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LIQUEFACTION OF NATURAL GAS FOR PEAK DEMANDS USING SPLIT-STREAM REFRIGERATION

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Fig 3.

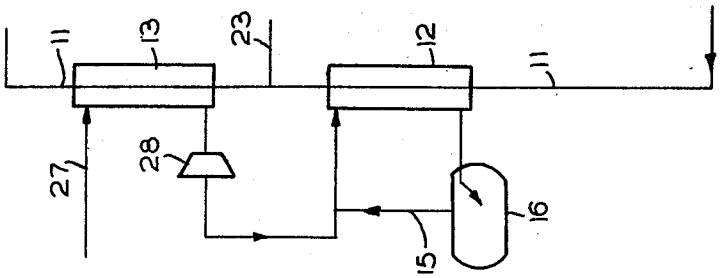


Fig 2.

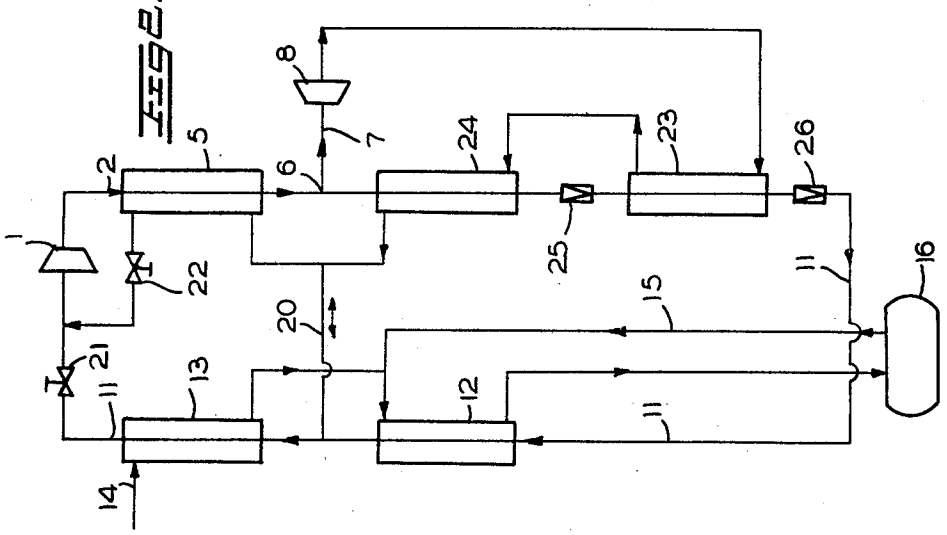
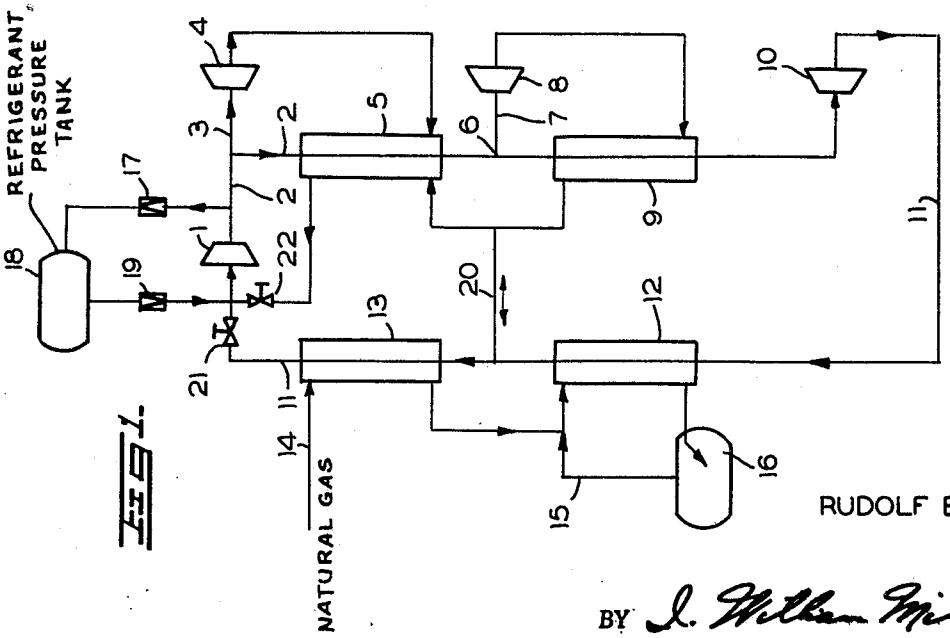


Fig 1.



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LIQUEFACTION OF NATURAL GAS FOR PEAK DEMANDS USING SPLIT-STREAM REFRIGERATION

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ABSTRACT OF THE DISCLOSURE

The liquefaction of natural gas wherein refrigerant gas is compressed in a circulation compressor and divided into a first and at least one other partial stream, the first partial stream being cooled by heat exchange with expanded other partial stream and then passed in heat exchange relationship to the natural gas. The expansion of the other partial stream is conducted with the production of external work, and the expanded gas is eventually recycled to the intake of the circulation compressor.

BACKGROUND OF THE INVENTION

This invention relates generally to a process and apparatus for the liquefaction of natural gas and, in particular, to a process and apparatus for liquefying natural gas by cooling through the means of indirect heat exchange with an external refrigerant gas having a lower boiling point than methane.

With the advent of wide consumer acceptance, the peak demand of gaseous heating fuel in winter months often cannot be met by the gas flowing from the long-range pipelines. The storage capability afforded by long-distance supply lines suffices only for short-term peaks that occur within a daily period. For increased demand over a longer period of time, additional storage capability must be provided, such storage capability entailing considerable expense. One solution to this problem involves a reduction in volume of the gas transported. For example, solid or liquid fuels can be gasified, or liquid fuel can be transported, vaporized, and fed to the consumer line. Each of these measures requires considerable investment in equipment and, in addition, high transmission expenses. It has therefore been the practice, previously, to construct large storage facilities to store liquefied or pressurized gases for the purposes of handling peak demands.

If the gases to be stored in the liquid phase, as a means of reducing the size of storage containers required, it is necessary to furnish a plant for liquefaction of gas during periods of low consumption. Such a plant must furthermore be capable of reliquefying gases vaporized from the storage containers through the unavoidable transfer of heat from the surroundings or, alternatively, forcing this vaporized gas under pressure back into the pipeline network. In this respect, the ambient pressures in the lines vary, depending upon the rate gas is supplied and consumed; thus, the liquefying plant must be capable of continuously adapting to the changing conditions.

Furthermore, gas transported over long distances, in most cases, still contains traces of moisture, carbon dioxide, and sulfur compounds which must be removed in order to prevent clogging of the heat exchangers and expansion devices in the liquefaction plant. These purification plants are extremely expensive since the entire quantity of gas to be expanded must be cleaned while only a small portion, in many cases only 1/5 or even only

1/50 thereof, ends up as stored liquid, depending upon the pressure differential available.

Since a liquefaction plant obviously operates only during the warm season, investment costs as compared to operating costs are of particular significance. (Furthermore, the liquefaction plant is only required when there is, in fact, an excess of gas.) During operation of the plant, the gas consumption required for operating the expansion devices must, from a standpoint of cost, be low. Finally, the operation of the plant also must be simple and as fully automated as possible, since it is difficult to find suitable experienced personnel for the short time the plant is to operate.

SUMMARY OF THE INVENTION

This invention provides a process for the liquefaction of natural gas by refrigeration. Refrigeration is obtained by means of a closed refrigeration cycle employing as the refrigerant an external gas, such as nitrogen having a lower normal boiling point than natural gas, i.e., lower than methane. The process is readily adaptable to the varying pressures of gas supplied from the long-distance gas supply lines and involves low initial investment costs without the necessity of expensive control means. Aside from nitrogen, other preferred refrigerants include, among others, argon and helium.

In accordance with the invention, the compressed refrigerant gas is branched into two or more partial streams, the first of which streams is cooled by heat exchange with expanded remaining partial stream. When the first partial stream is cooled by two or more expanded partial streams, such expanded partial streams are expanded in parallel to one another to the inlet or vacuum pressure of the refrigerant compressor. This expansion of the remaining partial gas streams is accomplished by means of engine expansion, i.e., expansion with the production of external work.

The first stream is cooled to such a degree that, after being expanded to the vacuum or intake pressure of the refrigerant compressor, the first stream is in the fluid phase at or close to saturation or to the saturation line of the temperature-entropy diagram for that refrigerant gas, that is 100% liquid to 95% liquid and 5% vapor.

In this respect, the inlet pressure of the circulation refrigerant compressor is predetermined so that, by subsequent heat exchange between the first partial stream boiling at the compressor inlet pressure and the natural gas under the storage pressure therefor, the natural gas is liquefied. Preferably, the first partial stream is cooled to such a degree that, after expansion, at least 95% of the stream is in the liquid phase.

The above-described mode of operation provides for the liquefaction of a natural gas, such as methane, under storage pressure, i.e., in most cases at about atmospheric pressure, thereby eliminating the need for a long-distance gas compressor for long-range low gas pressure transmission. Furthermose, the stored natural gas vaporized by the effect of heat transfer from the surroundings can be reliquefied without requiring the heating of the gas to ambient temperature for recompression. Since the vacuum or inlet pressure of a circulation compressor can be relatively high, the process can be operated at a relatively low pressure ratio, thereby requiring less compression stages. For example, in the case of pure methane as the gas to be liquefied and nitrogen as the refrigerant or cycle gas, the inlet pressure for the compressor is approximately 12 atmospheres absolute.

The required outlet pressure for the compressor depends upon the output demand. For smaller outputs, for example, on the order of 5,000 Nm.^{3}/h. (cubic meters at 0° C. and 1 atmosphere absolute per hour) of liquid

methane and below, the final compressor pressure is preferably up to 300 atmospheres gauge. For these purposes, a piston compressor may be utilized. For larger outputs, the final compressor pressure is preferably between approximately 50 and 200 atmospheres gauge. For this purpose, a tubocompressor is most suitable.

Due to the high operating pressures, more efficient heat transfer is achieved with a minimum pressure drop so that a minimum heat transfer surface is required. Also, as a result of the high pressures, the volume of gas to be cycled is reduced and therefore the size of the plant required is substantially smaller. In addition, an important advantage gained from the high pressures utilized in this process is that there is a relatively low over-all energy consumption.

In a further embodiment of this invention, where the natural gas is available under elevated supply pressures, the gas can be engine-expanded with the production of refrigeration, thereby reducing the required amount of external refrigeration for liquefaction thereof. The energy saving thereby obtained is particularly important where expanded, gaseous-phase natural gas can be fed into the consumer line under low pressure.

According to a further embodiment of the invention, the natural gas, if available at an elevated pressure of about 5 to 120, preferably 20 to 60 atmospheres absolute, is liquefied at the elevated pressure by correspondingly increasing the pressure level of the refrigerant gas to about 8 to 80, preferably 20 to 50 atmospheres absolute at the inlet pressure to the compressor. In all cases, the outlet pressure of the compressor is about 50 to 350, preferably 150 to 250 atmospheres. Since refrigeration is produced, in this manner, at a higher temperature level, a saving of energy results therefrom.

Because the entire refrigeration cycle in accordance with this invention operates at only two pressures, the refrigeration output of the apparatus can be easily regulated. Preferably, this is done by varying the amount of refrigerant in the system depending upon the pressure level in the storage tank in such a manner that, as soon as the pressure in the storage tank falls below a certain value, refrigerant gas is withdrawn from the cycle and fed into a pressure tank, thereby decreasing the amount of refrigerant in the cycle and the refrigeration produced by the device. When the pressure in the storage tank exceeds a predetermined value, refrigerant gas from the pressure tank is fed into the refrigeration system, thereby increasing the amount of refrigerant in the cycle and increasing the refrigeration output of the device.

The first partial stream to be liquefied can be either engine-expanded or throttle-expanded after precooling in heat exchangers. If, for simplicity, the throttle expansion method is preferred, at pressures above approximately 100 atmospheres absolute, it is advantageous to accomplish the expansion in two stages with intermediate cooling. By this means, the pressure-temperature range wherein the Joule-Thomson effect is negative, i.e., wherein temperature increase would occur during throttle expansion, can be circumvented.

An apparatus for conducting the process in accordance with this invention comprises a first high pressure line leading from the pressure side of a circulation compressor to an expansion device and a first low pressure line leading from the expansion device to the vacuum or inlet side of the circulation compressor. One or more further expansion devices, each of the high pressure sides of which are connected respectively to a further high pressure line branching off from the first high pressure line, and each of the low pressure sides of which are connected, by way of the first cross sections of heat exchangers, with the low pressure side of the circulation compressor, are likewise provided. The second cross section of the heat exchangers communicates with the first high pressure line. In addition, the first cross section of at least one heat exchanger is connected with the

first low pressure line, the second cross section thereof connecting the natural gas conduit with the storage tank.

BRIEF DESCRIPTION OF THE DRAWINGS

The process of this invention will now be described by way of example with reference to the drawings wherein:

FIG. 1 is a schematic illustration of an apparatus in accordance with the invention;

FIG. 2 is a schematic illustration of a variation of the embodiment of FIG. 1 in accordance with the invention; and

FIG. 3 is a partially schematic illustration of a variation of the embodiments of either FIG. 1 or FIG. 2 in accordance with the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

With reference now specifically to FIG. 1, the refrigerant gas is compressed in the compressor **1** to 100 atmospheres absolute, fed to the high pressure line **2**, and is thereafter branched off into first and second partial streams. The second partial stream, generally about 20 to 40%, preferably about 25 to 30% of the total compressed refrigerant, is conducted, by way of the conduit **3**, to a turbine **4** and expanded therein to the vacuum or inlet pressure of the compressor **1**. The refrigeration resulting from the expansion of the second partial stream is then transmitted to the heat exchanger **5** for cooling of the first partial stream as it flows therethrough. Downstream of the heat exchanger **5**, the first partial stream, flowing through the line **2**, is again divided at **6** and the third partial stream, generally about 30 to 60%, preferably about 35 to 50% of the total compressed refrigerant, is conducted by way of the conduit **7** to a turbine **8** for expansion therein to the inlet pressure of the compressor **1**. The expanded third partial stream is then conducted to a heat exchanger **9** for further cooling of the first partial stream flowing through the line **2**. The precooled first partial stream then is expanded in a turbine **10** to the inlet pressure of the compressor **1** at which point, due to the design of the system, the fluid therein is substantially completely in the liquid phase. Refrigerant is then conducted to countercurrent heat exchangers **12** and **13** through a low pressure line **11** for heat exchange with natural gas supplied by way of conduit **14** at a pressure of at least one atmosphere absolute. The natural gas is precooled in the heat exchanger **13** and then liquefied in the heat exchanger **12**. From the heat exchanger **12**, the incoming natural gas is directed to a storage tank **16**. Gas vaporized as an effect of heat transfer from the surroundings in the tank **16**, is circulated through the conduit **15** to the heat exchanger **12** for reliquefaction thereof.

The output of refrigeration is regulated as follows. When the output of refrigeration is too great, natural gas is liquefied at a greater rate than it is supplied to the device and vaporized in the storage tank **16** and, as a consequence, the pressure in the storage tank **16** decreases. Once the pressure in the tank has fallen below a predetermined value, usually about 0.9 to 1.5, preferably about 0.95 to 1.2 atmospheres absolute, a control valve **17** between a pressure tank **18** and the line **2** is opened to allow a portion of the refrigerant to escape from the refrigeration cycle into the pressure tank. As the pressure in the refrigeration system is reduced, the compressor and the turbines **8** and **10** process smaller quantites of gas, decreasing the rate of refrigeration, and thus produce lower outputs of liquefied product. This continues until the gas supply and the liquefaction product output are balanced, at which point the pressure in the storage tank **16** is increased until the valve **17** is closed. Conversely, when the output of the cycle is insufficient to liquefy the natural gas as it is supplied, the pressure in the storage tank **16** increases. As this pressure exceeds a predeter-

mined value, usually about 1.2 to 2, preferably about 1.4 to 1.6 atmospheres absolute, a control valve **19** between the pressure tank **18** and the upstream side of the compressor **7** is opened and the volume of refrigerant in the cycle is increased, thereby increasing the amount of refrigeration in the cycle, and concomitantly increasing the output of liquefied natural gas, until the pressure decreases to a point where the supply and the output are balanced, at which point the valve **19** closes.

Valves **21** and **22**, disposed on the upstream side of the heat exchangers **5** and **13**, respectively, serve in conjunction with a cross connection conduit **20** disposed to interconnect the lines between the heat exchangers **13**, **12** and **5**, **9**, respectively, to control the temperature available at the cold end of the heat exchangers **5** and **13**.

As an example, a system in accordance with aforedescribed method operated to liquefy methane utilizing a nitrogen refrigerant, functions with the compressor **1** having an inlet pressure of 12 atmospheres absolute and an output pressure of 100 atmospheres absolute. After expansion through the turbines **4**, **8**, and **10**, respectively, the various partial streams are at the inlet pressure of the compressor **1**, i.e., 12 atmospheres absolute.

Referring now to FIG. 2, another embodiment in accordance with this invention is illustrated schematically. In this process, the inlet or vacuum pressure of the compressor **1** is 12 atmospheres absolute while the outlet or final pressure thereof is 300 atmospheres absolute. Elements of the embodiment of FIG. 2 identical to those of FIG. 1 are indicated by like reference numerals.

The compressed refrigerant is first cooled in a heat exchanger **5** and is then divided into partial streams at **6**. One partial stream, generally about 50 to 75%, preferably about 60 to 70% of the total compressed refrigerant, is expanded to the inlet pressure of the compressor **1** through an expansion turbine **8** and is then recycled to the vacuum line of the compressor by way of countercurrent heat exchangers **23**, **24** and the countercurrent heat exchanger **5**. The remaining partial stream is cooled to a lower temperature in the heat exchanger **24**, expanded to an intermediate pressure of 30 atmospheres absolute in an expansion valve **25**, and, after further cooling in the heat exchanger **23**, is brought to a pressure of 12 atmospheres absolute by further expansion through a valve **26**. At this point, the refrigerant is in the liquid phase and is transmitted countercurrently through heat exchanger **12** and **13** in heat transfer relationship with the natural gas entering the device through line **14** at about 1 atmosphere absolute and then is recycled to the compressor **1**.

In the embodiment of FIG. 2, regulation of refrigeration output is accomplished by varying the rate of flow of refrigerant through the compressor **1** and the expansion turbine **8** by means of conventional process control devices

Referring now to FIG. 3, another embodiment in accordance with this invention is illustrated schematically. Components of the apparatus of FIG. 3 which are identical to those of the embodiments of FIGS. 1 and 2 are indicated like numerals. In the embodiment of FIG. 3, natural gas is supplied through line **27** at elevated pressure. As in the aforedescribed embodiments, the natural gas is precooled in the heat exchanger **13**. After precooling, the natural gas is engine-expanded in an expansion turbine to the pressure of the storage tank. **16**. The natural gas is then liquefied in the heat exchanger **12** and stored in the tank **16**. The remaining portion of the process can be identical to either that described for the embodiment of FIG. 1 or the embodiment of FIG. 2. As an example, natural gas supplied through the conduit **27** at a pressure of 30 atmospheres absolute, for example, is expanded to the pressure of the storage tank **16**. In heat exchanger **12**, the resultant engine-expanded gas is liquefied, together with the natural gas vaporized by the effect of the ambient heat in the tank **16**.

The preceding examples can be repeated with similar success by substituting the generically and specifically described reactants and operating conditions of this invention for those used in the preceding examples.

From the foregoing description, one skilled in the art can easily ascertain the essential characteristics of this invention, and without departing from the spirit and scope thereof, can make various changes and modifications of the invention to adapt it to various usages and conditions. Consequently, such changes and modifications are properly, equitably, and intended to be, within the full range of equivalence of the following claims.

What is claimed is:

1. In a process for the liquefaction of natural gas by a closed refrigeration cycle with an external refrigerant gas having a lower boiling point than methane, the steps comprising:

(a) compressing the refrigerant gas in a circulation compressor;

(b) dividing the compressed refrigerant gas into a plurality of partial streams;

(c) cooling a first partial stream by indirect heat exchange with remaining partial stream previously engine-expanded to substantially the inlet pressure of the circulation compressor;

(d) expanding the first partial stream to substantially the inlet pressure of the circulation compressor, said first partial stream, after cooling and expansion, being a fluid containing at least 95% liquid;

(e) passing said fluid containing at least 95% liquid in indirect heat exchange with the natural gas for complete liquefaction of said natural gas;

(f) maintaining the liquefied natural gas in a liquefied state and storing the entire quantity in a storage tank, the inlet pressure of the circulation compressor being such that the natural gas at storage pressure is liquefied by cooling in heat exchange with the first partial stream boiling at substantially the inlet pressure of the circulation compressor; and

(g) passing resultant vaporized refrigerant fluid from the step (e) to the inlet side of said circulation compressor.

2. A process according to claim **1** wherein said refrigerant gas is compressed to about 100–300 atmospheres gauge.

3. A process according to claim **1** wherein said refrigerant gas is compressed to about 50–200 atmospheres gauge.

4. A process according to claim **1** wherein the natural gas is available at an elevated pressure, and wherein the natural gas is engine-expanded to reduce the amount of refrigerant gas required for cooling thereof.

5. A process according to claim **1** wherein the natural gas is available at an elevated pressure, said elevated pressure being the liquefaction pressure of the natural gas.

6. A process as defined by claim **1**, wherein the refrigerant is nitrogen and is compressed in step (a) to 50–350 atmospheres gauge.

7. A process as defined by claim **1**, wherein said first partial stream in step (d) after cooling and expansion is about 100% liquid.

8. A process according to claim **1** with the provision that after cooling by said remaining partial stream the first partial stream is further cooled by at least a partial stream branched therefrom and engine expanded in parallel to said remaining partial stream.

9. In a process for the liquefaction of natural gas by a closed refrigeration cycle with an external refrigerant gas having a lower boiling point than methane, the steps comprising:

(a) compressing the refrigerant gas in a circulation compressor;

(b) dividing the compressed refrigerant gas into a plurality of partial streams;

(c) cooling a first partial stream by indirect heat exchange with remaining partial stream previously engine-expanded to substantially the inlet pressure of the circulation compressor;

(d) expanding the first partial stream to substantially the inlet pressure of the circulation compressor, said first partial stream, after cooling and expansion, being a fluid containing at least 95% liquid;

(e) passing said fluid containing at least 95% liquid in indirect heat exchange with the natural gas for complete liquefaction of said natural gas;

(f) maintaining the liquefied natural gas in a liquefied state and storing the entire quantity in a storage tank, the inlet pressure of the circulation compressor being such that the natural gas at storage pressure is liquefied by cooling in heat exchange with the first partial stream boiling at substantially the inlet pressure of the circulation compressor;

(g) passing resultant vaporized refrigerant fluid from the step (e) to the inlet side of said circulation compressor, and

(h) sensing the pressure in said storage tank and adjusting the flow of refrigerant fluid by discharging warm refrigerant gas into a pressure tank when the pressure in said storage tank falls below a predetermined value and feeding refrigerant fluid from the pressure tank into the inlet side of said circulation compressor when the pressure in the storage tanks exceeds a predetermined value.

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