

**NATURAL GAS LIQUEFACTION BY A HIGH PRESSURE EXPANSION PROCESS  
USING MULTIPLE TURBOEXPANDER COMPRESSORS**

CROSS REFERENCE TO RELATED APPLICATION

- 5   **[0001]**    This application claims the priority benefit of U. S. Provisional Application No. 62/576,989, filed October 25, 2017 entitled "Natural Gas Liquefaction by a High Pressure Expansion Process Using Multiple Turboexpander Compressors," the entirety of which is incorporated herein.

BACKGROUND

10    Field of Disclosure

**[0002]**    The disclosure relates generally to liquefied natural gas (LNG) production. More specifically, the disclosure relates to LNG production at high pressures.

Description of Related Art

- 15    **[0003]**    This section is intended to introduce various aspects of the art, which may be associated with the present disclosure. This discussion is intended to provide a framework to facilitate a better understanding of particular aspects of the present disclosure. Accordingly, it should be understood that this section should be read in this light, and not necessarily as an admission of prior art.

- 20    **[0004]**    Because of its clean burning qualities and convenience, natural gas has become widely used in recent years. Many sources of natural gas are located in remote areas, which are great distances from any commercial markets for the gas. Sometimes a pipeline is available for transporting produced natural gas to a commercial market. When pipeline transportation is not feasible, produced natural gas is often processed into liquefied natural gas (LNG) for transport to market.

- 25    **[0005]**    In the design of an LNG plant, one of the most important considerations is the process for converting the natural gas feed stream into LNG. Currently, the most common liquefaction processes use some form of refrigeration system. Although many refrigeration cycles have been used to liquefy natural gas, the three types most commonly used in LNG plants today are: (1) the "cascade cycle," which uses multiple single component refrigerants in  
30    heat exchangers arranged progressively to reduce the temperature of the gas to a liquefaction temperature; (2) the "multi-component refrigeration cycle," which uses a multi-component

refrigerant in specially designed exchangers; and (3) the "expander cycle," which expands gas from feed gas pressure to a low pressure with a corresponding reduction in temperature. Most natural gas liquefaction cycles use variations or combinations of these three basic types.

[0006] The refrigerants used in liquefaction processes may comprise a mixture of components such as methane, ethane, propane, butane, and nitrogen in multi-component refrigeration cycles. The refrigerants may also be pure substances such as propane, ethylene, or nitrogen in "cascade cycles." Substantial volumes of these refrigerants with close control of composition are required. Further, such refrigerants may have to be imported and stored, which impose logistics requirements, especially for LNG production in remote locations.

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10 Alternatively, some of the components of the refrigerant may be prepared, typically by a distillation process integrated with the liquefaction process.

[0007] The use of gas expanders to provide the feed gas cooling, thereby eliminating or reducing the logistical problems of refrigerant handling, is seen in some instances as having advantages over refrigerant-based cooling. The expander system operates on the principle that the refrigerant gas can be allowed to expand through an expansion turbine, thereby performing work and reducing the temperature of the gas. The low temperature gas is then heat exchanged with the feed gas to provide the refrigeration needed. The power obtained from cooling expansions in gas expanders can be used to supply part of the main compression power used in the refrigeration cycle. The typical expander cycle for making LNG operates at the feed gas pressure, typically under about (1,000 psia). Supplemental cooling is typically needed to fully liquefy the feed gas and this may be provided by additional refrigerant systems, such as secondary cooling and/or sub-cooling loops. For example, U. S. Pat. No. 6,412,302 and U. S. Pat. No. 5,916,260 present expander cycles which describe the use of nitrogen as refrigerant in the sub-cooling loop.

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[0008] Previously proposed expander cycles have all been less efficient thermodynamically, however, than the current natural gas liquefaction cycles based on refrigerant systems. Expander cycles have therefore not offered any installed cost advantage to date, and liquefaction cycles involving refrigerants are still the preferred option for natural gas liquefaction.

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[0009] Because expander cycles result in a high recycle gas stream flow rate and high inefficiency for the primary cooling (warm) stage, gas expanders have typically been used to further cool feed gas after it has been pre-cooled to temperatures well below -20 °C using an external refrigerant in a closed cycle, for example. Thus, a common factor in most proposed

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expander cycles is the requirement for a second, external refrigeration cycle to pre-cool the gas before the gas enters the expander. Such a combined external refrigeration cycle and expander cycle is sometimes referred to as a "hybrid cycle." While such refrigerant-based pre-cooling eliminates a major source of inefficiency in the use of expanders, it significantly reduces the benefits of the expander cycle, namely the elimination of external refrigerants.

**[0010]** U. S. Patent Application US2009/0217701 introduced the concept of using high pressure within the primary cooling loop to eliminate the need for external refrigerant and improve efficiency, at least comparable to that of refrigerant-based cycles currently in use. The high pressure expander process (HPXP), disclosed in U. S. Patent Application US2009/0217701, is an expander cycle which uses high pressure expanders in a manner distinguishing from other expander cycles. A portion of the feed gas stream may be extracted and used as the refrigerant in either an open loop or closed loop refrigeration cycle to cool the feed gas stream below its critical temperature. Alternatively, a portion of LNG boil-off gas may be extracted and used as the refrigerant in a closed loop refrigeration cycle to cool the gas stream below its critical temperature. This refrigeration cycle is referred to as the primary cooling loop. The primary cooling loop is followed by a sub-cooling loop which acts to further cool the feed gas. Within the primary cooling loop, the refrigerant is compressed to a pressure greater than 1,500 psia, or more preferably, to a pressure of approximately 3,000 psia. The refrigerant is then cooled against an ambient cooling medium (air or water) prior to being near isentropically expanded to provide the cold refrigerant needed to liquefy the feed gas.

**[0011]** Figure 1 schematically depicts an example of a known HPXP liquefaction system **100**, and is similar to one or more systems and processes disclosed in U. S. Patent Application US2009/0217701. In Figure 1, an expander loop **102** (i.e., an expander cycle) and a sub-cooling loop **104** are used. Feed gas stream **106** enters the HPXP liquefaction process at a pressure less than about 1,200 psia, or less than about 1,100 psia, or less than about 1,000 psia, or less than about 900 psia, or less than about 800 psia, or less than about 700 psia, or less than about 600 psia. Typically, the pressure of feed gas stream **106** will be about 800 psia. Feed gas stream **106** generally comprises natural gas that has been treated to remove contaminants using processes and equipment that are well known in the art.

**[0012]** In the expander loop **102**, a compression unit **108** compresses a refrigerant stream **109** (which may be a treated gas stream) to a pressure greater than or equal to about 1,500 psia, thus providing a compressed refrigerant stream **110**. Alternatively, the refrigerant stream **109** may be compressed to a pressure greater than or equal to about 1,600 psia, or greater than or

equal to about 1,700 psia, or greater than or equal to about 1,800 psia, or greater than or equal to about 1,900 psia, or greater than or equal to about 2,000 psia, or greater than or equal to about 2,500 psia, or greater than or equal to about 3,000 psia, thus providing compressed refrigerant stream **110**. After exiting compression unit **108**, compressed refrigerant stream **110** is passed to a cooler **112** where it is cooled by indirect heat exchange with a suitable cooling medium to provide a compressed, cooled refrigerant stream **114**. Cooler **112** may be of the type that provides water or air as the cooling medium, although any type of cooler can be used. The temperature of the compressed, cooled refrigerant stream **114** depends on the ambient conditions and the cooling medium used, and is typically from about 35 °F. to about 105 °F. Compressed, cooled refrigerant stream **114** is then passed to an expander **116** where it is expanded and consequently cooled to form an expanded refrigerant stream **118**. Expander **116** is a work-expansion device, such as a gas expander, which produces work that may be extracted and used for compression. Expanded refrigerant stream **118** is passed to a first heat exchanger **120**, and provides at least part of the refrigeration duty for first heat exchanger **120**. Upon exiting first heat exchanger **120**, expanded refrigerant stream **118** is fed to a compression unit **122** for pressurization to form refrigerant stream **109**.

[0013] Feed gas stream **106** flows through first heat exchanger **120** where it is cooled, at least in part, by indirect heat exchange with expanded refrigerant stream **118**. After exiting first heat exchanger **120**, the feed gas stream **106** is passed to a second heat exchanger **124**. The principal function of second heat exchanger **124** is to sub-cool the feed gas stream. Thus, in second heat exchanger **124** the feed gas stream **106** is sub-cooled by sub-cooling loop **104** (described below) to produce sub-cooled gas stream **126**. Sub-cooled gas stream **126** is then expanded to a lower pressure in an expander **128** to form a liquid fraction and a remaining vapor fraction. Expander **128** may be any pressure reducing device, including, but not limited to a valve, control valve, Joule Thompson valve, Venturi device, liquid expander, hydraulic turbine, and the like. The sub-cooled gas stream **126**, which is now at a lower pressure and partially liquefied, is passed to a surge tank **130** where the liquefied fraction **132** is withdrawn from the process as an LNG stream **134**, which has a temperature corresponding to the bubble point pressure. The remaining vapor fraction (flash vapor) stream **136** may be used as fuel to power the compressor units.

[0014] In sub-cooling loop **104**, an expanded sub-cooling refrigerant stream **138** (preferably comprising nitrogen) is discharged from an expander **140** and drawn through second and first heat exchangers **124**, **120**. Expanded sub-cooling refrigerant stream **138** is then

sent to a compression unit **142** where it is re-compressed to a higher pressure and warmed. After exiting compression unit **142**, the re-compressed sub-cooling refrigerant stream **144** is cooled in a cooler **146**, which can be of the same type as cooler **112**, although any type of cooler may be used. After cooling, the re-compressed sub-cooling refrigerant stream is passed to first heat exchanger **120** where it is further cooled by indirect heat exchange with expanded refrigerant stream **118** and expanded sub-cooling refrigerant stream **138**. After exiting first heat exchanger **120**, the re-compressed and cooled sub-cooling refrigerant stream is expanded through expander **140** to provide a cooled stream which is then passed through second heat exchanger **124** to sub-cool the portion of the feed gas stream to be finally expanded to produce LNG.

**[0015]** Figure 2 is a schematic diagram of another liquefaction system **200** according to known principles. Liquefaction system **200** is similar to HPXP liquefaction system **100**, and for the sake of brevity similarly depicted or numbered components may not be further described. Liquefaction system **200** includes a primary cooling loop **202** and a sub-cooling loop **204**. In liquefaction system **200**, the sub-cooling loop **204** is an open refrigeration loop where a portion **249** of the expanded, sub-cooled gas stream **248** is recycled and used as the sub-cooling refrigerant stream. Specifically, the portion **249** of the expanded, sub-cooled gas stream is directed through the second heat exchanger **124** and first heat exchanger **120** as previously described before being compressed in a compressor **242**, cooled in a cooler **246**, and re-inserted into the feed gas stream **206**.

**[0016]** U. S. Patent Application US2010/0107684 disclosed an improvement to the performance of the HPXP through the discovery that adding external cooling to further cool the compressed refrigerant to temperatures below ambient conditions provides significant advantages which in certain situations justifies the added equipment associated with external cooling. The HPXP embodiments described in the aforementioned patent applications perform comparably to alternative mixed external refrigerant LNG production processes such as single mixed refrigerant processes. However, there remains a need to further improve the efficiency of the HPXP as well as overall train capacity. There remains a particular need to improve the efficiency of the HPXP in cases where the feed gas pressure is less than 1,200 psia.

**[0017]** U. S. Patent Application 2010/0186445 disclosed the incorporation of feed compression up to 4,500 psia to the HPXP. Compressing the feed gas prior to liquefying the gas in the HPXP's primary cooling loop has the advantage of increasing the overall process efficiency. For a given production rate, this also has the advantage of significantly reducing

the required flow rate of the refrigerant within the primary cooling loop which enables the use of compact equipment, which is particularly attractive for floating LNG applications. Furthermore, feed compression provides a means of increasing the LNG production of an HPXP train by more than 30% for a fixed amount of power going to the primary cooling and sub-cooling loops. This flexibility in production rate is again particularly attractive for floating LNG applications where there are more restrictions than land based applications in matching the choice of refrigerant loop drivers with desired production rates.

**[0018]** The advantages of the HPXP are made possible through the use of turboexpanders capable of expanding the refrigerant gas from a high pressure (1,500 to 3,500 psia) down to the low pressure required to achieve the desired refrigerant temperature to liquefy the feed gas. For most applications of the HPXP, the required pressure drop for the refrigerant is significantly greater than 1,000 psi. For this reason, the expansion of the refrigerant may occur within a train comprising at least two expanders operating in series. In such a configuration, each expander is mechanically coupled to a compressor such that the mechanical power recovered from the expander is used to partially recompress the refrigerant back to its maximum pressure. A compressor that is mechanically coupled to an expander is hereto known as a turboexpander-compressor (TEC). Figure 3 illustrates a liquefaction system **300** that uses a configuration of turboexpander-compressors (TEC) within its primary cooling loop **302**, according to known aspects. A compressed refrigerant stream **308** is cooled in a cooler **310** against an ambient cooling medium (air or water) to produce a compressed, cooled refrigerant stream **312**. The compressed, cooled refrigerant stream, which may be at a pressure of, for example, 3,000 psia, is expanded in a first expander **314** to an intermediate pressure of, for example, 1,300 psia, to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream **316**. The first expanded, cooled refrigerant stream is additionally expanded in a second expander **318** to further cool the first expanded, cooled refrigerant stream **316** and thereby produce a second expanded, cooled refrigerant stream **320**. The second expanded, cooled refrigerant stream **320**, which may be at a pressure of, for example, 500 psia, is directed to one or more heat exchangers **322** where it exchanges heat with the feed gas stream **306** to produce a warm refrigerant stream **324** and a liquefied gas stream **326**. The liquefied gas stream **326** is further cooled in a sub-cooling heat exchanger **328** using a sub-cooling loop **304**, which functions in a similar manner as previously described sub-cooling loop **104** (Figure 1). The warm refrigerant stream **324**, which may be at a pressure of, for example, 500 psia, is compressed by a first compressor **330** (to a pressure of, for example, 700 psia), followed by a second compressor **332** (to a pressure of, for example,

900 psia), and is then cooled in a cooler **334** against a cooling medium, which may be an ambient cooling medium (air or water), to produce a first compressed refrigerant stream **336**. The first compressor **330** is coupled to the second expander **318** using a first mechanical coupling **338** to form a low-pressure TEC. The second compressor **332** is coupled to the first  
5 expander **314** using a second mechanical coupling **340** to form a high-pressure TEC. The first compressed refrigerant stream **336** is further compressed in one or more compressors **342**, **344** to produce the compressed refrigerant stream **308**. A cooler **343** may be disposed between the one or more compressors **342**, **344**.

[0019] In liquefaction system **300**, the low pressure TEC's operating conditions are within  
10 the operating experience of commercially available turboexpander-compressors. However, the high pressure TEC's inlet pressure (3,000 psia), the first expander pressure drop (3,000 psia – 1,300 psia = 1,700 psia), and the thrust differential between the expander outlet side and compressor inlet side of the high-pressure TEC (1,300 psia - 700 psia = 600 psia) are outside industry operating experience. It is believed that the high inlet pressure and high expander  
15 pressure drop can be handled with a proper design of the high pressure TEC, which takes into account these step out conditions. Managing the higher thrust, however, may require significant TEC design changes. These changes may add cost and complexity and decrease efficiency by 1 to 3%. For this reason, there is a need to develop a new configuration for the TEC of HPXP to eliminate the need for significant design changes to manage the thrust.

## 20 SUMMARY

[0020] Aspects of the disclosure provide a method for liquefying a feed gas stream comprising a natural gas feed gas stream is provided at a pressure less than 1,200 psia. A compressed refrigerant stream is provided with a pressure greater than or equal to 1,500 psia. The compressed refrigerant stream is cooled by indirect heat exchange with a cooling medium,  
25 thereby producing a compressed, cooled refrigerant stream. The compressed, cooled refrigerant stream is expanded in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream. The first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor. The first expanded, cooled refrigerant stream is  
30 expanded in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream. The second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor. The second expanded, cooled refrigerant stream is passed through

one or more heat exchangers, thereby forming a warm refrigerant stream. The feed gas stream is passed through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream. Using the second coupled compressor and a first driven  
5 compressor, the warm refrigerant stream is compressed to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream. The first compressed refrigerant stream is compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream. The second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

10 **[0021]** Aspects of the disclosure also provide a natural gas liquefaction system. A first heat exchanger cools a compressed refrigerant stream by indirect heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant stream, wherein the compressed refrigerant stream is provided to the first heat exchanger at a pressure of at least 1,500 psia. A first expander expands the compressed, cooled refrigerant stream to an intermediate  
15 pressure, to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream. A first coupled compressor is mechanically coupled to the first expander to together form a first turboexpander-compressor. A second expander expands the first expanded, cooled refrigerant stream to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream. A second  
20 coupled compressor is mechanically coupled to the second expander to together form a second turboexpander-compressor. One or more heat exchangers arranged to permit the second expanded, cooled refrigerant stream and a feed gas stream to pass therethrough and exchange heat therein through indirect heat exchange, thereby forming a warm refrigerant stream and a cool feed gas stream. The feed gas stream comprises natural gas and is supplied to the one or  
25 more heat exchangers at a pressure of less than 1,200 psia. A first driven compressor and the second coupled compressor compress the warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream. The first compressed refrigerant stream is further compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream. The second compressed  
30 refrigerant stream is compressed to provide the compressed refrigerant stream.

**[0022]** Aspects of the disclosure also provide a method for liquefying a feed gas stream comprising natural gas. The feed gas stream is provided at a pressure less than 1,200 psia. A compressed refrigerant stream is provided with a pressure greater than or equal to 1,500 psia.

The compressed refrigerant stream is cooled by indirect heat exchange with a first cooling medium, thereby producing a compressed, cooled refrigerant stream. The compressed, cooled refrigerant stream is expanded in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream. The first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor. The first expanded, cooled refrigerant stream is expanded in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream. The second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor. The second expanded, cooled refrigerant stream is passed through one or more heat exchangers, thereby forming a warm refrigerant stream. The feed gas stream is passed through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream. Using a sub-cooling loop, the cool feed gas stream is further cooled to form a sub-cooled feed gas stream having a liquid portion. Using the second coupled compressor and a first driven compressor, the warm refrigerant stream is compressed to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream. The warm refrigerant stream is cooled by indirect heat exchange with a second cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor. The first compressed refrigerant stream is cooled via heat exchange with a third cooling medium. The first compressed refrigerant stream is compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream. The second compressed refrigerant stream is cooled via heat exchange with a fourth cooling medium. The second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

[0023] The foregoing has broadly outlined the features of the present disclosure so that the detailed description that follows may be better understood. Additional features will also be described herein.

#### BRIEF DESCRIPTION OF THE DRAWINGS

[0024] These and other features, aspects and advantages of the disclosure will become apparent from the following description, appending claims and the accompanying drawings, which are briefly described below.

[0025] Figure 1 is a schematic diagram of a system for LNG production according to

known principles.

[0026] Figure 2 is a schematic diagram of a system for LNG production according to known principles.

[0027] Figure 3 is a schematic diagram of a system for LNG production according to  
5 known principles.

[0028] Figure 4 is a schematic diagram of a system for LNG production according to disclosed aspects.

[0029] Figure 5 is a schematic diagram of a system for LNG production according to disclosed aspects.

10 [0030] Figure 6 is a flowchart of a method according to aspects of the disclosure.

[0031] Figure 7 is a flowchart of a method according to aspects of the disclosure.

[0032] It should be noted that the figures are merely examples and no limitations on the scope of the present disclosure are intended thereby. Further, the figures are generally not drawn to scale, but are drafted for purposes of convenience and clarity in illustrating various  
15 aspects of the disclosure.

#### DETAILED DESCRIPTION

[0033] To promote an understanding of the principles of the disclosure, reference will now be made to the features illustrated in the drawings and specific language will be used to describe the same. It will nevertheless be understood that no limitation of the scope of the disclosure is  
20 thereby intended. Any alterations and further modifications, and any further applications of the principles of the disclosure as described herein are contemplated as would normally occur to one skilled in the art to which the disclosure relates. For the sake of clarity, some features not relevant to the present disclosure may not be shown in the drawings.

[0034] At the outset, for ease of reference, certain terms used in this application and their  
25 meanings as used in this context are set forth. To the extent a term used herein is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in at least one printed publication or issued patent. Further, the present techniques are not limited by the usage of the terms shown below, as all equivalents, synonyms, new developments, and terms or techniques that serve the same or a similar purpose are  
30 considered to be within the scope of the present claims.

[0035] As one of ordinary skill would appreciate, different persons may refer to the same

feature or component by different names. This document does not intend to distinguish between components or features that differ in name only. The figures are not necessarily to scale. Certain features and components herein may be shown exaggerated in scale or in schematic form and some details of conventional elements may not be shown in the interest of clarity and conciseness. When referring to the figures described herein, the same reference numerals may be referenced in multiple figures for the sake of simplicity. In the following description and in the claims, the terms “including” and “comprising” are used in an open-ended fashion, and thus, should be interpreted to mean “including, but not limited to.”

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[0036] The articles “the,” “a” and “an” are not necessarily limited to mean only one, but rather are inclusive and open ended so as to include, optionally, multiple such elements.

[0037] As used herein, the terms “approximately,” “about,” “substantially,” and similar terms are intended to have a broad meaning in harmony with the common and accepted usage by those of ordinary skill in the art to which the subject matter of this disclosure pertains. It should be understood by those of skill in the art who review this disclosure that these terms are intended to allow a description of certain features described and claimed without restricting the scope of these features to the precise numeral ranges provided. Accordingly, these terms should be interpreted as indicating that insubstantial or inconsequential modifications or alterations of the subject matter described and are considered to be within the scope of the disclosure. According to disclosed aspects, these terms are intended to mean within 2%, or within 5%, or within 10%, of a specified number or amount.

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[0038] As used herein, the terms “compression unit” and “compressor” mean any one type or combination of similar or different types of compression equipment, and may include auxiliary equipment, known in the art for compressing a substance or mixture of substances. A compression unit or compressor may utilize one or more compression stages. Illustrative compression units or compressors may include, but are not limited to, positive displacement types, such as reciprocating and rotary compressors for example, and dynamic types, such as centrifugal and axial flow compressors, for example.

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[0039] As used herein, the term “cooling medium” means any type of medium, whether in a solid, liquid, or gaseous state, that serves to cool a fluid using indirect heat exchange therewith. A cooling medium may be at ambient temperature, below ambient temperature, or above ambient temperature, depending on the needed cooling and available types of cooling media. As non-limiting examples, a cooling medium may be water or air.

[0040] "Exemplary" is used exclusively herein to mean "serving as an example, instance, or illustration." Any embodiment or aspect described herein as "exemplary" is not to be construed as preferred or advantageous over other embodiments.

[0041] The term "gas" is used interchangeably with "vapor," and is defined as a substance or mixture of substances in the gaseous state as distinguished from the liquid or solid state. Likewise, the term "liquid" means a substance or mixture of substances in the liquid state as distinguished from the gas or solid state.

[0042] As used herein, "heat exchange area" means any one type or combination of similar or different types of equipment known in the art for facilitating heat transfer. Thus, a "heat exchange area" may be contained within a single piece of equipment, or it may comprise areas contained in a plurality of equipment pieces. Conversely, multiple heat exchange areas may be contained in a single piece of equipment.

[0043] A "hydrocarbon" is an organic compound that primarily includes the elements hydrogen and carbon, although nitrogen, sulfur, oxygen, metals, or any number of other elements can be present in small amounts. As used herein, hydrocarbons generally refer to components found in natural gas, oil, or chemical processing facilities.

[0044] As used herein, the terms "loop" and "cycle" are used interchangeably.

[0045] As used herein, "natural gas" means a gaseous feedstock suitable for manufacturing LNG, where the feedstock is a methane-rich gas containing methane (CH<sub>4</sub>) as a major component. Natural gas may include gas obtained from a crude oil well (associated gas) or from a gas well (non-associated gas).

[0046] Aspects the disclosure provide a process for liquefying natural gas and other methane-rich gas streams to produce liquefied natural gas (LNG) and/or other liquefied methane-rich gases. According to the disclosed aspect, the turboexpander compressors and gas turbine (or motor) driven compressors of the primary cooling loop are arranged to significantly reduce the TEC thrust differential. Specifically, the turbo machinery within the primary cooling loop are configured such that the absolute difference in pressure between the TEC's compressor suction pressure and the high pressure TEC's expander discharge pressure is less than 300 psi. This configuration reduces the thrust differential to a more easily managed level.

[0047] According to disclosed aspects, a method and system are provided for liquefying a feed gas stream, particularly one rich in methane. The method and system include: (a) providing the feed gas stream at a pressure less than 1,200 psia; (b) providing a compressed refrigerant stream with a pressure greater than or equal to 1,500 psia; (c) cooling the

compressed refrigerant stream by indirect heat exchange with a cooling fluid, thereby producing a compressed, cooled refrigerant stream; (d) expanding the compressed, cooled refrigerant stream in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream; (e) 5 expanding the first expanded, cooled refrigerant stream in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream; (f) passing the second expanded, cooled refrigerant stream to heat exchanger areas, thereby forming a warm refrigerant stream; (g) passing the feed gas stream through the heat exchanger areas to cool at least part of the feed gas stream by indirect heat exchange with 10 the second expanded, cooled refrigerant stream, thereby forming a cool gas stream; (h) compressing the warm refrigerant stream to a discharge pressure within 300 psi of the intermediate pressure, thereby forming a first compressed refrigerant stream; (i) cooling the first compressed refrigerant stream by indirect heat exchange with a cooling medium, thereby producing a first compressed, cooled refrigerant stream; (j) compressing the first compressed, 15 cooled refrigerant stream using a compressor mechanically coupled to the first expander, thereby forming a second compressed refrigerant stream; and (k) compressing the second compressed refrigerant stream to provide the compressed refrigerant stream.

**[0048]** The first compressed refrigerant stream may be formed by compressing the warm refrigerant stream in a compressor mechanically coupled to the second expander and then 20 further compressing the warm refrigerant stream in a first compressor driven by a reciprocating engine, a steam turbine, or a gas turbine and/or motor. The warm refrigerant stream may be cooled by indirect heat exchange with a cooling medium after being compressed in the compressor mechanically coupled to the second expander and prior to being compressed in the first compressor.

25 **[0049]** The TEC configuration according to disclosed aspects has the advantage of reducing or eliminating the high thrust differential of the high pressure TEC compared to the TEC arrangement of known TEC arrangements. A pressure differential below approximately 200 psia should be manageable without any significant changes to the conventional thrust balancing mechanism. The efficiency of the HPXP may be increased by 1 to 3% using the 30 disclosed TEC configurations. It may be the case that the disclosed TEC configurations of the present invention requires extra piping and controls, since the high pressure and low pressure TECs may be located apart from the gas turbine (or motor driven) driven compressor in a facility layout. Additionally, the number of gas turbine or motor driven compressor bodies

may increase. It may also be desirable to add an intercooler between the first and second compression stages in order to improve efficiency and reduce volumetric flow into the first compressor. Nevertheless, such additional costs are likely to be outweighed by the efficiency increases to the HPXP process.

- 5 [0050] Figure 4 illustrates a liquefaction system 400 according to disclosed aspects. Liquefaction system includes a primary cooling loop 402 and a sub-cooling loop 404. A compressed refrigerant stream 408 is cooled in a first heat exchanger having one or more coolers 410, which may use one or more cooling mediums to produce a compressed, cooled refrigerant stream 412. The compressed, cooled refrigerant stream 412 is expanded in a first  
10 expander 414 to an intermediate pressure, and is thereby further cooled to produce a first expanded, cooled refrigerant stream 416. The first expander 414 is coupled, using a first mechanical coupling 444, to a first coupled compressor 438 to together form a high-pressure turboexpander/compressor (TEC). The first expanded, cooled refrigerant stream is additionally expanded in a second expander 418 to further cool the first expanded, cooled refrigerant stream  
15 416 and thereby produce a second expanded, cooled refrigerant stream 420. The second expander 414 is coupled, using a second mechanical coupling 446, to a second coupled compressor 429 to together form a low-pressure TEC. The second expanded, cooled refrigerant stream 420 is directed to a main heat exchange area 422 comprising one or more heat exchangers, where the second expanded, cooled refrigerant stream exchanges heat with the  
20 feed gas stream 406 to produce a warm refrigerant stream 424 and a liquefied gas stream 426. The liquefied gas stream 426 is further cooled in a sub-cooling heat exchanger 428 using the sub-cooling loop 404, which will be further described. The warm refrigerant stream 424 is compressed by second coupled compressor 429, cooled via indirect heat exchange with a cooling medium in a second cooler 430, and is further compressed by a first driven compressor  
25 431 to produce a first compressed refrigerant stream 432. The first driven compressor may be driven by a gas turbine 431a, or alternatively may be driven by a reciprocating engine, a steam turbine, or a motor. The first compressed refrigerant stream 432 has a discharge pressure what is within 300 psia, or within 250 psia, or within 200 psia, or within 150 psia, or within 100 psia, of the intermediate pressure of the first expanded, cooled refrigerant stream 416. The first  
30 compressed refrigerant stream is cooled in a third cooler 434 via indirect heat exchange with a cooling medium to form a first compressed, cooled refrigerant stream 436, which is then compressed in first coupled compressor 438 to form a second compressed refrigerant stream 440. The second compressed refrigerant stream may be cooled in a fourth cooler 441 via indirect heat exchange with a cooling medium and then further compressed in a second driven

compressor **442** to produce the compressed refrigerant stream **408**. The second driven compressor **442** may be driven by a gas turbine **442a**, or alternatively may be driven by a reciprocating engine, a steam turbine, or a motor. The second driven compressor **442** may share a common driver with first driven compressor **431**. The first and second driven  
5 compressors **431**, **442** may even be disposed within a single compressor casing.

[0051] In sub-cooling loop **404**, an expanded sub-cooling refrigerant stream **448** (preferably comprising nitrogen) is discharged from a sub-cooling expander **450** and drawn through the sub-cooling heat exchanger **428** and the heat exchangers in the main heat exchange area **422**. Expanded sub-cooling refrigerant stream **448** is then sent to a sub-cooling  
10 compression unit **452** where it is re-compressed to a higher pressure and warmed, thereby forming a re-compressed sub-cooling refrigerant stream **454**. After exiting compression unit **442**, the re-compressed sub-cooling refrigerant stream **454** is cooled in a fifth heat exchanger comprising a cooler **456**, which can be of the same type as coolers **410** and/or **434**, although any type of cooler may be used. After cooling, the re-compressed sub-cooling refrigerant  
15 stream **454** is passed through the heat exchangers in the main heat exchange area **422** where it is further cooled by indirect heat exchange with second expanded, cooled refrigerant stream **420** and expanded sub-cooling refrigerant stream **448**. After exiting the heat exchange area **422**, the re-compressed and cooled sub-cooling refrigerant stream is expanded through sub-cooling expander **450** to provide the expanded, sub-cooled refrigerant stream **448**, which is  
20 then passed through sub-cooling heat exchanger **428** to sub-cool the feed gas stream, and thereby produce a sub-cooled feed gas stream **458**. Sub-cooled feed gas stream **458** is then expanded to a lower pressure in an expander **460** to form an expanded, sub-cooled gas stream **461** with a liquid fraction and a remaining vapor fraction. In an aspect, the expanded, sub-cooled gas stream **461** may have a pressure greater than or equal to 50 psia and less than or  
25 equal to 450 psia. Expander **460** may be any pressure reducing device, including, but not limited to a valve, control valve, Joule Thompson valve, Venturi device, liquid expander, hydraulic turbine, and the like. The expanded sub-cooled gas stream **461**, which is now at a lower pressure and partially liquefied, is passed to a surge tank **462** where the liquefied fraction **464** is withdrawn from the process as an LNG stream **466**. The LNG stream **466** has a  
30 temperature corresponding to the bubble point pressure. The remaining vapor fraction (flash vapor) stream **468** may be used as fuel to power the compressor units.

[0052] The discharge pressure of one or more of the compressors and/or expanders disclosed herein may be controlled by a control system **401**. Such a control system may include control logic to optimize cycle efficiency by maximizing certain parameters within a measured

thrust bearing limit, such as temperature. The control logic may also control one or more of, for example, the driven compressor speed, driven compressor recycle valves, first coupled compressor recycle valves, second coupled compressor recycle valves, first expander bypass valves, second expander bypass valves, first expander throttling valves, second expander throttling valves, first expander inlet guide vanes, second expander inlet guide vanes, or any combination of the foregoing based on the suction pressure of the driven compressor, discharge pressure of the driven compressor, discharge pressure of the first couple compressor, discharge pressure of the second coupled compressor, discharge pressure of the first expander, discharge pressure of the second expander, and/or suction pressure of the second expander, or any combination thereof. The control system may adjust one or more of (a) a discharge pressure of one or more of the compressors, and (b) an inlet pressure of one or more of the expanders, to thereby maintain a fixed differential pressure between the discharge pressure and the inlet pressure. The fixed differential pressure may be obtained through control algorithms using one or more of compressor speed of one or more of the compressors, inlet guide vanes of one or more of the expanders, recycle valves of one or more of the compressors, and bypass valves of one or more of the expanders. Furthermore, cycle efficiency may be optimized by maximizing certain parameters within a measured thrust bearing limit, such as temperature. For the sake of clarity in the Figures, necessary connections from control system **401** to the various valves, compressors and expanders, are not shown.

**[0053]** Figure 5 is a schematic diagram that illustrates a liquefaction system **500** according to another aspect of the disclosure. Liquefaction system **500** is similar to liquefaction system **400** (Figure 4), and for the sake of brevity similarly depicted or numbered components may not be further described. Liquefaction system **500** includes a primary cooling loop **502**, which is substantially identical to primary cooling loop **402**, and a sub-cooling loop **504**. The sub-cooling loop **504** is an open refrigeration loop where a portion **570** of the expanded, sub-cooled feed gas stream **561** is recycled and used as the sub-cooling refrigerant stream. Specifically, the portion **570** of the expanded, sub-cooled gas stream **561** is directed through a sub-cooling heat exchanger **526** and one or more heat exchangers in a main heat exchange area **522** before being compressed in a compressor **572**, cooled in a cooler **574** via indirect heat exchange with a cooling medium, and re-inserted into the feed gas stream **506**. The feed gas stream **506** passes through the heat exchangers in the heat exchange area **522**, where it is cooled by indirect heat exchange with the portion of the expanded, sub-cooled gas stream **561** and the second expanded, cooled refrigerant stream **520** of the primary cooling loop **502**. After being expanded in an expander **560**, the portion **575** of the sub-cooled feed gas stream **561** not used

as the sub-cooling refrigerant stream is further expanded and cooled in an expander **576**, which may be any pressure reducing device, including, but not limited to a valve, control valve, Joule Thompson valve, Venturi device, liquid expander, hydraulic turbine, and the like. The sub-cooled gas stream, which is now at a lower pressure and partially liquefied, is passed to a surge tank **580** where the liquefied fraction **582** is withdrawn from the process as an LNG stream **584**. The LNG stream **584** has a temperature corresponding to the bubble point pressure. The remaining vapor fraction (flash vapor) stream **586** may be used as fuel to power the compressor units. Liquefaction system 500 also includes a control system **501** having similar functionality as control system **401** (Figure 4).

10 **[0054]** The sub-cooling refrigerant stream in Figure 5 may be one stream, as shown, or may comprise multiple streams at different pressures: for example, a portion of the expanded, sub-cooling gas stream - not to exceed 50% thereof – may be diverted and pass through one or more pressure reduction valves to reduce its pressure to a range of about 30 to 300 psia, to thereby produce one or more reduced pressure gas streams. The reduced pressure gas streams  
15 may then be passed through the first heat exchanger zone as the sub-cooling refrigerant. Having multiple streams improves the efficiency of the sub-cooling process. Alternatively, this sub-cooling loop may be configured to be a closed refrigeration loop.

**[0055]** Aspects of the disclosure illustrated in Figure 5 demonstrate that the primary refrigerant stream may comprise part of the feed gas stream, which in a preferred aspect may  
20 be primarily or nearly all methane. Indeed, it may be advantageous for the refrigerant in the primary cooling loop of Figure 4 to be comprised of at least 85% methane, or at least 90% methane, or at least 95% methane, or greater than 95% methane. This is because methane may be readily available in various parts of the disclosed processes, and the use of methane may eliminate the need to transport refrigerants to remote LNG processing locations. As a non-  
25 limiting example, the refrigerant in the primary cooling loop **402** in Figure 4 may be taken directly from feed gas stream **406** if the feed gas is high enough in methane to meet the compositions as described above. Alternatively, part or all of a boil-off gas stream **469a** from an LNG storage tank **469** may be used to supply refrigerant for the primary cooling loop **402**. Furthermore, if the feed gas stream is sufficiently low in nitrogen, part or all of the end flash  
30 gas stream **468** (which would then be low in nitrogen) may be used to supply refrigerant for the primary cooling loop **402**. Lastly, any combination of feed gas stream **406**, boil-off gas stream **469a**, and end flash gas stream **468** may be used to provide or even occasionally replenish the refrigerant in the primary cooling loop **402**.

[0056] Aspects of the disclosure have shown how two TECs – i.e., a high pressure TEC and a low-pressure TEC – can be disposed in series in a high-pressure refrigerant stream for liquefying natural gas. It is within the scope of the disclosed aspects to employ three or more TECs in series in the high-pressure refrigerant stream for liquefying natural gas.

5 [0057] The coolers disclosed in Figures 4 and 5 may use any type of cooling media, including air or water. For purposes of clarity, the various disclosed cooling media may be denoted as a ‘first cooling medium,’ ‘second cooling medium,’ etc., it being understood that one or more of the cooling media used herein have similar or identical composition, regardless of how they have been denoted.

10 [0058] Figure 6 is a flowchart of a method **600** for liquefying a feed gas stream comprising natural gas. At block **602** the feed gas stream is provided at a pressure less than 1,200 psia. At block **604** a compressed refrigerant stream is provided with a pressure greater than or equal to 1,500 psia. At block **606** the compressed refrigerant stream is cooled by indirect heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant stream. At block  
15 **608** the compressed, cooled refrigerant stream is expanded in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream. The first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor. At block **610** the first expanded, cooled refrigerant stream is expanded in a second expander to further cool the first  
20 expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream. The second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor. At block **612** the second expanded, cooled refrigerant stream is passed through one or more heat exchangers, thereby forming a warm refrigerant stream. At block **614** the feed gas stream is passed through the one or more heat  
25 exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream. At block **616**, using the second coupled compressor and a first driven compressor, the warm refrigerant stream is compressed to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream. At block **618** the first compressed  
30 refrigerant stream is compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream. At block **620** the second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

[0059] Figure 7 is a flowchart of a method **700** for liquefying a feed gas stream comprising

natural gas. At block **702** the feed gas stream is provided at a pressure less than 1,200 psia. At block **704** a compressed refrigerant stream is provided with a pressure greater than or equal to 1,500 psia. At block **706** the compressed refrigerant stream is cooled by indirect heat exchange with a first cooling medium, thereby producing a compressed, cooled refrigerant stream. At block **708** the compressed, cooled refrigerant stream is expanded in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream. The first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor. At block **710** the first expanded, cooled refrigerant stream is expanded in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream. The second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor. At block **712** the second expanded, cooled refrigerant stream is passed through one or more heat exchangers, thereby forming a warm refrigerant stream. At block **714** the feed gas stream is passed through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream. At block **716**, using a sub-cooling loop, the cool feed gas stream is further cooled to form a sub-cooled feed gas stream having a liquid portion. At block **718**, using the second coupled compressor and a first driven compressor, the warm refrigerant stream is compressed to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream. At block **720** the warm refrigerant stream is cooled by indirect heat exchange with a second cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor. At block **722** the first compressed refrigerant stream is cooled via heat exchange with a third cooling medium. At block **724** the first compressed refrigerant stream is compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream. At block **726** the second compressed refrigerant stream is cooled via heat exchange with a fourth cooling medium. At block **728** the second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

**[0060]** The steps depicted in Figures 6 and 7 are provided for illustrative purposes only and a particular step may not be required to perform the disclosed methodology. Moreover, Figures 6-7 may not illustrate all the steps that may be performed. The claims, and only the claims, define the disclosed system and methodology.

[0061] The aspects described herein have several advantages over known technologies. For example, the described technology may greatly reduce the size and cost of systems that treat sour natural gas.

[0062] Aspects of the disclosure may include any combinations of the methods and systems shown in the following numbered paragraphs. This is not to be considered a complete listing of all possible aspects, as any number of variations can be envisioned from the description above.

1. A method for liquefying a feed gas stream comprising natural gas, the method comprising:
  - 10 providing the feed gas stream at a pressure less than 1,200 psia;  
providing a compressed refrigerant stream with a pressure greater than or equal to 1,500 psia;  
cooling the compressed refrigerant stream by indirect heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant stream;
  - 15 expanding the compressed, cooled refrigerant stream in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream, wherein the first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor;
  - 20 expanding the first expanded, cooled refrigerant stream in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream, wherein the second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor;  
passing the second expanded, cooled refrigerant stream to one or more heat exchangers,  
25 thereby forming a warm refrigerant stream;  
passing the feed gas stream through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream;  
using the second coupled compressor and a first driven compressor, compressing the  
30 warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;

compressing the first compressed refrigerant stream using the first coupled compressor, thereby forming a second compressed refrigerant stream; and

compressing the second compressed refrigerant stream to provide the compressed refrigerant stream.

5     2.     The method of paragraph 1, further comprising driving the first driven compressor using at least one of a reciprocating engine, a steam turbine, a gas turbine, and a motor.

3.     The method paragraph 1 or paragraph 2, wherein cooling the compressed refrigerant stream comprises cooling the compressed refrigerant stream via indirect heat exchange with a cooling medium.

10    4.     The method of any one of paragraphs 1-3, wherein cooling the compressed refrigerant stream comprises cooling the compressed refrigerant stream by indirect heat exchange with a cooling medium having a temperature lower than ambient conditions.

5.     The method of any one of paragraphs 1-4, further comprising:

15    cooling the warm refrigerant stream by indirect heat exchange with a cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor.

6.     The method of any one of paragraphs 1-5, further comprising:

cooling the first compressed refrigerant stream prior to being compressed in the first coupled compressor.

20    7.     The method of any one of paragraphs 1-6, further comprising:

cooling the second compressed refrigerant stream via indirect heat exchange with a cooling medium prior to being compressed to provide the compressed refrigerant stream.

8.     The method of any one of paragraphs 1-7, wherein the compressed refrigerant stream has a pressure of approximately 3,000 psia.

25    9.     The method of any one of paragraphs 1-8, wherein the intermediate pressure is less than 1,500 psia and greater than 1,000 psia.

10.    The method of any one of paragraphs 1-9, wherein compressing the second compressed refrigerant stream is accomplished using a second driven compressor.

11.    The method of paragraph 10, further comprising:

30    driving the second driven compressor using at least one of a reciprocating engine, a

steam turbine, a gas turbine, and a motor.

12. The method of paragraph 10 or paragraph 11, wherein the first driven compressor and the second driven compressor share a common driver.

13. The method of any one of paragraphs 10-12, wherein the first driven compressor and  
5 the second driven compressor are within a single compressor casing.

14. The method of any one of paragraphs 1-13, further comprising:

using a sub-cooling loop, further cooling the cool feed gas stream to form a sub-cooled feed gas stream.

15. The method of paragraph 14, further comprising:

10 expanding the sub-cooled feed gas stream to a pressure greater than or equal to 50 psia and less than or equal to 450 psia, to produce an expanded, sub-cooled feed gas stream.

16. The method of paragraph 14 or paragraph 15, wherein the sub-cooled feed gas stream is expanded within a hydraulic turbine.

17. The method of any one of paragraphs 14-16, wherein the sub-cooling loop is a closed  
15 loop gas phase refrigeration cycle where nitrogen gas is the refrigerant.

18. The method of paragraph 14, wherein the sub-cooling loop comprises:

withdrawing a portion not to exceed 50% of the expanded, sub-cooled gas stream and reducing its pressure in a pressure reduction valve to a range of about 30 to 300 psia to produce one or more reduced pressure gas streams; and

20 passing the one or more reduced pressure gas streams through the one or more heat exchangers as the sub-cooling refrigerant stream.

19. The method of paragraph 18, wherein the one or more reduced pressure gas streams are at different pressures from each other.

20. The method of paragraph 18 or paragraph 19, wherein the sub-cooling refrigerant  
25 stream exiting the one or more heat exchangers is compressed to a pressure approximate to that of the feed gas stream and is cooled by indirect heat exchange with a cooling medium before mixing the sub-cooling refrigerant stream with the feed gas stream.

21. The method of paragraph 15, wherein at least a portion of the expanded, sub-cooled gas stream is further expanded and then directed to a separation tank from which liquid natural gas  
30 is withdrawn and remaining gaseous vapors are withdrawn as a flash gas stream.

22. The method of paragraph 21, wherein the compressed refrigerant stream comprises boil off gas of the liquid natural gas.
23. The method of any one of paragraphs 1-22, further comprising:  
adjusting one or more of  
5 a discharge pressure of one or more of the compressors, and  
an inlet pressure of one or more of the expanders,  
to thereby maintain a fixed differential pressure between the discharge pressure and the inlet pressure.
24. The method of paragraph 23, wherein the fixed differential pressure is obtained through  
10 control algorithms using one or more of compressor speed of one or more of the compressors,  
inlet guide vanes of one or more of the expanders, recycle valves of one or more of the compressors, and bypass valves of one or more of the expanders.
25. The method of paragraph 23 or paragraph 24, further comprising:  
using expander thrust bearing temperature as a limit to protect thrust bearing integrity  
15 while maximizing cycle efficiency.
26. A natural gas liquefaction system comprising:  
a first heat exchanger configured to cool a compressed refrigerant stream by indirect  
heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant  
stream, wherein the compressed refrigerant stream is provided to the first heat exchanger at a  
20 pressure of at least 1,500 psia;  
a first expander configured to expand the compressed, cooled refrigerant stream to an  
intermediate pressure, to further cool the compressed, cooled refrigerant stream, thereby  
producing a first expanded, cooled refrigerant stream;  
a first coupled compressor mechanically coupled to the first expander to together form  
25 a first turboexpander-compressor;  
a second expander configured to expand the first expanded, cooled refrigerant stream  
to further cool the first expanded, cooled refrigerant stream, thereby producing a second  
expanded, cooled refrigerant stream;  
a second coupled compressor mechanically coupled to the second expander to together  
30 form a second turboexpander-compressor;

one or more heat exchangers arranged to permit the second expanded, cooled refrigerant stream and a feed gas stream to pass therethrough and exchange heat therein through indirect heat exchange, thereby forming a warm refrigerant stream and a cool feed gas stream, wherein the feed gas stream comprises natural gas and is supplied to the one or more heat exchangers  
5 at a pressure of less than 1,200 psia;

a first driven compressor configured to, along with the second coupled compressor, compress the warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;

wherein the first compressed refrigerant stream is further compressed using the first  
10 coupled compressor, thereby forming a second compressed refrigerant stream; and

wherein the second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

27. The system of paragraph 26, further comprising a driving element configured to drive the first driven compressor, wherein the driving element comprises at least one of a  
15 reciprocating engine, a steam turbine, a gas turbine, and a motor.

28. The system of paragraph 26 or paragraph 27, further comprising:

a first cooler configured to cool the compressed refrigerant stream via indirect heat exchange with a cooling medium.

29. The system of paragraph 28, wherein the cooling medium has a temperature lower than  
20 ambient conditions.

30. The system of any one of paragraphs 26-29, further comprising:

a second cooler configured to cool the warm refrigerant stream by indirect heat exchange with a cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor;

25 a third cooler configured to cool the first compressed refrigerant stream prior to being compressed in the first coupled compressor; and

a fourth cooler configured to cool the second compressed refrigerant stream via indirect heat exchange with a cooling medium prior to being compressed, to thereby provide the compressed refrigerant stream.

30 31. The system of any one of paragraphs 26-30, wherein the compressed refrigerant stream

- has a pressure of approximately 3,000 psia.
32. The system of any one of paragraphs 26-31, wherein the intermediate pressure is less than 1,500 psia and greater than 1,000 psia.
33. The system of any one of paragraphs 26-32, further comprising:
- 5 a second driven compressor configured to compress the second compressed refrigerant stream.
34. The system of paragraph 33, further comprising:
- a driving element configured to drive the second driven compressor, wherein the driving element comprises at least one of a reciprocating engine, a steam turbine, a gas turbine,
- 10 and a motor.
35. The system of paragraph 33 or paragraph 34, wherein the first driven compressor and the second driven compressor share a common driver.
36. The system of any one of paragraphs 32-34, wherein the first driven compressor and the second driven compressor are within a single compressor casing.
- 15 37. The system of any one of paragraphs 26-33, further comprising a sub-cooling loop configured to further cool the cool feed gas stream to form a sub-cooled feed gas stream.
38. The system of paragraph 37, further comprising:
- a hydraulic turbine configured to expand the sub-cooled feed gas stream to a pressure greater than or equal to 50 psia and less than or equal to 450 psia, to thereby produce an
- 20 expanded, sub-cooled feed gas stream.
39. The system of paragraph 37 or paragraph 38, wherein the sub-cooling loop is a closed loop gas phase refrigeration cycle where nitrogen gas is the refrigerant.
40. A method for liquefying a feed gas stream comprising natural gas, the method comprising:
- 25 providing the feed gas stream at a pressure less than 1,200 psia;
- providing a compressed refrigerant stream with a pressure greater than or equal to 1,500 psia;
- cooling the compressed refrigerant stream by indirect heat exchange with a first cooling medium, thereby producing a compressed, cooled refrigerant stream;

expanding the compressed, cooled refrigerant stream in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream, wherein the first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor;

5       expanding the first expanded, cooled refrigerant stream in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream, wherein the second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor;

10       passing the second expanded, cooled refrigerant stream to one or more heat exchangers, thereby forming a warm refrigerant stream;

passing the feed gas stream through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream;

15       using a sub-cooling loop, further cooling the cool feed gas stream to form a sub-cooled feed gas stream having a liquid portion;

using the second coupled compressor and a first driven compressor, compressing the warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;

20       cooling the warm refrigerant stream by indirect heat exchange with a second cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor;

cooling the first compressed refrigerant stream via heat exchange with a third cooling medium;

25       compressing the first compressed refrigerant stream using the first coupled compressor, thereby forming a second compressed refrigerant stream;

cooling the second compressed refrigerant stream via heat exchange with a fourth cooling medium; and

30       compressing the second compressed refrigerant stream to provide the compressed refrigerant stream.

41. The method of paragraph 40, wherein at least one of the first cooling medium, the

second cooling medium, the third cooling medium, and the fourth cooling medium comprises air or water.

- [0063]** It should be understood that the numerous changes, modifications, and alternatives to the preceding disclosure can be made without departing from the scope of the disclosure.
- 5 The preceding description, therefore, is not meant to limit the scope of the disclosure. Rather, the scope of the disclosure is to be determined only by the appended claims and their equivalents. It is also contemplated that structures and features in the present examples can be altered, rearranged, substituted, deleted, duplicated, combined, or added to each other.

## CLAIMS

**What is claimed is:**

1. A method for liquefying a feed gas stream comprising natural gas, the method comprising:
  - 5 providing the feed gas stream at a pressure less than 1,200 psia;  
providing a compressed refrigerant stream with a pressure greater than or equal to 1,500 psia;  
cooling the compressed refrigerant stream by indirect heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant stream;
  - 10 expanding the compressed, cooled refrigerant stream in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream, wherein the first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor;
  - 15 expanding the first expanded, cooled refrigerant stream in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream, wherein the second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor;  
passing the second expanded, cooled refrigerant stream through one or more heat  
20 exchangers, thereby forming a warm refrigerant stream;  
passing the feed gas stream through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream;  
using the second coupled compressor and a first driven compressor, compressing the  
25 warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;  
compressing the first compressed refrigerant stream using the first coupled compressor, thereby forming a second compressed refrigerant stream; and  
compressing the second compressed refrigerant stream to provide the compressed  
30 refrigerant stream.

2. The method of claim 1, further comprising driving the first driven compressor using at least one of a reciprocating engine, a steam turbine, a gas turbine, and a motor.
3. The method claim 1 or claim 2, wherein cooling the compressed refrigerant stream comprises cooling the compressed refrigerant stream via indirect heat exchange with a cooling  
5 medium.
4. The method of any one of claims 1-3, wherein cooling the compressed refrigerant stream comprises cooling the compressed refrigerant stream by indirect heat exchange with a cooling medium having a temperature lower than ambient conditions.
5. The method of any one of claims 1-4, further comprising:  
10 cooling the warm refrigerant stream by indirect heat exchange with a cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor.
6. The method of any one of claims 1-5, further comprising:  
cooling the first compressed refrigerant stream prior to being compressed in the first  
15 coupled compressor.
7. The method of any one of claims 1-6, further comprising:  
cooling the second compressed refrigerant stream via indirect heat exchange with a cooling medium prior to being compressed to provide the compressed refrigerant stream.
8. The method of any one of claims 1-7, wherein the compressed refrigerant stream has a  
20 pressure of approximately 3,000 psia.
9. The method of any one of claims 1-8, wherein the intermediate pressure is less than 1,500 psia and greater than 1,000 psia.
10. The method of any one of claims 1-9, wherein compressing the second compressed refrigerant stream is accomplished using a second driven compressor.
- 25 11. The method of claim 10, further comprising:  
driving the second driven compressor using at least one of a reciprocating engine, a steam turbine, a gas turbine, and a motor.
12. The method of claim 10 or claim 11, wherein the first driven compressor and the second driven compressor share a common driver.
- 30 13. The method of any one of claims 10-12, wherein the first driven compressor and the

second driven compressor are within a single compressor casing.

14. The method of any one of claims 1-13, further comprising:

using a sub-cooling loop, further cooling the cool feed gas stream to form a sub-cooled feed gas stream.

5 15. The method of claim 14, further comprising:

expanding the sub-cooled feed gas stream to a pressure greater than or equal to 50 psia and less than or equal to 450 psia, to produce an expanded, sub-cooled feed gas stream.

16. The method of claim 14 or claim 15, wherein the sub-cooled feed gas stream is expanded within a hydraulic turbine.

10 17. The method of any one of claims 14-16, wherein the sub-cooling loop is a closed loop gas phase refrigeration cycle where nitrogen gas is the refrigerant.

18. The method of claim 14, wherein the sub-cooling loop comprises:

withdrawing a portion not to exceed 50% of the expanded, sub-cooled gas stream and reducing its pressure in a pressure reduction valve to a range of about 30 to 300 psia to produce

15 one or more reduced pressure gas streams; and

passing the one or more reduced pressure gas streams through the one or more heat exchangers as the sub-cooling refrigerant stream.

19. The method of claim 18, wherein the one or more reduced pressure gas streams are at different pressures from each other.

20 20. The method of claim 18 or claim 19, wherein the sub-cooling refrigerant stream exiting the one or more heat exchangers is compressed to a pressure approximate to that of the feed gas stream and is cooled by indirect heat exchange with a cooling medium before mixing the sub-cooling refrigerant stream with the feed gas stream.

21. The method of claim 15, wherein at least a portion of the expanded, sub-cooled gas stream is further expanded and then directed to a separation tank from which liquid natural gas is withdrawn and remaining gaseous vapors are withdrawn as a flash gas stream.

22. The method of claim 21, wherein the compressed refrigerant stream comprises boil off gas of the liquid natural gas.

23. The method of any one of claims 1-22, further comprising:

30 adjusting one or more of

a discharge pressure of one or more of the compressors, and

an inlet pressure of one or more of the expanders,

to thereby maintain a fixed differential pressure between the discharge pressure and the inlet pressure.

5 24. The method of claim 23, wherein the fixed differential pressure is obtained through control algorithms using one or more of compressor speed of one or more of the compressors, inlet guide vanes of one or more of the expanders, recycle valves of one or more of the compressors, and bypass valves of one or more of the expanders.

25. The method of any one of claims 23 and 24, further comprising:

10 using expander thrust bearing temperature as a limit to protect thrust bearing integrity while maximizing cycle efficiency.

26. A natural gas liquefaction system comprising:

a first heat exchanger configured to cool a compressed refrigerant stream by indirect heat exchange with a cooling medium, thereby producing a compressed, cooled refrigerant stream, wherein the compressed refrigerant stream is provided to the first heat exchanger at a pressure of at least 1,500 psia;

a first expander configured to expand the compressed, cooled refrigerant stream to an intermediate pressure, to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream;

20 a first coupled compressor mechanically coupled to the first expander to together form a first turboexpander-compressor;

a second expander configured to expand the first expanded, cooled refrigerant stream to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream;

25 a second coupled compressor mechanically coupled to the second expander to together form a second turboexpander-compressor;

one or more heat exchangers arranged to permit the second expanded, cooled refrigerant stream and a feed gas stream to pass therethrough and exchange heat therein through indirect heat exchange, thereby forming a warm refrigerant stream and a cool feed gas stream, wherein the feed gas stream comprises natural gas and is supplied to the one or more heat exchangers

at a pressure of less than 1,200 psia;

a first driven compressor configured to, along with the second coupled compressor, compress the warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;

5        wherein the first compressed refrigerant stream is further compressed using the first coupled compressor, thereby forming a second compressed refrigerant stream; and

wherein the second compressed refrigerant stream is compressed to provide the compressed refrigerant stream.

27.    The system of claim 26, further comprising a driving element configured to drive the  
10    first driven compressor, wherein the driving element comprises at least one of a reciprocating engine, a steam turbine, a gas turbine, and a motor.

28.    The system of claim 26 or claim 27, further comprising:

a first cooler configured to cool the compressed refrigerant stream via indirect heat exchange with a cooling medium.

15    29.    The system of claim 28, wherein the cooling medium has a temperature lower than ambient conditions.

30.    The system of any one of claims 26-29, further comprising:

a second cooler configured to cool the warm refrigerant stream by indirect heat exchange with a cooling medium after being compressed in the second coupled compressor  
20    and prior to being compressed in the first driven compressor;

a third cooler configured to cool the first compressed refrigerant stream prior to being compressed in the first coupled compressor; and

a fourth cooler configured to cool the second compressed refrigerant stream via indirect heat exchange with a cooling medium prior to being compressed, to thereby provide the  
25    compressed refrigerant stream.

31.    The system of any one of claims 26-30, wherein the compressed refrigerant stream has a pressure of approximately 3,000 psia.

32.    The system of any one of claims 26-31, wherein the intermediate pressure is less than 1,500 psia and greater than 1,000 psia.

30    33.    The system of any one of claims 26-32, further comprising:

a second driven compressor configured to compress the second compressed refrigerant stream.

34. The system of claim 33, further comprising:

5 a driving element configured to drive the second driven compressor, wherein the driving element comprises at least one of a reciprocating engine, a steam turbine, a gas turbine, and a motor.

35. The system of claim 33 or claim 34, wherein the first driven compressor and the second driven compressor share a common driver.

36. The system of any one of claims 32-34, wherein the first driven compressor and the  
10 second driven compressor are within a single compressor casing.

37. The system of any one of claims 26-33, further comprising a sub-cooling loop configured to further cool the cool feed gas stream to form a sub-cooled feed gas stream.

38. The system of claim 37, further comprising:

15 a hydraulic turbine configured to expand the sub-cooled feed gas stream to a pressure greater than or equal to 50 psia and less than or equal to 450 psia, to thereby produce an expanded, sub-cooled feed gas stream.

39. The system of claim 37 or claim 38, wherein the sub-cooling loop is a closed loop gas phase refrigeration cycle where nitrogen gas is the refrigerant.

40. A method for liquefying a feed gas stream comprising natural gas, the method  
20 comprising:

providing the feed gas stream at a pressure less than 1,200 psia;

providing a compressed refrigerant stream with a pressure greater than or equal to 1,500 psia;

25 cooling the compressed refrigerant stream by indirect heat exchange with a first cooling medium, thereby producing a compressed, cooled refrigerant stream;

expanding the compressed, cooled refrigerant stream in a first expander to an intermediate pressure to further cool the compressed, cooled refrigerant stream, thereby producing a first expanded, cooled refrigerant stream, wherein the first expander is mechanically coupled to a first coupled compressor to together form a first turboexpander-compressor;  
30

expanding the first expanded, cooled refrigerant stream in a second expander to further cool the first expanded, cooled refrigerant stream, thereby producing a second expanded, cooled refrigerant stream, wherein the second expander is mechanically coupled to a second coupled compressor to together form a second turboexpander-compressor;

- 5            passing the second expanded, cooled refrigerant stream through one or more heat exchangers, thereby forming a warm refrigerant stream;

             passing the feed gas stream through the one or more heat exchangers to cool at least part of the feed gas stream by indirect heat exchange with the second expanded, cooled refrigerant stream, thereby forming a cool feed gas stream;

- 10           using a sub-cooling loop, further cooling the cool feed gas stream to form a sub-cooled feed gas stream having a liquid portion;

             using the second coupled compressor and a first driven compressor, compressing the warm refrigerant stream to a discharge pressure within 300 psia of the intermediate pressure, thereby forming a first compressed refrigerant stream;

- 15           cooling the warm refrigerant stream by indirect heat exchange with a second cooling medium after being compressed in the second coupled compressor and prior to being compressed in the first driven compressor;

             cooling the first compressed refrigerant stream via heat exchange with a third cooling medium;

- 20           compressing the first compressed refrigerant stream using the first coupled compressor, thereby forming a second compressed refrigerant stream;

             cooling the second compressed refrigerant stream via heat exchange with a fourth cooling medium; and

- compressing the second compressed refrigerant stream to provide the compressed  
25    refrigerant stream.

41.    The method of claim 40, wherein at least one of the first cooling medium, the second cooling medium, the third cooling medium, and the fourth cooling medium comprises air or water.