separate solids from the liquids. Additionally, filters may be used to further remove solids from the liquids. A sublimation tank may be coupled to the hydrocyclones and configured to receive the solids and sublime them back to a gaseous state.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0024] The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0025] FIG. 1 is a schematic overview of a liquefaction plant according to one embodiment of the present invention;

[0026] FIG. 2 is a process flow diagram depicting a liquefaction cycle according to one embodiment of the present invention;

[0027] FIG. 3 is a process flow diagram depicting a liquefaction cycle according to another embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0028] Referring to FIG. 1, a schematic overview of a portion of a liquefied natural gas (LNG) station 100 is shown according to one embodiment of the present invention. It is noted that, while the present invention is set forth in terms of liquefaction of natural gas, the present invention may be utilized for the liquefaction of other gases as will be appreciated and understood by those of ordinary skill in the art.

[0029] The liquefaction station 100 includes a “small scale” natural gas liquefaction plant 102 which is coupled to a source of natural gas such as a pipeline 104, although other sources, such as a well head, are contemplated as being equally suitable. The term “small scale” is used to differentiate from a larger scale plant having the capacity of producing, for example 70,000 gallons of LNG or more per day. In comparison, the presently disclosed liquefaction plant may have capacity of producing, for example, approximately 10,000 gallons of LNG a day but may be scaled to produce a different output as needed and is not limited to small scale operations or plants. Additionally, the liquefaction plant 102 of the present invention is considerably smaller in physical size than conventional large-scale plants and may be readily transported from one site to another.

[0030] One or more pressure regulators 106 may be positioned along the pipeline 104 for controlling the pressure of the gas flowing therethrough. Such a configuration is representative of a pressure letdown station wherein the pressure of the natural gas is reduced from the high transmission pressures at an upstream location to a pressure suitable for distribution to one or more customers at a downstream location. Upstream of the pressure regulators 106, for example, the pressure in the pipeline may be approximately 600 to 800 pounds per square inch gauge (psig) while the pressure downstream of the regulators may be reduced to approximately 470 psig or less. Of course, such pressures are merely examples and may vary depending on the particular pipeline 104 and the needs of the downstream customers. It is noted that the available pressure of the upstream gas in the pipeline 104 (i.e., at plant entry 112) is not critical as the pressure thereof may be raised, for example by use of an auxiliary booster pump, compressor, or other appropriate mechanism prior to the gas entering the liquefaction process described herein. It is further noted that the regulators may be positioned near the plant 100 or at some distance therefrom. As will be appreciated by those of ordinary skill in the

art, in some embodiments such regulators 106 may be associated with, for example, low pressure lines crossing with high pressure lines or with a different flow circuits.

[0031] Prior to any reduction in pressure along the pipeline 104, a stream of feed gas 108 is split off from the pipeline 104 and fed through a flow meter 110 which measures and records the amount of gas flowing there-through. The stream of feed gas 108 then enters the small scale liquefaction plant 102 through a plant inlet 112 for processing, as will be detailed hereinbelow. A portion of the feed gas entering the liquefaction plant 102 becomes LNG and exits the plant 102 at a plant outlet 114 for storage in a suitable tank or vessel 116. In one embodiment, the vessel 116 is configured to hold at least 10,000 gallons of LNG at a pressure of approximately 35 pounds per square inch absolute (psia) and at temperatures, for example, as low as approximately -240° F. However, other vessel sizes and configurations may be utilized, for example, depending on specific output and storage requirements of the plant 102.

[0032] A vessel outlet 118 is coupled to a flow meter 120 in association with dispensing the LNG from the vessel 116, such as to a vehicle which is powered by LNG or into a transport vehicle as may be required. A vessel inlet 122, coupled with a valve/meter set 124 which could include flow and or process measurement devices, enables the venting and/or purging of a vehicle's tank during dispensing of LNG from the vessel 116. Piping 126 associated with the vessel 116 and connected with a second plant inlet 128 provides flexibility in controlling the flow of LNG from the liquefaction plant 102 and also enables the flow to be diverted away from the vessel 116, or for drawing vapor from the vessel 116, should conditions ever make such action desirable.

[0033] The liquefaction plant 102 is also coupled to a downstream section 130 of the pipeline 104 at a second plant outlet 132 for discharging the portion of natural gas not liquefied during the process conducted within liquefaction plant 102 along with other constituents which may be removed during production of the LNG. Optionally, adjacent the vessel inlet 122, vent piping 134 may be coupled with piping of liquefaction plant 102 as indicated by interface points 136A and 136B. Such vent piping 134 will similarly carry gas into the downstream section 130 of the pipeline 104. As noted above, while the second plant outlet 132 is shown as being coupled with the pipeline 104, the second plant outlet 132 could actually be configured for discharging into a different pipeline, a different circuit of the same pipeline, or into some other structure if desired.

[0034] Assuming that the second plant outlet 132 is coupled with the pipeline 104, as the various gas components leave the liquefaction plant 102 and enter into the downstream section 130 of the pipeline 104, a valve/meter set 138, which could include flow and/or process measuring devices, may be used to measure the flow of gas there-through. The valve/meter sets 124 and 138, as well as the flow meters 110 and 120, may be positioned outside of the plant 102 and/or inside the plant as may be desired. Thus, flow meters 110 and 120, when the outputs thereof are compared, help to determine the net amount of feed gas removed from the pipeline 104 as the upstream flow meter 110 measures the gross amount of gas removed and the downstream flow meter 138 measures the amount of gas

placed back into the pipeline **104**, the difference being the net amount of feed gas removed from pipeline **104**. Similarly, optional flow meters **120** and **124** indicate the discharge of LNG and vapor from the vessel **116**.

[0035] Referring now to FIG. 2, a process flow diagram is shown, representative of one embodiment of the liquefaction plant **102** schematically depicted in FIG. 1 and as discussed in detail in U.S. patent application Ser. No. 11/383,411 filed on May 15, 2006 (one of the applications from which the present application claims priority). As previously indicated with respect to FIG. 1, a high pressure stream of feed gas **140** (i.e., 600 to 800 psia), for example, at a temperature of approximately 60° F. enters the liquefaction plant **102** through the plant inlet **112**. While not specifically depicted, prior to processing the feed gas, a small portion of feed gas **140** may be split off, passed through a drying filter and utilized as instrument control gas in conjunction with operating and controlling various components in the liquefaction plant **102**.

[0036] In another embodiment, a separate source of instrument gas, such as, for example, nitrogen, may be provided for controlling various instruments and components within the liquefaction plant **102**. As will be appreciated by those of ordinary skill in the art, other instrument controls including, for example, mechanical, electromechanical, or electromagnetic actuation, may likewise be implemented.

[0037] Upon entry into the liquefaction plant **102**, the feed gas **140** flows through a filter **142** to remove any sizeable objects which might cause damage to, or otherwise obstruct, the flow of gas through the various components of the liquefaction plant **102**. The filter **142** may additionally be utilized to remove certain liquid and solid components. For example, the filter **142** may be a coalescing type filter. An example filter is available from Parker Filtration, located in Tewksbury, Mass. and is designed to process approximately 5000 standard cubic feet per minute (SCFM) of natural gas at approximately 60° F. at a pressure of approximately 500 psia. Another example of a filter that may be utilized includes a model AKH-0489-DXJ with filter #200-80-DX available from MDA Filtration, Ltd. of Cambridge, Ontario, Canada.

[0038] The filter **142** may be provided with an optional drain which may discharge, for example, into piping near the plant exit **132** or it may discharge to some other desired location. In one embodiment, the discharge from the filter **142** may ultimately reenter the downstream section **130** of the pipeline **104** (see FIG. 1). Bypass piping may be routed around the filter **142**, allowing the filter **142** to be isolated and serviced as may be required without interrupting the flow of gas into the liquefaction plant **102**.

[0039] After the feed gas **140** flows through the filter **142**, it may flow through a compressor **144**, if necessary, to raise the pressure of the feed gas **140** to a desired level. For example, if the feed gas entering the inlet **112** from the pipeline **104** (or other source) does not exhibit a desired pressure of, for example, 600 to 800 psig, the compressor **144** may be used to boost the pressure of the feed gas **140** to the desired pressure. If the pressure of the feed gas **140** entering the inlet **112** is sufficient, the feed gas **140** may be routed around the compressor **144**.

[0040] A water clean-up cycle may be incorporated into the plant **102**. In one example, a water clean-up cycle may

include a source of methanol **146**, or some other water absorbing product, which is injected into the feed gas **140**, such as, for example, by means of a pump, at a location relatively early in the flow of feed gas **140** through the plant **102**. Such a pump or other device may desirably include variable flow capability to inject methanol into the gas stream such as, for example, by way of at least one of an atomizing or a vaporizing nozzle. In another embodiment, multiple types of nozzles may be utilized such that an appropriate nozzle may be selectively utilized depending on the flow characteristics of the feed gas **140** at a given point in time.

[0041] In one embodiment, a suitable pump for injecting the methanol may include variable flow control in the range of 0.4 to 2.5 gallons per minute (GPM) at a design pressure of approximately 1000 psia for a water content of approximately 2 to 7 pounds mass per millions of standard cubic feet (lbm/mm scf). The variable flow control may be accomplished through the use of a variable frequency drive coupled to a motor of the pump. For example, one such pump is available from America LEWA located in Holliston, Mass. as model number EKM7-2-10MM.

[0042] When methanol is used, it is mixed with the gas stream to lower the freezing point of any water which may be contained therein. The methanol mixes with the gas stream and binds with the water to prevent the formation of ice in one or more flow paths defined within the liquefaction process.

[0043] Subsequent any desired compression of the feed gas **140** and any injection of methanol or other water absorbing materials thereinto, the feed gas **140** is split into two streams, a cooling stream **152** and a process stream **154**. In one embodiment, the cooling stream **152** enters a turbo expander **156** at a pressure of approximately 840 psig and at a temperature of approximately 60° F. and is expanded to form an expanded cooling stream **152'** exhibiting a lower pressure, for example approximately 50 psig, and a reduced temperature of, for example, approximately -140° F. As will be seen hereinbelow, the expanded cooling stream **152'** is a cold mass of fluid that provides cooling during the process of producing liquefied gas.

[0044] The turbo expander **156** is a turbine which expands the gas and extracts power from the expansion process. A rotary compressor **158** may be coupled to the turbo expander **156** by mechanical means, such as through a shaft **160**, so as to utilize the power generated by the turbo expander **156** to compress the process stream **154**. In one embodiment, the reduction of pressure from the transmission line or pipeline **104** to a distribution pressure, effected by the turbo expander **156**, provides the majority of the energy used in the plant **102** making it extremely economical to operate the plant **102**.

[0045] By compressing the process stream **154**, a larger volume of produced liquid will be realized. Additionally, elevated pressures help to keep any CO₂ contained within the process stream **154** from plugging the various downstream flow paths.

[0046] The proportion of gas in each of the cooling and process lines **152** and **154** is determined by the power requirements of the compressor **158** as well as the flow and pressure drop across the turbo expander **156**. Vane control

valves within the turbo expander **156** may be used to control the proportion of gas between the cooling and process lines **152** and **154** as is required according to the above stated parameters. In one embodiment, the feed gas **140** may be proportioned substantially evenly between the cooling and process lines **152** and **154**.

[0047] An example of a turbo expander **156** and compressor **158** system includes a frame size ten (10) system available from GE Rotoflow, Inc., located in Gardona, Calif. In one embodiment, the expander **156** compressor **158** system may be designed to operate at approximately 840 psig at 5,000 pounds mass per hour at about 60° F. The expander/compressor system may also be fitted with gas bearings. Such gas bearings may be supplied with gas through a supply line **155** which draws a portion of the feed gas therethrough. However, the portion of gas directed to any such gas bearing is relatively insubstantial as compared to the mass of gas flowing through the cooling and process lines **152** and **154**. In another embodiment, gas bearings may be supplied by a separate flow of gas such as nitrogen. In yet another embodiment, the expander/compressor system may be fitted with other types of bearings including, for example, magnetic or oil bearings.

[0048] Bypass piping **162** routes the cooling stream **152** around the turbo expander **156**. Likewise, bypass piping **164** routes the process stream **154** around the compressor **158**. The bypass piping **162** and **164** may be used during startup of the plant **102** to bring certain components to a steady state condition prior to the processing of LNG within the liquefaction plant **102**. For example, the bypass piping **162** and **164** may be used while various components (such as the heat exchanger **166** which will be discussed hereinbelow), are gradually brought to a steady state temperature so as to avoid inducing thermal shock in such components. Additionally, if the pressure of the feed gas **140** is sufficient, the compressor **158** need not be used and the process stream may continue through the bypass piping **164**. Indeed, if it is known that the pressure of the feed gas **108** will remain at a sufficiently high pressure, the compressor **158** could conceivably be eliminated. In such a case where the compressor **158** is not being utilized, the work generated by the expander **156** could be utilized to drive a generator or provide power to some other component if desired. The bypass piping **164** additionally protects the compressor **158** from surging in the event of off-normal flow disruption. For example, if a reduced level of flow through the compressor **158** is sensed or otherwise determined for a given RPM of the compressor **158**, valves may be opened to recirculate high pressure gas through the bypass piping **164** to the inlet side of the compressor **158**.

[0049] Without bypass piping **162** and **164**, thermal shock might result from the immediate flow of gas from the turbo expander **156** and compressor **154** into certain downstream components. Depending on the design of specific components being used in the liquefaction plant **102** (e.g., the heat exchanger **166**), several hours may be required to bring the system to a thermally steady state condition upon start-up of the liquefaction plant **102**.

[0050] For example, by routing the process stream **154** around the compressor **158**, the temperature of the process stream **154** is not increased prior to its introduction into the heat exchanger **166**. However, the cooling stream **152**, as it bypasses the expander **156**, may pass through an expansion

valve, such as a Joule-Thomson (JT) valve **163**, allowing the cooling stream to expand thereby reducing its temperature. As will be appreciated by those of ordinary skill in the art, the JT valve **163** utilizes the Joule-Thomson principle that expansion of gas will result in an associated cooling of the gas as well. The cooling stream **152** may then be used to incrementally reduce the temperature of the heat exchanger **166**.

[0051] In one embodiment, the heat exchanger **166** is a high efficiency heat exchanger made from aluminum. In start-up situations it may be desirable to reduce the temperature of such a heat exchanger **166** by, for example, as much as approximately 1.8° F. per minute until a defined temperature limit is achieved. During start-up of the liquefaction plant **102**, the temperature of the heat exchanger **166** may be monitored as it incrementally decreases. The JT valve **163** and other valving or instruments may be controlled in order to effect the rate and pressure of flow in the cooling stream **152** and process stream **154'** which ultimately controls the cooling rate of heat exchanger **166** and/or other components of the liquefaction plant.

[0052] Additionally, during start-up, it may be desirable to have an amount of LNG already present in the tank **116** (FIG. 1). Some of the LNG may be cycled through the system in order to cool various components if so desired or deemed necessary. Also, as will become apparent upon reading the additional description below, other cooling devices, including additional JT valves, located in various "loops" or flow streams may likewise be controlled during start-up in order to cool down the heat exchanger **166** or other components of the liquefaction plant **102**.

[0053] When the plant **102** or liquefaction system is in a steady state condition, the process stream **154** flows through the compressor **158** raising the pressure of the process stream **154**. In one embodiment, the ratio of the outlet to inlet pressures of a rotary compressor may be approximately 1.5 to 2.0, with an average ratio being around 1.7. The compression process is not thermodynamically ideal and, therefore, adds heat to the process stream **154** as it is compressed. To remove heat from the compressed process stream **154'**, it is flowed through a heat exchanger **166** and is cooled to a very low temperature, for example approximately -200° F. at a pressure, for example, of approximately 1,100 psig. It is noted that, if the heat of compression is too high, the gas may be precooled, for example, by an ambient heat exchanger prior to its entry into the heat exchanger **166**. The heat exchanger **166** may include a high efficiency heat exchanger and, in one embodiment, may be formed as a countercurrent flow, plate and fin type heat exchanger. Additionally, the plates and fins may be formed of a highly thermally conductive material such as, for example, aluminum. In one embodiment, the high efficiency heat exchanger **166** may include a multipass, plate and fin heat exchanger such as is available from Chart Industries, Inc. of La Crosse, Wis.

[0054] The heat exchanger **166** is positioned and configured to efficiently transfer as much heat as possible away from the compressed process stream **154'** as it passes therethrough. The liquefaction plant **102** is desirably configured such that temperatures generated within the heat exchanger **166** are never low enough to generate solid CO₂ which may be present in the feed gas **140**, and which formation of solid

CO₂ might result in blockage in the flow path of the compressed process stream 154'.

[0055] As noted hereinabove, methanol may be mixed with the feed gas to lower the freezing point of any water which may be contained therein. The methanol mixes with the gas stream and binds with the water to prevent the formation of ice in the cooling stream 152 during expansion in the turbo expander 156. Thus, the methanol is present in the process stream 154 and passes therewith through the compressor 158. About midway through the heat exchange process (i.e., between approximately -60° F. and -90° F.) the methanol and water become liquid. The compressed process stream 154' is temporarily diverted from the heat exchanger 166 and passed through a separating tank 168 wherein the methanol/water liquid is separated from the compressed process stream 154'. The liquid is discharged through a valve 170A and the gas flows to a coalescing filter 172 to remove an additional amount of the methanol/water mixture. The methanol/water mixture may be discharged from the coalescing filter 172 through a valve 170B while the dried gas reenters the heat exchanger 166 for further cooling and processing. As is indicated by interface connections 136A and 136C, both valves 170A and 170B discharge the removed methanol/water mixture into piping near the plant exit 132 for discharge into the downstream section 130 of the pipeline 104 (see FIG. 1).

[0056] In one example, a coalescing filter 172 used for removing the methanol/water mixture may exhibit an efficiency of removing the methane/water mixture to less than approximately 75 ppm/w. One such filter is available from Parker Filtration, located in Tewksbury, Mass.

[0057] The liquefaction process shown in FIG. 2 thus provides for efficient production of natural gas by integrating the removal of water during the process without expensive equipment and preprocessing required prior to the liquefaction cycle, and particularly prior to the expansion of the gas through the turbine expander 156.

[0058] After exiting the heat exchanger 166, the cooled, compressed process stream 154" (referred to hereinafter as the product stream 154" for purposes of convenience) flows through two expansion valves, such as JT valves 174 and 176 and into a liquid/vapor separator 180. The two valves 174 and 176 are arranged in a parallel flow configuration and work in concert with one another to control the flow of the product stream 154" into the separator 180. In one embodiment, the two valves 174 and 176 are of different sizes. In other words, the two valves may exhibit different flow coefficients (C_v). For example, in one embodiment, one valve 174 may be sized and configured to accommodate approximately 80% of the flow entering into the separator from the product stream 154" while the other valve 176 may be sized and configured to accommodate the remaining approximately 20% of the flow.

[0059] Of the two valves 174 and 176, the larger valve is held at a constant position while the valve carrying the remaining flow is used for the fine control required to maintain a desired flow rate. As the gas expands through the valves, a Joule-Thomson effect reduces the temperature and pressure from, for example, approximately 1100 psig at approximately -185° F. to approximately 35 psig and approximately -230° F. (which is the saturation temperature and pressure for the liquid). This pressure drop also precipi-

tates solid CO₂. The three phase (gas, liquid, and solid CO₂) mixture exiting the valves is collected in the separator tank 180.

[0060] While a single valve may be used instead of the two JT valves 174 and 176, the use of two (or more) valves 174 and 176 provides a more controlled flow and reduces shock or fluctuation in the stream. Additionally, the use of multiple valves may be beneficial during start-up of the plant 102 because the gas is less dense in such circumstances. An accumulator 177 may be coupled with the product stream 154" at a location upstream from the valves 174 and 176 to further dampen flow pulses that may be introduced into the stream 154" by the valves 174 and 176. A pressure sense line 178 may extend between the accumulator and the product stream 154" and may be buffered by a restrictive valve 179. Additionally, the accumulator 177 may be directly coupled to the product stream 154".

[0061] When the product stream 154" passes through the two expansion valves 174 and 176, the stream follows a constant enthalpy pressure drop that changes from a high pressure, single phase mixture at a high pressure and low temperature (e.g., approximately 1,100 psig and approximately -200° F.) to three phases (solid, liquid and gas) with approximately 10% to 28% mass flow being vapor, at a reduced pressure of, for example, 35 psig. The solid component includes solid CO₂. The vapor component from the separator 180 is collected and removed therefrom through piping 182 and is routed back to the heat exchanger 166 to provide additional cooling by way of a compressor 186. While shown to be located on the warm side of the heat exchanger 166, the compressor 186 could be positioned on the cold side of the heat exchanger 166, although such positioning might require the compressor to be configured as a cryogenic compressor. In one embodiment, the compressor 186 may be powered by an internal combustion engine driven by a portion of the natural gas flowing through the plant 102. In another embodiment, the compressor 186 may be powered by electricity or other means as will be appreciated by those of ordinary skill in the art. It is further noted that an ejector or an eductor might be utilized in place of the compressor 186 in another embodiment.

[0062] To maintain the separator 180 at a desired pressure, for example at approximately 35 psig, the compressor 186 may be used to recompress the excess gas from the separator 180 to pressures suitable, for example, for introduction of the gas into the heat exchanger 166. For example, the compressor 186 may be used to increase the pressure of the gas from approximately 35 psig to approximately 50 psig. The compressor 186 may also be coupled to a vent line associated with the storage tank 116 to likewise help maintain the pressure within storage tank 116 at substantially the same pressure as that of the separator 180.

[0063] A make up line 187 having a regulator 188 may be routed around the compressor 186 to prevent flow surges as may be the case when gas flow from the separator 180 and/or storage tank 116 is relatively low. The pressure of such a regulator may be set at a level that is just under the desired saturation pressure for the separator 180. In one embodiment, a floating ball check valve may also be installed in the suction line of the compressor 186 to prevent a sudden surge of liquid. If the compressor 186 is located on the cold side of the heat exchanger 166, the floating ball check valve may

also be used to prevent any accumulated liquid from entering the suction side of the pump. It is noted that if the compressor **186** is located on the warm side of the heat exchanger **166**, no liquid will be present at the suction side of the compressor **186** under normal operating conditions.

[0064] A back-pressure regulator may be located in the vapor piping **182** to also help control the pressure within the separator **180**. In one example, the back pressure regulator **184** may be configured with set-point of approximately 35 psig so as to create a saturation pressure of the liquid that is below a desired transfer pressure (i.e., the pressure used to transfer liquid from the separator **180** to other components within the plant **102**).

[0065] In one embodiment, the storage tank **116** may be maintained at substantially the same pressure as that of the separator **180**. By maintaining the liquid saturation pressure below associated transfer pressures, the liquid is prevented from boiling when the liquid experiences a pressure drop such as will occur when the liquid flows through piping, valves and other equipment as it is transferred from the separator **180**. The pressure difference between the separator **180** (e.g., approximately 35 psig) and a transfer pressure may be specified such that it is sufficient to ensure that any and all line pressure drops encountered en route to the storage tank **116** are accounted for. The liquid will then arrive at the storage tank **116** at saturation pressure, minimizing loss and flow complications that might otherwise occur due to boiling of the liquid during the transfer thereof.

[0066] As noted above, solid CO₂ mostly forms as small crystals in the liquid as it exits the JT valves **174** and **176**. With the appropriate resident time in the liquid, the CO₂ becomes a sub-cooled solid particle. In the sub-cooled state the particles are less likely to clump together. Keeping the particles suspended in the liquid provides more effective and efficient transfer and separation of the solids from the liquid component. If allowed to settle, the particles have a tendency to clump or stick together. To aid in keeping the CO₂ particles suspended in the liquid, gas bubbles may be introduced into the bottom of the separator **180**. Introduction of the gas bubbles helps to agitate the CO₂ solids within the liquid and keep the particles continually moving within the liquid. While not specifically shown in FIG. 2, gas may be drawn from, for example, a location subsequent the coalescing filter **172**, to provide the bubbling and agitation of the solids within the separator.

[0067] As the separator **180** is filled, the level may be monitored by appropriate sensors. The level of the liquid/solid within the separator **180** may be desirably monitored and controlled in order to provide desired resident times for the CO₂ and thereby ensure that the CO₂ particles are subcooled.

[0068] When a specified maximum level of liquid/solid slurry is reached within the separator **180**, the liquid/solid slurry will be transferred to at least one of a plurality of transfer tanks **190A** and **190B**. In one embodiment, the transfer tanks **190A** and **190B** are used alternately. The transfer tanks **190A** and **190B** are utilized to transfer the slurry from the separator **180** to one of a plurality of hydrocyclones **192A** and **192B**. While it is possible to transfer the slurry from the separator **180** to the hydrocyclones **192A** and **192B** without the use of the transfer tanks **190A** and **190B**, it is believed that, in the currently described

embodiment, the use of transfer tanks **190A** and **190B** provides improved control over the transfer of the slurry (including transfer of the slurry to the hydrocyclones **192A** and **192B** and subsequent transfer of the liquid from the hydrocyclones **192A** and **192B** to downstream components such as the storage tank **116**), and ensures that adequate transfer pressures are maintained during such transfer. If pressures are not properly maintained during transfer of the slurry, the liquid may boil due to pressure losses associated with piping and other components. Additionally, failure to maintain proper pressures during transfer of the slurry may result in inadequate solid-liquid separation. The use of separate, alternating tanks **190A** and **190B** to effect the transfer of the slurry from the separator **180**, is one means that may be used to maintain the pressure integrity of the liquefaction plant **102**.

[0069] When the separator **180** has reached its specified maximum level, two valves will open allowing the fluid to move into one of the transfer tanks (e.g., transfer tank **190A** for purposes of the present discussion). The first valve **220A** allows the transfer of liquid/CO₂ slurry, while the second valve **222A** vents the transfer tank **190A** back to the separator **180** enabling the captured gases in the transfer tank **190A** to escape as it is being filled with the slurry. Depending, for example, on the length of the piping run between the separator **180** and the transfer tank **190A**, bubbler locations may be added to the bottom of the pipe to prevent the CO₂ from settling during the transfer of the slurry (similar to that which has been previously described with respect to the separator **180**). It is noted that a single valve may be utilized instead of multiple valves if the single valve is properly located (e.g., physically below the separator **180**).

[0070] When the level in the separator **180** tank is reduced to a specified minimum level, the valves **220A** and **222A** to the transfer tank **190A** close. The liquid CO₂ transfer alternates between the two transfer tanks **190A** and **190B** associated with the separator tank **180**. Once the valves connecting the separator **180** and transfer tank are closed the liquid/CO₂ mixture is ready to be transferred to the hydrocyclone separator. The pressure sensitive hydrocyclone separates the CO₂ from the liquid by cyclonic action. The transfer tank is pressurized to the desired pressure and the transfer valve is opened. The transfer pressure is approximately 20 psi higher than the saturation pressure of the liquid. This pressure head provides the motive force for the liquid/CO₂ mixture, prevents the liquid from boiling as pressure drops are realized, and prevents the formation of additional CO₂ that could occur if the pressure were to drop below saturation pressure.

[0071] By alternating the filling of the two (or more) transfer tanks **190A** and **190B**, a constant flow of slurry to a selected hydrocyclone (e.g., **192A**) may be easily maintained. The alternating use of transfer tanks **190A** and **190B** also improves the efficiency and effectiveness of the separation process performed by the hydrocyclones **192A** and **192B**. It is noted that, if the rate at which liquid is produced (i.e., within the separator **180**) falls behind with respect to a desired separation rate of a hydrocyclone **192A**, the flow to the hydrocyclone **192A** may be suspended while the separator **180** and transfer tanks **190A** and **190B** fill to a desired level. The transfer tanks **190A** and **190B** and hydrocyclones **192A** and **192B** may be oversized to prevent the possibility

of producing liquid in the separator **180** faster than the transfer/separation capabilities of the hydrocyclones **192A** and **192B**.

[0072] The transfer tank (considering tank **190A** as an example) is pressurized by use of a pressure regulator **224** which is set at a desired transfer pressure. If the feed line to the transfer tank **190A** is sufficient and the regulator **224** is large enough, a regulator **224** can be mounted directly on the transfer tank **190A**. This would require one regulator for each tank. However, in another embodiment, both transfer tanks **190A** and **190B** could be maintained with a smaller feed line and a single regulator **224** as shown in FIG. 2. Use of a single regulator may require the use of storage or accumulator tanks (e.g., **226A**) to ensure that the proper volume of gas is used so as to maintain a constant pressure during the complete transfer process. It is noted that the gas used to transfer the liquid will be warmer than the liquid/solid slurry being transferred. As such, any heat transfer effects are accounted for in configuring and sizing the regulator(s) **224** and accumulator tank(s) **226A**.

[0073] As previously noted, the liquid/solid slurry is transferred to, and processed by, one of the hydrocyclones **192A** and **192B**. The hydrocyclones **192A** and **192B** act as separators to remove the solid CO_2 from the slurry allowing the LNG or other liquid product to be collected and stored. The hydrocyclones **192A** and **192B** may be configured to be substantially identical to one another. As such, only a single hydrocyclone **192A** is referenced with respect to the particular details thereof. In one embodiment, the hydrocyclone **192A** may be designed, for example, to operate at a pressure of approximately 125 psia at a temperature of approximately -238°F . The hydrocyclone **192A** uses a pressure drop to create a centrifugal force which separates the solids from the liquid. A thickened slush, formed of a portion of the liquid natural gas with the solid CO_2 , exits the hydrocyclone **192A** through an underflow **194A**. The remainder of the liquid natural gas is passed through an overflow **196A** for additional filtering. A slight pressure differential, for example, between approximately -0.5 psid and 1.5 psid, exists between the underflow **194A** and the overflow **196A** of the hydrocyclone **192A**. The pressure in the hydrocyclone **192A** is provided and maintained by the transfer tank (**190A** or **190B**). A control valve **240A** may be positioned at the overflow **196A** of the hydrocyclone **192A** to assist in controlling the pressure differential developed within the hydrocyclone **192A**. The underflow pressure may be controlled by the mid-system pressure as may be maintained by the suction side of a recompression compressor **228** (if one is being used) or by the distribution line pressure at the plant outlet **132**.

[0074] A suitable hydrocyclone **192A** is available, for example, from Krebs Engineering of Tucson, Ariz. In one example, the hydrocyclone **192A** may be configured to operate at design pressures of up to approximately 125 psi within a temperature range of approximately 100°F . to -300°F . Additionally, the hydrocyclone **192A** may desirably include an interior surface which exhibits a specified surface finish.

[0075] It is noted that the hydrocyclones **192A** and **192B** are selectively coupled with each of the transfer tanks **190A** and **190B** through appropriate valving and piping such that each of the transfer tanks **190A** and **190B** may selectively

flow slurry to either of the hydrocyclones **192A** and **192B**. The use of two hydrocyclones **192A** and **192B** provides redundancy in the system so that if one hydrocyclone becomes plugged (or partially plugged), the other hydrocyclone may be used while appropriate maintenance is performed on the first. If desired, warm gas may be routed from another location in the plant **102** to assist in unplugging a hydrocyclone such as by melting or sublimation of solid CO_2 that may be the source of any such plugging. The selection and control of the transfer tanks **190A** and **190B** and hydrocyclones **192A** and **192B** will be further discussed hereinbelow with respect to the control and operation of the plant **102**.

[0076] The liquid natural gas flows through the overflow **196A** of the hydrocyclone **192A** and may flow through one of a plurality of filters **200A** and **200B** placed in a parallel flow configuration. The filters **200A** and **200B** capture any remaining solid CO_2 which may not have been separated out in the hydrocyclone **192A**. The filters **200A** and **200B** may be configured such as substantially described in the priority patent applications and patents that have been incorporated by reference. Generally, in one embodiment, such filters **200A** and **200B** may include a first filter screen of coarse stainless steel mesh, a second conical shaped filter screen of stainless steel mesh less coarse than the first filter screen, and a third filter screen formed of fine stainless steel mesh. In another embodiment, all three filter screens may be formed of the same grade of mesh.

[0077] The filters **200A** and **200B** may, from time to time, become clogged or plugged with solid CO_2 captured therein. Thus, as one filter, i.e., **200A**, is being used to capture CO_2 (or other solids) from the liquid stream, the other filter, i.e., **200B**, may be purged of CO_2 by passing a relatively high temperature natural gas therethrough in a counter flowing fashion. For example, gas may be drawn from a relatively warmer gas stream, as indicated at interface points **202B** (or **202A** for filter **200A**) and **202C** to flow through and clean the filter **200B**.

[0078] During cleaning of the filter **200B**, the cleaning gas may be discharged to a downstream location within the plant **102** adjacent the plant outlet **132** as indicated by interface connections **136E** (**136D** for filter **202A**) and **136A**. Appropriate valving and piping including, for example, three way valves **204A** and **204B**, which may be used to enable the filters **200A** and **200B** to be switched and isolated from one another as may be required. Other methods of removing CO_2 solids (or other solids) that have accumulated in the filters **200A** and **200B** are readily known by those of ordinary skill in the art.

[0079] In another embodiment, the filters **200A** and **200B** may be configured to include a floating bed that traps solid CO_2 while permitting fluid to pass therethrough. As the floating bed becomes filled with CO_2 , the trapped CO_2 settles to the bottom. When the filter (e.g., **200A**) is filled with CO_2 , an elevated pressure differential develops indicating that the filter **200A** needs to be cleaned and flow can be switched to the redundant filter (e.g., **200B**). The first filter **200A** may then be cleaned in a manner similar to that which has been described hereinabove.

[0080] The filtered liquid passes from the filter **200A** (or **200B**) to a diversion tank **206**. Liquid in the diversion tank **206** may be selectively passed to the storage tank **116**,

utilized for additional cooling within the liquefaction **102**, or both. When used for additional cooling, the liquid in the diversion tank **206** may be routed back to the heat exchanger **166**, such as through stream **208** and by use of an appropriate pump **210** (referred to herein as a diversion pump). The diversion pump **210** may also be used to elevate the pressure of the liquid such that it may be subsequently recirculated through the liquefaction plant **102** or reintroduced into the pipeline **104**. For example, a positive displacement pump may be used to pump liquid out of the diversion tank **208** to the heat exchanger **166** while increasing the pressure of the liquid to, for example, approximately 495 psig if the liquid is going to be passed back to the pipeline **104** (or some other receiving line) or, for example, to approximately 800 psig if the liquid is to be recirculated back through the plant **102**. By pressurizing to liquid to a distribution or recirculation pressure, the load on the recompressor **228** is reduced, it being more efficient to compress a liquid than it is to compress a gas.

[0081] The diversion tank **206** may also be supplied with liquid by way of a make-up pump **210** coupled with an outlet of the storage tank **116**. In the event of off normal or startup conditions, where the plant **102** is not supplying adequate liquid to keep the diversion tank **206** full, the make-up pump **212** may be used to supply the needed liquid. When the liquid level drops to a predetermined level within the diversion tank **206**, the pump **212** will start and fill the tank **206** back to a desired level. Thus, a supply of liquid may be maintained in the diversion tank **206** which may be pumped into the heat exchanger **166** to assist in preparing the plant **102** for the liquid production process. In other words, the cryogenic liquid in the diversion tank **206** may be used provide cooling during in the final stages of the heat exchanger **166** in order to reduce the temperature of what becomes the compressed product stream **154"** to temperatures required for liquid production.

[0082] In one embodiment, the flow of liquid from the diversion tank **206** to the heat exchanger may be controlled based on the temperature of the product stream **154"**. Thus, for example, as the temperature of the product stream **154"** becomes warmer, the pump **210** may provide additional flow of liquid from the diversion tank **206** to the heat exchanger **166**. Additionally, as the temperature of the product stream **154"** decreases, the pump **210** may be controlled to reduce the amount of liquid being provided to the heat exchanger **166**. The pump **210** may be configured as a variable flow pump and controlled, for example, by a proportional, integral, derivative (PID) controller.

[0083] Referring back to the hydrocyclones **192A** and **192B**, the thickened slush formed in the hydrocyclone (e.g., **192A**) exits the underflow **194A** and passes through piping **213A** to a sublimation tank **214**. The sublimation tank **214** may include, for example, a heat exchanger configured to convert the solid CO_2 to a gaseous state.

[0084] In one particular embodiment, the sublimation tank **214** may include a tube-in-shell heat exchanger such as that which is disclosed in the priority applications and patents previously incorporated by reference. The slush may enter such a heat exchanger on the tube side thereof. In one embodiment, the slush entering the sublimation tank **214** will include approximately 10% solid CO_2 by mass in a liquid carrier. Warm gas, for example, gas at a temperature

of approximately 100° F., may flow through the sublimation tank **214** by way of a flow path **216** from the heat exchanger **166**, or from some other location, to heat the slush and effect sublimation of the solid CO_2 .

[0085] It has been determined that, in natural gas mixtures found in conventional U.S. pipelines, CO_2 becomes a solid at approximately -160° F. at approximately 35 psig. However, once the CO_2 has frozen, it no longer follows the phase change path it would when found in the natural gas mixture. Instead, the solid CO_2 acts as pure CO_2 which sublimates at approximately -80° F. and at approximately 35 psig.

[0086] As the slush enters the sublimation tank **214**, the liquid carrier violently flashes to a gas which, in addition to transferring heat to the solid CO_2 , provides a positive motive flow for the solid CO_2 . Due to the turbulent nature of the flow, the CO_2 constantly interacts with the tube walls as it progresses through the tubes. Additionally, the tube walls become progressively warmer along the flow path of the CO_2 . Once all of the liquid has flashed to a gas and warmed to approximately -80° F., the CO_2 will start to sublime, aided by the relatively warm tube walls and the warmed gases. It is noted that the sublimation tank **214** may be configured such that the warm gas from stream **216** will warm all areas of the shell (when configured as a tube-in-shell heat exchanger) to a temperature above the sublimation temperature of the CO_2 . In this manner, the sublimation tank becomes "self-thawing" in the case of any potential plugs caused by the solid CO_2 passing through the tube side thereof.

[0087] The gas leaving the sublimation tank (including both the warming gas and the sublimed CO_2) may be routed back to the expanded cooling stream **152'** to assist in cooling the compressed process stream **154'** in heat exchanger **166**.

[0088] As previously noted hereinabove, the plant **102** may include a recompression compressor **228**. The recompression compressor **228** may be used to recompress gas to a desired pressure prior to reintroduction of the gas into the pipeline **104** (or other receiving station or system) or prior to the recirculation of gases into the plant **102** for reprocessing thereof. Gas from the separator **180** and from the storage tank **116** may be used, for example, as fuel for a combustion engine that drives the recompression compressor **228**.

[0089] It is noted that, while not specifically shown, a number of valves may be placed throughout the liquefaction plant **102** for various purposes such as facilitating physical assembly and startup of the plant **102**, maintenance activities, or for collecting of material samples at desired locations throughout the plant **102** as will be appreciated by those of ordinary skill in the art.

[0090] It is further noted that the plant **102** may be configured as a relatively compact structure such as described in the applications and patents previously incorporated by reference. Generally, the plant **102** may be constructed on one or more skids for simple transportation and erection of the plant **102**.

[0091] The plant **102** may further include controls such that minimal operator input is required for the operation of the plant **102**. Indeed, it may be desirable that the plant be able to function without an on-site operator. Thus, with proper programming and control design, the plant may be

accessed through remote telemetry for monitoring and/or adjusting the operations of the plant. Similarly, various alarms may be built into such controls so as to alert a remote operator or to shut down the plant in an upset condition. One suitable controller, for example, may be a DL405 series programmable logic controller (PLC) commercially available from Automation Direct of Cumming, Ga.

[0092] Reviewing now the operation of the plant 102 and considering various control aspects thereof, when the plant 102 is started, the JT valves 174 and 176 are closed such that the product stream 154" is diverted back into the heat exchanger 166 after passing through a JT valve 230. This produces a cooling stream that may be used to cool the heat exchanger 166 until the temperature of the product stream 154" approaches approximately -90° F. at a pressure of approximately 800 psig. When starting, the expander 156/compressor 158 will be manually accelerated at a rate that corresponds with approximately 2° F. per minute temperature reduction in the heat exchanger 166. This acceleration may stop when the pressure of the compressed process stream 154' builds to approximately 800 psig. If the pressure of the pipeline 104 or other source is running at a pressure of approximately 800 psig, use of the compressor 158 may not be necessary. However, the compressor 158 may be started to provide a desired boost in pressure to the process stream 154.

[0093] Prior to closing the JT valve 230 in the cooling stream and opening valves 174 and 176, the diversion tank 206 may be filled with liquid from the storage tank 116. The flow may simply fill the diversion tank 206 or it may recirculate back into the storage tank 116. When the temperature of the product stream 154" reaches a desired temperature, the flow of product stream 154" is routed to the separator 180. At this time the diversion tank pump 210 will start pumping liquid from the diversion tank 206 to the heat exchanger 166 to aid in the final and rapid cooling of the compressed process stream 154'.

[0094] Switching the flow of the product stream 154" into the separator 180 will prevent CO_2 from building up in the heat exchanger 166. It is noted that CO_2 formation begins when the pressure drops from approximately 800 psig at approximately -160° F. to a pressure of approximately 35 psig at a temperature of approximately -220° F. The initially warm tank of the separator 180 will flash the small amount of liquid and CO_2 to a gas, as the temperature of the product stream 154" decreases. Decreased temperatures in the product stream 154" result in the production of additional liquid. The liquid quality will also improve as the temperature drops and the CO_2 will be suspended in the liquid as the tank of the separator 180 cools to a point at which the liquid remains.

[0095] If the separator 180 should fill before the temperature of the product stream is within the desired range, the separator 180 may be flushed. Flushing the cold liquid into the warm transfer tanks 190A and 190B will boil off most of the liquid and any remaining liquid may be used to continue cooling off various components of the plant 102. As the temperature of the product stream 154" reaches a desired range of, for example, approximately -180° F. to approximately -200° F., the expander 156 will have been accelerated to a desired operational speed.

[0096] During operation of the plant 102, the relationship between the "back-end flow loop" and the "cooling loop"

may be used as the basis for the liquid production and control of the plant 102. The back-end flow loop generally refers to the flow of fluid through the liquid handling components of the plant and particularly the flow through the valve or valves (e.g., valves 174 and 176) leading into the gas-liquid separator 180. The cooling loop refers generally to flow of fluid that provides cooling via the heat exchanger 166 during normal operating conditions and particularly includes the flow of liquid from the diversion tank 206. Further details regarding the control of the plant 102 are set forth in the various U.S. patents and U.S. patent applications previously incorporated by reference including, for example, U.S. patent application Ser. No. 11/383,411 filed on May 15, 2006 previously incorporated by reference.

[0097] Referring now to FIG. 3, a process flow diagram is shown which is representative of another embodiment of a liquefaction plant 102'. The plant 102' is similar to the plant 102 previously discussed herein with respect to FIG. 2 and similar components and flow paths are identified using similar reference numerals.

[0098] It is noted that the plant 102 discussed with respect to FIG. 2 utilizes a substantial portion of the gas for cooling of the process/product streams. In one example, depending on scale of the plant 102 and the specific design implemented, such a plant 102 might produce between approximately 6,000 to approximately 40,000 volumetric gallons of liquid product per day. This output may represent a production rate of approximately 6% to approximately 20% of the gas that is introduced into the plant 102. The balance of the gas entering the plant 102 that is not liquefied product is used primarily for refrigeration of the liquefied product. Of the gas being used as a refrigerant, up to approximately 40% may be liquefied with approximately 20% being returned to the plant 102 for use in the cooling required to convert the gas to a liquid and, therefore, is not available to be utilized as liquid product. Stated another way, approximately half of the total liquid produced by the plant may be required for refrigeration purposes and is discharged to the receiver (e.g., pipeline, reservoir or other receiving station). Such a configuration can pose limits on the amount of liquid a plant 102 is able to produce. Such a configuration may also be limited by the size of receiver (e.g., pipeline, reservoir or other receiving station) that receives gas (also referred to as tail gas) from the outlet 132 of the plant 102.

[0099] The plant 102' shown and described with respect to FIG. 3 reduces the amount of gas required for refrigerant purposes, resulting in higher liquefied product volumes, and provides additional flexibility in site location of the plant 102', including the ability to install and operate the plant 102' at a location where tail gas reservoirs or receivers are limited or smaller than desired for operating previously described plants (e.g., plant 102).

[0100] Upon entry into the liquefaction plant 102', the feed gas 140 may flow through a filter 142 such as previously discussed. After the feed gas 140 flows through the filter 142, it may flow through a compressor 144, if necessary, to raise the pressure of the feed gas 140 to a desired level. If the pressure of the feed gas 140 entering the inlet 112 is sufficient, the feed gas 140 may be routed around the compressor 144.

[0101] A water clean-up cycle may again be incorporated into the plant 102. In one example, a water clean-up cycle

may include a source of methanol **146**, or some other water absorbing product, which is injected into the feed gas **140**, such as, for example, by means of a pump, at a location relatively early in the flow of feed gas **140** through the plant **102**. Other possible water clean-up methods are also contemplated as will be appreciated by those of ordinary skill in the art.

[0102] Subsequent any desired compression of the feed gas **140** and any injection of methanol or other water absorbing materials thereinto, the feed gas **140** is split into a cooling stream **152** and a process stream **154**. In one embodiment, the cooling stream **152** enters a turbo expander **156** at a pressure of approximately 840 psig and at a temperature of approximately 60° F. and is expanded to form an expanded cooling stream **152'** exhibiting a lower pressure, for example approximately 50 psig, and a reduced temperature of, for example, approximately -140° F. As will be seen hereinbelow, the expanded cooling stream **152'** is a cold mass of fluid that provides cooling during the process of producing liquefied gas.

[0103] The turbo expander **156** is a turbine which expands the gas and extracts power from the expansion process. A rotary compressor **158** may be coupled to the turbo expander **156** by mechanical means, such as through a shaft **160**, so as to utilize the power generated by the turbo expander **156** to compress the process stream **154**. In one embodiment, the reduction of pressure from the transmission line or pipeline **104** to a distribution pressure, effected by the turbo expander **156**, provides the majority of the energy used in the plant **102** making it extremely economical to operate the plant **102**.

[0104] By compressing the process stream **154**, a larger volume of produced liquid will be realized. Additionally, elevated pressures help to keep any CO₂ contained within the process stream **154** from plugging the various downstream flow paths.

[0105] The proportion of gas in each of the cooling and process lines **152** and **154** may be determined by the power requirements of the compressor **158** as well as the flow and pressure drop across the turbo expander **156**. Vane control valves within the turbo expander **156** may be used, to a certain extent, to control the proportion of gas between the cooling and process lines **152** and **154**. Additionally, some flow adjustments through the compressor **156** and expander **158** may be effected by altering the downstream pressure through adjustment of the JT valves **174** and **176**. For example, adjusting the valves **174** and **176** to increase the pressure within the product stream **154"** results in a reduced flow through the compressor **156**. In one embodiment, the feed gas **140** may be proportioned substantially evenly between the cooling and process lines **152** and **154**.

[0106] The expander/compressor system may also be fitted with gas bearings. Such gas bearings may be supplied with gas through a supply line **155** which draws a portion of the feed gas therethrough. However, the portion of gas directed to any such gas bearing is relatively insubstantial as compared to the mass of gas flowing through the cooling and process lines **152** and **154**. In another embodiment, gas bearings may be supplied by a separate flow of gas such as nitrogen. In yet another embodiment, the expander/compressor system may be fitted with other types of bearings including, for example, magnetic or oil bearings.

[0107] Bypass piping **162** routes the cooling stream **152** around the turbo expander **156**. Likewise, bypass piping **164** routes the process stream **154** around the compressor **158**. The bypass piping **162** and **164** may be used during startup of the plant **102** to bring certain components to a steady state condition prior to the processing of LNG within the liquefaction plant **102**. Additionally, if the pressure of the feed gas **140** is sufficient, the compressor **158** need not be used and the process stream may continue through the bypass piping **164**. In such a case, the compressor **156** could be replaced by a generator or other device to take advantage of the power produced by the expander **158**.

[0108] In one embodiment, the heat exchanger **166** is a high efficiency heat exchanger made from aluminum. In start-up situations it may be desirable to reduce the temperature of such a heat exchanger **166** by, for example, as much as approximately 1.8° F. per minute until a defined temperature limit is achieved. During start-up of the liquefaction plant **102**, the temperature of the heat exchanger **166** may be monitored as it incrementally decreases. The JT valve **163** and other valving or instruments may be controlled in order to effect the rate and pressure of flow in the cooling stream **152** and process stream **154'** which ultimately controls the cooling rate of heat exchanger **166** and/or other components of the liquefaction plant.

[0109] Additionally, during start-up, it may be desirable to have an amount of LNG already present in the tank **116** (FIG. 1). Some of the LNG may be cycled through the system in order to cool various components if so desired or deemed necessary. Also, as will become apparent upon reading the additional description below, other cooling devices, including additional JT valves, located in various "loops" or flow streams may likewise be controlled during start-up in order to cool down the heat exchanger **166** or other components of the liquefaction plant **102**.

[0110] When the plant **102** or liquefaction system is in a steady state condition, the process stream **154** flows through the compressor **158** raising the pressure of the process stream **154**. The compression process is not thermodynamically ideal and, therefore, adds heat to the process stream **154** as it is compressed. Thus, the compressed process stream is subjected to one or more cooling processes including, for example, a heat exchange process carried out in heat exchanger **166**. It is noted that, if the heat of compression is too high, the gas may be precooled, for example, by an ambient heat exchanger prior to its entry into the heat exchanger **166**. The heat exchanger **166** may include a high efficiency heat exchanger and, in one embodiment, may be formed as a countercurrent flow, plate and fin type heat exchanger. Additionally, the plates and fins may be formed of a highly thermally conductive material such as, for example, aluminum. In one embodiment, the high efficiency heat exchanger **166** may include a multipass, plate and fin heat exchanger such as is available from Chart Industries, Inc. of La Crosse, Wis.

[0111] If methanol or some other component is used to absorb water in the incoming gas stream, the methanol and water may be removed from the flow at a location about midway through the heat exchange process as previously described herein.

[0112] After exiting the heat exchanger **166**, the cooled, compressed process stream **154"** (referred to hereinafter as

the product stream 154" for purposes of convenience) flows through a second heat exchanger 300 that is associated with a refrigeration system 302. The refrigeration system includes a refrigerant loop 304 that maintains the refrigerant separate and independent from the flow of any gas within the plant 102'. In other words, the refrigerant being used in the refrigerant loop 304 does not include any of the gas introduced into the plant 102' through the inlet 112. The refrigerant in the refrigerant loop 304 does not come into physical contact with, or otherwise intermix with the various gas or liquid streams of the plant 102' (i.e., cooling stream 152, expanded cooling stream 152', process stream 154, compressed process stream 154', product stream 153", the liquid streams flowing from the hydrocyclones 192A and 192B through the filters 200A and 200B to the storage tank 116, or the slush streams flowing from the hydrocyclones 192A and 192B to the sublimation tank 214). Various types of refrigerants and refrigeration components may be utilized depending on cooling requirements of the plant 102' as will be recognized by those of ordinary skill in the art. For example, refrigerants such as propane, ethane, methane, or nitrogen may be used. Cycles such as mixed refrigerant or cascade cycles may also be employed.

[0113] The combination of the high efficiency heat exchanger 166 and the second heat exchanger serve to remove heat from the compressed process stream 154', to a very low temperature, for example between approximately -185° F. and approximately -200° F. at a pressure, for example, of approximately 1,100 psig. The heat exchangers 166 and 300 are positioned and configured to efficiently transfer as much heat as possible away from the compressed process stream 154' and product stream 154" as it passes through such heat exchangers 166 and 300. The liquefaction plant 102' is desirably configured such that temperatures generated within the heat exchangers 166 and 300 are never low enough to generate solid CO₂ which may be present in the feed gas 140, and which formation of solid CO₂ might result in blockage in the flow path of the compressed process stream 154' or product stream 154".

[0114] During start up, it may be desirable to flow a portion of the product stream 154" back through the heat exchanger 166 to help bring the plant 102', and various components thereof, to a steady state operating temperature. In one embodiment, the portion may be flowed through a JT valve 230 to expand the gas and provide additional cooling. Depending on the cooling requirements, the portion of gas may be split from the product stream 154" at a location prior to the second heat exchanger 300 (such as shown by dashed lines) or at a location subsequent the second heat exchanger 300.

[0115] When in a steady state operating condition, after flowing through the second heat exchanger 300, the product stream 154" flows through two expansion valves, such as JT valves 174 and 176 and into a liquid/vapor separator 180 (although a different number of valves may be utilized). As previously described, the two valves 174 and 176 may be arranged in a parallel flow configuration and work in concert with one another to control the flow of the product stream 154" into the separator 180. As the gas expands through the valves, a Joule-Thomson effect reduces the temperature and pressure from, for example, approximately 1100 psig at approximately -185° F. to approximately 35 psig and approximately -230° F. (which is the saturation temperature

and pressure for the liquid). This pressure drop also precipitates solid CO₂. The three phase (gas, liquid, and solid CO₂) mixture exiting the valves is collected in the separator tank 180 wherein a liquid/solid slurry is formed and the gas or vapor is separated from the liquid/solid slurry.

[0116] An accumulator 177 may be coupled with the product stream 154" at a location upstream from the valves 174 and 176 to further dampen flow pulses that may be introduced into the stream 154" by the valves 174 and 176. A pressure sense line 178 may extend between the accumulator 177 and the product stream 154" and may be buffered by a restrictive valve 179. Additionally, the accumulator 177 may be directly coupled to the product stream 154".

[0117] When the product stream 154" passes through the expansion valves 174 and 176, the stream follows a constant enthalpy pressure drop that changes from a high pressure, single phase mixture at a high pressure and low temperature (e.g., approximately 1,100 psig and approximately -200° F.) to three phases (solid, liquid and gas) with approximately 10% to 28% mass flow being vapor, at a reduced pressure of, for example, 35 psig. The solid component includes solid CO₂. The vapor component from the separator 180 is collected and removed therefrom through piping 182 and is routed back to the heat exchanger 166 to provide additional cooling by way of a compressor 186. While shown to be located on the warm side of the heat exchanger 166, the compressor 186 could be positioned on the cold side of the heat exchanger 166, although such positioning might require the compressor to be configured as a cryogenic compressor. In one embodiment, the compressor 186 may be powered by an internal combustion engine driven by a portion of the natural gas flowing through the plant 102. In another embodiment, the compressor 186 may be powered by electricity or other means as will be appreciated by those of ordinary skill in the art. It is further noted that an ejector or an eductor might be utilized in place of the compressor 186 in other embodiments.

[0118] To maintain the separator 180 at a desired pressure, for example at approximately 35 psig, the compressor 186 may be used to recompress the excess gas from the separator 180 to pressures suitable, for example, for introduction of the gas into the heat exchanger 166. For example, the compressor 186 may be used to increase the pressure of the gas from approximately 35 psig to approximately 50 psig. The compressor 186 may also be coupled to a vent line associated with the storage tank 116 to likewise help maintain the pressure within storage tank 116 at substantially the same pressure as that of the separator 180.

[0119] A make up line 187 having a regulator 188 may be routed around the compressor 186 to prevent flow surges as may be the case when gas flow from the separator 180 and or storage tank 116 is relatively low. The pressure of such a regulator may be set at a level that is just under the desired saturation pressure for the separator 180. In one embodiment, a floating ball check valve may also be installed in the suction line of the compressor 186 to prevent a sudden surge of liquid. If the compressor 186 is located on the cold side of the heat exchanger 166, the floating ball check valve may also be used to prevent any accumulated liquid from entering the suction side of the pump. It is noted that if the compressor 186 is located on the warm side of the heat exchanger 166, no liquid will be present at the suction side of the compressor 186 under normal operating conditions.

[0120] A back-pressure regulator may be located in the vapor piping **182** to also help control the pressure within the separator **180**. In one example, the back pressure regulator **184** may be configured with set-point of approximately 35 psig so as to create a saturation pressure of the liquid that is below a desired transfer pressure (i.e., the pressure used to transfer liquid from the separator **180** to other components within the plant **102**).

[0121] In one embodiment, and as previously described with respect to other embodiments, the storage tank **116** may be maintained at substantially the same pressure as that of the separator **180**. By maintaining the liquid saturation pressure below associated transfer pressures, the liquid is prevented from boiling when the liquid experiences a pressure drop such as will occur when the liquid flows through piping, valves and other equipment as it is transferred from the separator **180**. The pressure difference between the separator **180** (e.g., approximately 35 psig) and a transfer pressure may be specified such that it is sufficient to ensure that any and all line pressure drops encountered en route to the storage tank **116** are accounted for. The liquid will then arrive at the storage tank **116** at saturation pressure, minimizing loss and flow complications that might otherwise occur due to boiling of the liquid during the transfer thereof.

[0122] As noted above, solid CO₂ mostly forms as small crystals in the liquid as it exits the JT valves **174** and **176**. With the appropriate resident time in the liquid, the CO₂ becomes a sub-cooled solid particle. In the sub-cooled state the particles are less likely to clump together. Keeping the particles suspended in the liquid provides more effective and efficient transfer and separation of the solids from the liquid component. To aid in keeping the CO₂ particles suspended in the liquid, gas bubbles may be introduced into the bottom of the separator **180** in a manner similar to that previously described.

[0123] As the separator **180** is filled, the level may be monitored by appropriate sensors. The level of the liquid/solid within the separator **180** may be desirably monitored and controlled in order to provide desired resident times for the CO₂ and thereby ensure that the CO₂ particles are subcooled. When a specified maximum level of liquid/solid slurry is reached within the separator **180**, the liquid/solid slurry will be transferred to at least one of a plurality of transfer tanks **190A** and **190B** such as previously described.

[0124] When the separator **180** has reached its specified maximum level, two valves will open allowing the fluid to move into one of the transfer tanks (e.g., transfer tank **190A** for purposes of the present discussion). The first valve **220A** allows the transfer of liquid/CO₂ slurry, while the second valve **222A** vents the transfer tank **190A** back to the separator **180** enabling the captured gases in the transfer tank **190A** to escape as it is being filled with the slurry. Depending, for example, on the length of the piping run between the separator **180** and the transfer tank **190A**, bubbler locations may be added to the bottom of the pipe to prevent the CO₂ from settling during the transfer of the slurry (similar to that which has been previously described with respect to the separator **180**). It is noted that a single valve may be utilized instead of multiple valves if the single valve is properly located (e.g., physically below the separator **180**).

[0125] When the level in the separator **180** tank is reduced to a specified minimum level, the valves **220A** and **222A** to

the transfer tank **190A** close. The liquid CO₂ transfer alternates between the two transfer tanks associated with the SGL tank. Once the valves connecting the separator **180** and transfer tank **190A** are closed the liquid/CO₂ mixture is ready to be transferred to the hydrocyclone separator. The pressure sensitive hydrocyclone separates the CO₂ from the liquid by cyclonic action. The transfer tank is pressurized to the desired pressure and the transfer valve is opened. The transfer pressure is approximately 20 psi higher than the saturation pressure of the liquid. This pressure head provides the motive force for the liquid/CO₂ mixture, prevents the liquid from boiling as pressure drops are realized, and prevents the formation of additional CO₂ that could occur if the pressure were to drop below saturation pressure.

[0126] The transfer tank (considering tank **190A** as an example) is pressurized by use of a pressure regulator **224** which is set at a desired transfer pressure. If the feed line to the transfer tank **190A** is sufficient and the regulator **224** is large enough, a regulator **224** can be mounted directly on the transfer tank **192A**. This would require one regulator for each tank. However, in another embodiment, both transfer tanks **190A** and **190B** could be maintained with a smaller feed line and a single regulator **224** as shown in FIG. 3. Use of a single regulator may require the use of storage or accumulator tanks (e.g., **226A**) to ensure that the proper volume of gas is used so as to maintain a constant pressure during the complete transfer process. It is noted that the gas used to transfer the liquid will be warmer than the liquid/solid slurry being transferred. As such, any heat transfer effects are accounted for in configuring and sizing the regulator(s) **224A** and accumulator tank(s) **226A**.

[0127] As previously noted, the liquid/solid slurry is transferred to, and processed by, one of the hydrocyclones **192A** and **192B**. The hydrocyclones **192A** and **192B** act as separators to remove the solid CO₂ from the slurry allowing the LNG or other liquid product to be collected and stored in a manner similar to that previously described herein in association with other embodiments.

[0128] Generally, the liquid natural gas flows through the overflow **196A** of the hydrocyclone **192A** and may flow through one of a plurality of filters **200A** and **200B** placed in a parallel flow configuration. The filters **200A** and **200B** capture any remaining solid CO₂ which may not have been separated out in the hydrocyclone **192A**. The filters **200A** and **200B** may be configured such as substantially described in the priority patent applications and patents that have been incorporated by reference.

[0129] The filters **200A** and **200B** may, from time to time, become clogged or plugged with solid CO₂ captured therein. Thus, as one filter, i.e., **200A**, is being used to capture CO₂ (or other solids) from the liquid stream, the other filter, i.e., **200B**, may be purged of CO₂ by passing a relatively high temperature natural gas therethrough in a counter flowing fashion. For example, gas may be drawn from a relatively warmer gas stream, as indicated at interface points **202B** (or **202A** for filter **200A**) and **202C** to flow through and clean the filter **200B** as has been previously described. The filtered liquid passes from the filter **200A** (or **200B**) to the storage tank.

[0130] It is noted that, in the presently described embodiment, the plant **102'** does not include a diversion tank (e.g., diversion tank **206** in FIG. 2) or a make-up pump (e.g.,

make-up pump 210 in FIG. 2) since none of the liquid produced by the plant 102' is being returned or recycled to act as a refrigerant. Rather, the refrigeration system 302 described above is configured to provide adequate cooling such that all of the liquid produced by the plant 102' may be collected as a product.

[0131] Referring briefly back to the hydrocyclones 192A and 192B, the thickened slush formed in the hydrocyclone (e.g., 192A) exits the underflow 194A and passes through piping 213A to a sublimation tank 214 in a manner similar to that which has been previously described herein.

[0132] The gas leaving the sublimation tank (including both the warming gas and the sublimed CO₂) may be routed back to the expanded cooling stream 152' to assist in cooling the compressed process stream 154' in heat exchanger 166.

[0133] As previously noted hereinabove, the plant 102' may include a recompression compressor 228. The recompression compressor 228 may be used to recompress gas to a desired pressure prior to reintroduction of the gas into the pipeline 104 (or other receiving station, reservoir or system) or prior to the recirculation of gases into the plant 102 for reprocessing thereof. Gas from the separator 180 and from the storage tank 116 may be used, for example, as fuel for a combustion engine that drives the recompression compressor 228.

[0134] It is noted that, while not specifically shown, and as with other embodiments described herein, a number of valves may be placed throughout the liquefaction plant 102' for various purposes such as facilitating physical assembly and startup of the plant 102', maintenance activities, or for collecting of material samples at desired locations throughout the plant 102' as will be appreciated by those of ordinary skill in the art.

[0135] It is further noted that the plant 102' may also be configured as a relatively compact structure such as described in the applications and patents previously incorporated by reference. Generally, the plant 102' may be constructed on one or more skids for simple transportation and erection of the plant 102'.

[0136] As with other embodiments, the plant 102' may include a variety of controls for effective and efficient operation thereof. Examples of various control schemes are described in association with other embodiments set forth in the present application as well as the various patents and patent applications that have been incorporated by reference herein.

[0137] The liquefaction processes depicted and described herein with respect to the various embodiments provide for low cost, efficient and effective means of producing LNG without the requisite "purification" of the gas before subjecting the gas to the liquefaction cycle. Such enable the use of relatively "dirty" gas typically found in transmission and distribution lines, eliminates the requirement for expensive pretreatment equipment and provides a significant reduction in operating costs for processing such relatively "dirty" gas.

[0138] It is noted that, while the invention has been disclosed primarily in terms of liquefaction of natural gas, the present invention may be utilized simply for removal of gas components, such as, for example, CO₂ from a stream of relatively "dirty" gas. Additionally, other gases, such as for

example, hydrogen, may be liquefied and processed, and other gas components, such as, for example, nitrogen, may be removed from a given feed gas. Thus, the present invention is not limited to the liquefaction of natural gas and the removal of CO₂ therefrom. It is also noted that various teachings set forth in the documents incorporated by reference herein may be combined with one or more of the embodiments described herein and that the described embodiments are not limited by their specific examples.

[0139] While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention includes all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims.

What is claimed is:

1. A method of producing liquid natural gas, the method comprising:

providing a source of unpurified natural gas and flowing a portion of the natural gas from the source;

dividing the portion of natural gas into at least a process stream and a cooling stream;

flowing the process stream sequentially through a compressor and a first side of at least one heat exchanger,

flowing at least a portion of the process stream from the at least one heat exchanger through at least one expansion device and into a liquid-gas separator;

flowing the cooling stream sequentially through an expander and a second side of the at least one heat exchanger;

flowing a refrigerant in a heat exchange relationship with the process stream at a location of flow between the compressor and the liquid-gas separator; and maintaining the refrigerant separate from the process stream and the cooling stream.

2. The method according to claim 1, wherein flowing at least a portion of the process stream from the at least one heat exchanger through an expansion device and into a liquid-gas separator further includes flowing the at least a portion of the process stream sequentially from the at least one heat exchanger through the first side of a second heat exchanger, through the at least one expansion device and into the liquid-gas separator.

3. The method according to claim 2, wherein flowing a refrigerant in a heat exchange relationship with the process stream at a location of flow between the compressor and the liquid-gas separator further includes flowing the refrigerant through the second side of the second heat exchanger.

4. The method according to claim 3, wherein flowing the at least a portion of the process stream through an expansion device includes flowing the at least a portion of the process stream through at least two expansion valves.

5. The method according to claim 4, further comprising arranging the at least two expansion valves in a parallel flow configuration.

6. The method according to claim 5, further comprising configuring a first expansion valve of the at least two

expansion valves to exhibit a first flow capacity (Cv) and configuring a second valve of the at least two expansion valves to exhibit a second Cv, different from the first Cv.

7. The method according to claim 6, further comprising flowing approximately 80% of the at least a portion of the process stream through the first expansion valve of the at least two expansion valves.

8. The method according to claim 7, further comprising flowing the remainder of the at least a portion of the process stream through the second expansion valve of the at least two expansion valves.

9. The method according to claim 1, further comprising producing a slurry of liquid natural gas and solid carbon dioxide from the at least a portion of the process stream within the liquid-gas separator.

10. The method according to claim 9, further comprising agitating the slurry to keep the solid carbon dioxide substantially suspended within the liquid natural gas.

11. The method according to claim 10, wherein agitating the slurry further includes bubbling a gas through the slurry.

12. The method according to claim 11, further comprising transferring at least a portion of the slurry from the liquid-gas separator to at least one transfer tank.

13. The method according to claim 12, wherein transferring at least a portion of the slurry from the liquid-gas separator to at least one transfer tank further comprises selectively transferring at least a portion of the slurry from the liquid-gas separator to a plurality of transfer tanks.

14. The method according to claim 13, further comprising flowing the at least a portion of the slurry from at least one of the plurality of transfer tanks to at least one hydrocyclone.

15. The method according to claim 14, wherein flowing the at least a portion of the slurry from at least one of the plurality of transfer tanks to at least one hydrocyclone further comprises selectively flowing the at least a portion of slurry from at least one of the plurality of transfer tanks to a plurality of hydrocyclones.

16. The method according to claim 15, further comprising flowing a slush that is rich in solid carbon dioxide through an underflow of the at least one hydrocyclone to a sublimation tank.

17. The method according to claim 16, further comprising subliming the solid carbon dioxide to a gas.

18. The method according to claim 14, further comprising flowing liquid natural gas through an overflow of the hydrocyclone to a storage tank.

19. The method according to claim 18, further comprising flowing the liquid natural gas through at least one filter prior to flowing the liquid natural gas to the storage tank.

20. The method according to claim 19, further comprising flowing at least a portion of the cooling stream back into the source of unpurified natural gas.

21. The method according to claim 20, further comprising compressing the at least a portion of the cooling stream prior to flowing it into the source of unpurified natural gas.

22. The method according to claim 20, further comprising recirculating at least a portion of the cooling stream back into at least one of the cooling stream and the process stream.

23. The method according to claim 22, further comprising compressing the at least a portion of the cooling stream prior to recirculating it into at least one the cooling stream and the process stream.

24. The method according to claim 1, further comprising compressing the portion of the natural gas flowed from the source prior to dividing the portion of natural gas into at least a process stream and a cooling stream.

25. The method according to claim 1, wherein flowing at least a portion of the process stream sequentially from the at least one heat exchanger through the first side of a second heat exchanger, through an expansion device and into a liquid-gas separator includes flowing substantially all of the process stream sequentially from the at least one heat exchanger through the first side of a second heat exchanger, through the at least one expansion device and into the liquid-gas separator.

26. The method according to claim 25, further comprising producing a slurry of liquid natural gas and solid carbon dioxide from the at least a portion of the process stream within the liquid-gas separator.

27. The method according to claim 26, further comprising separating a vapor component from the slurry.

28. The method according to claim 27, further comprising substantially separating the liquid natural gas from the solid carbon dioxide.

29. The method according to claim 28, further comprising collecting and storing substantially all of the separated, liquid natural gas.

30. A liquefaction plant comprising:

a compressor;

a first expansion device;

a first heat exchanger;

at least a second expansion device;

a gas-liquid separator;

a first flow path defined and configured for sequential delivery of a first stream of gas through the compressor and a first side of the first heat exchanger;

a second flow path defined and configured for sequential delivery of a second stream of gas through the first expansion device and a second side of the first heat exchanger;

at least one additional flow path defined and configured for delivery of at least a portion of the first stream of gas from the first heat exchanger through the at least a second expansion device and into the gas-liquid separator; and

a refrigerant loop configured to flow a refrigerant stream in a heat exchange relationship with the first stream, wherein the refrigerant stream remains separate from the first stream and the second stream.

31. The liquefaction plant of claim 30, further comprising at least a second heat exchanger, and wherein the at least one additional flow path is defined and configured for sequential delivery of the at least a portion of the first stream of gas from the first heat exchanger through the first side of the second heat exchanger, through the at least a second expansion device and into the gas-liquid separator.

32. The liquefaction plant of claim 31, wherein the refrigerant loop is configured to flow the refrigerant stream through a second side of the second heat exchanger.

33. The liquefaction plant of claim 32, further comprising at least one transfer tank located and configured to receive a solid-liquid slurry from the gas-liquid separator.

34. The liquefaction plant of claim 33, wherein the at least one transfer tank includes at least two transfer tanks which are in selective communication with the gas-liquid separator.

35. The liquefaction plant of claim 33, further comprising at least one hydrocyclone in selective communication with the at least one transfer tank.

36. The liquefaction plant of claim 35, further comprising a storage tank in communication with an overflow of the at least one hydrocyclone.

37. The liquefaction plant of claim 36, wherein the at least one hydrocyclone includes at least two hydrocyclones and wherein the storage tank is in selective communication with each of the at least two hydrocyclones.

38. The liquefaction plant of claim 36, further comprising at least one filter disposed in a flow path between the at least one hydrocyclone and the storage tank.

39. The liquefaction plant of claim 38, further comprising a sublimation tank in communication with an underflow of the at least one hydrocyclone.

40. The liquefaction plant of claim 32, further comprising a recompression compressor configured to receive a flow of gas from the second side of the first heat exchanger.

41. The liquefaction plant of claim 40, further comprising a further flow path extending from the recompression compressor to an exit of the plant.

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