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(54) NATURAL GAS LIQUEFACTION PROCESS TO EXTEND LIFETIME OF GAS WELLS

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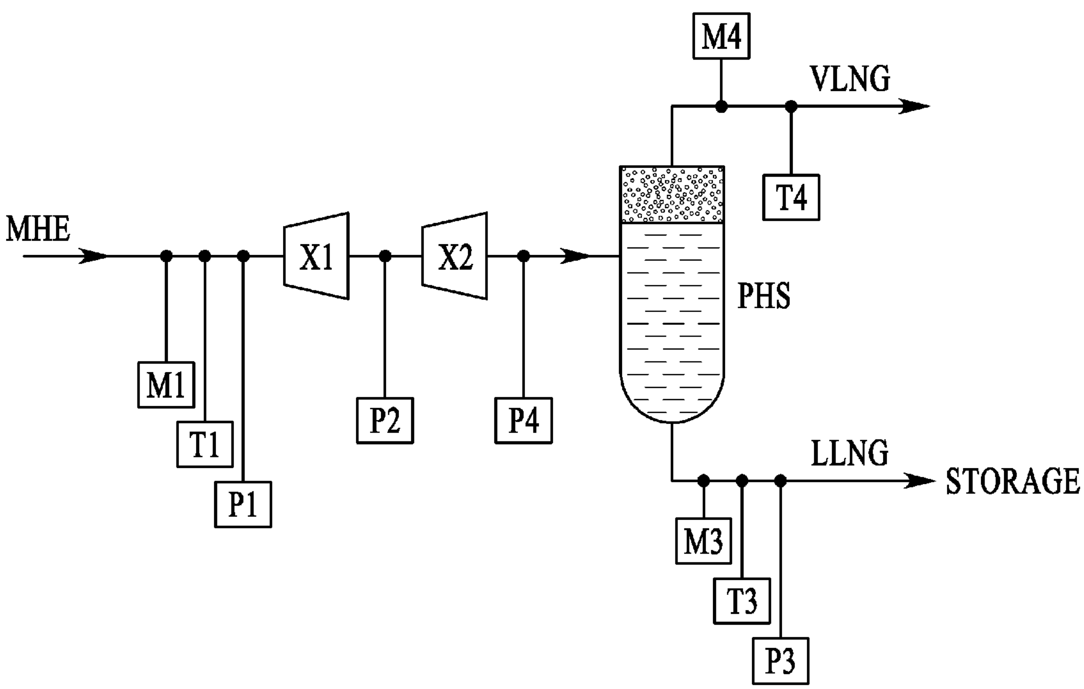
(57) **ABSTRACT**

A variable speed liquid LNG expander (X**1**) and a variable speed two-phase LNG expander (X**2**) in line, downstream from X**1**. The rotational speed of both expanders can be controlled and changed independent from each other. The speed of expander X**1** and expander X**2** is determined in such way that the amount of liquid LNG downstream from the PHS compared to the feed gas supply is maximized and the amount of vapor and boil-off downstream of X**2** is minimized.



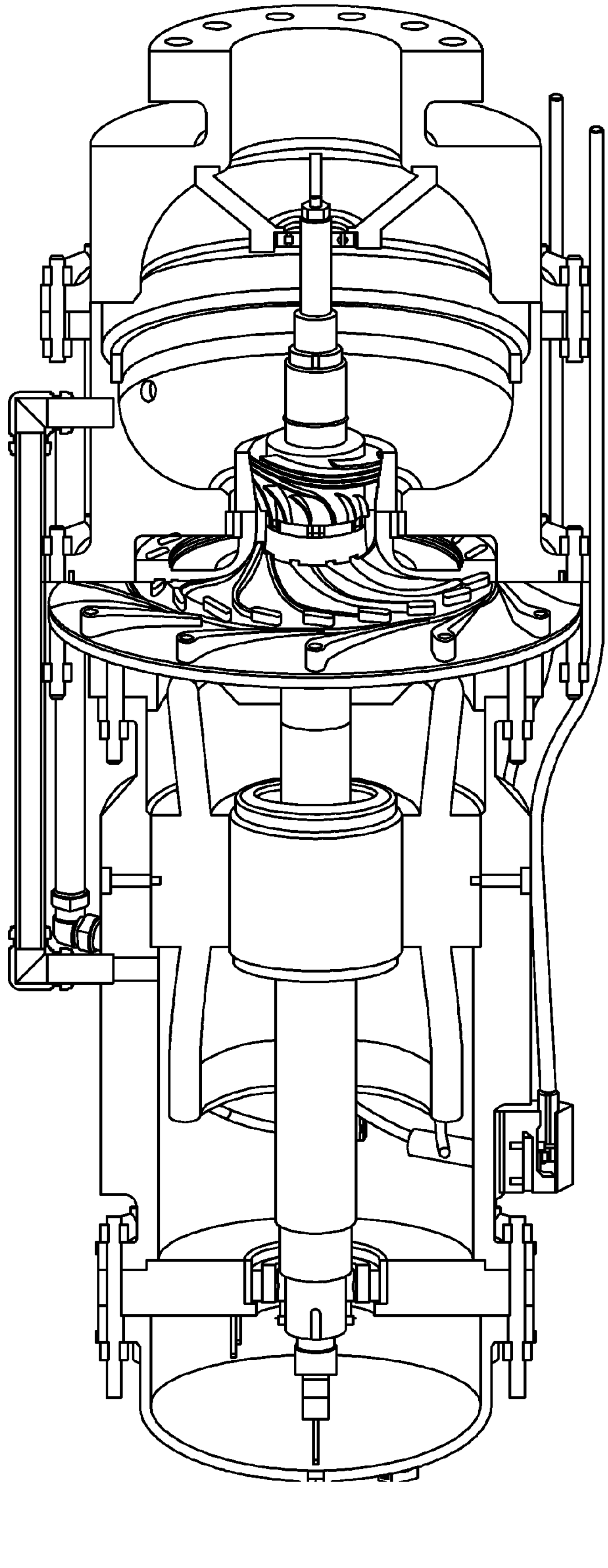


FIG.1
(PRIOR ART)

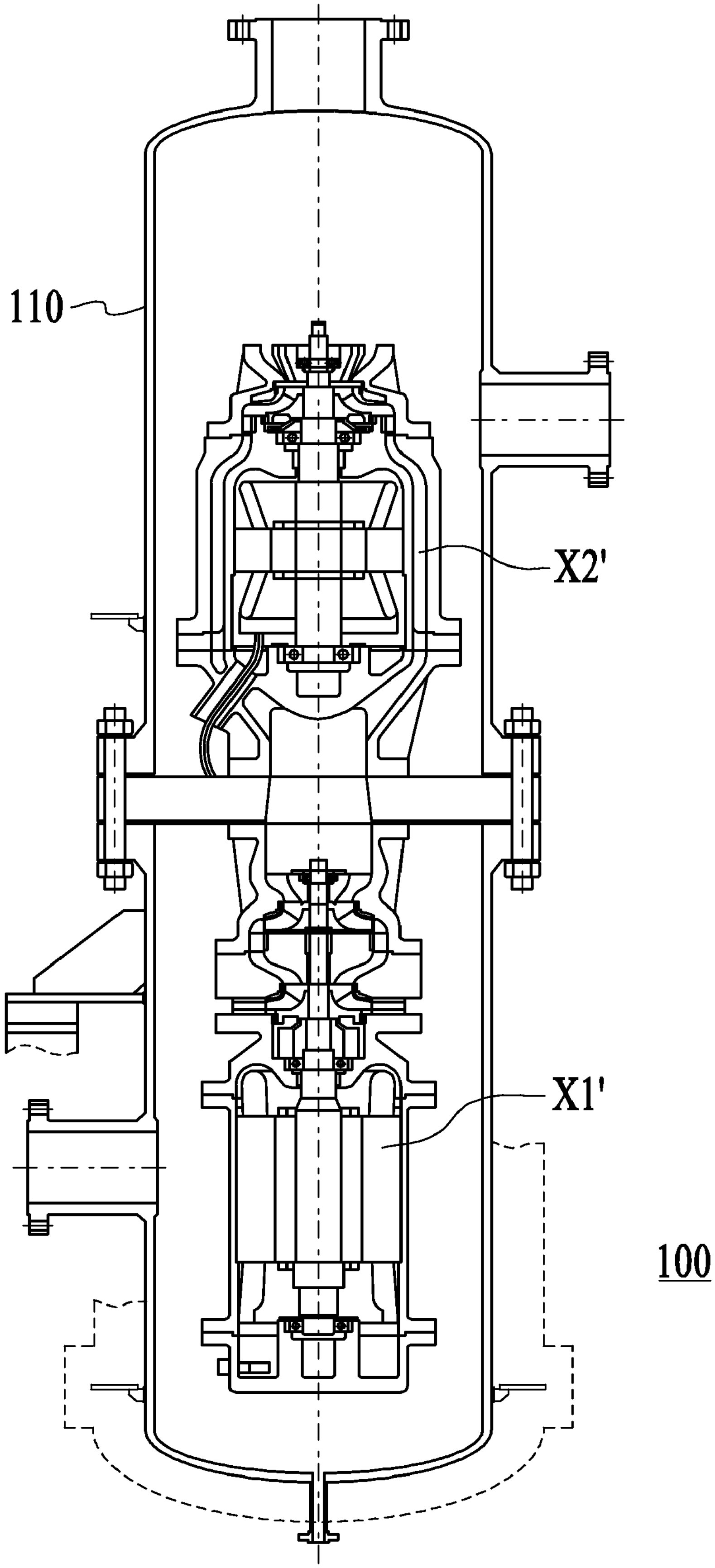


FIG.2

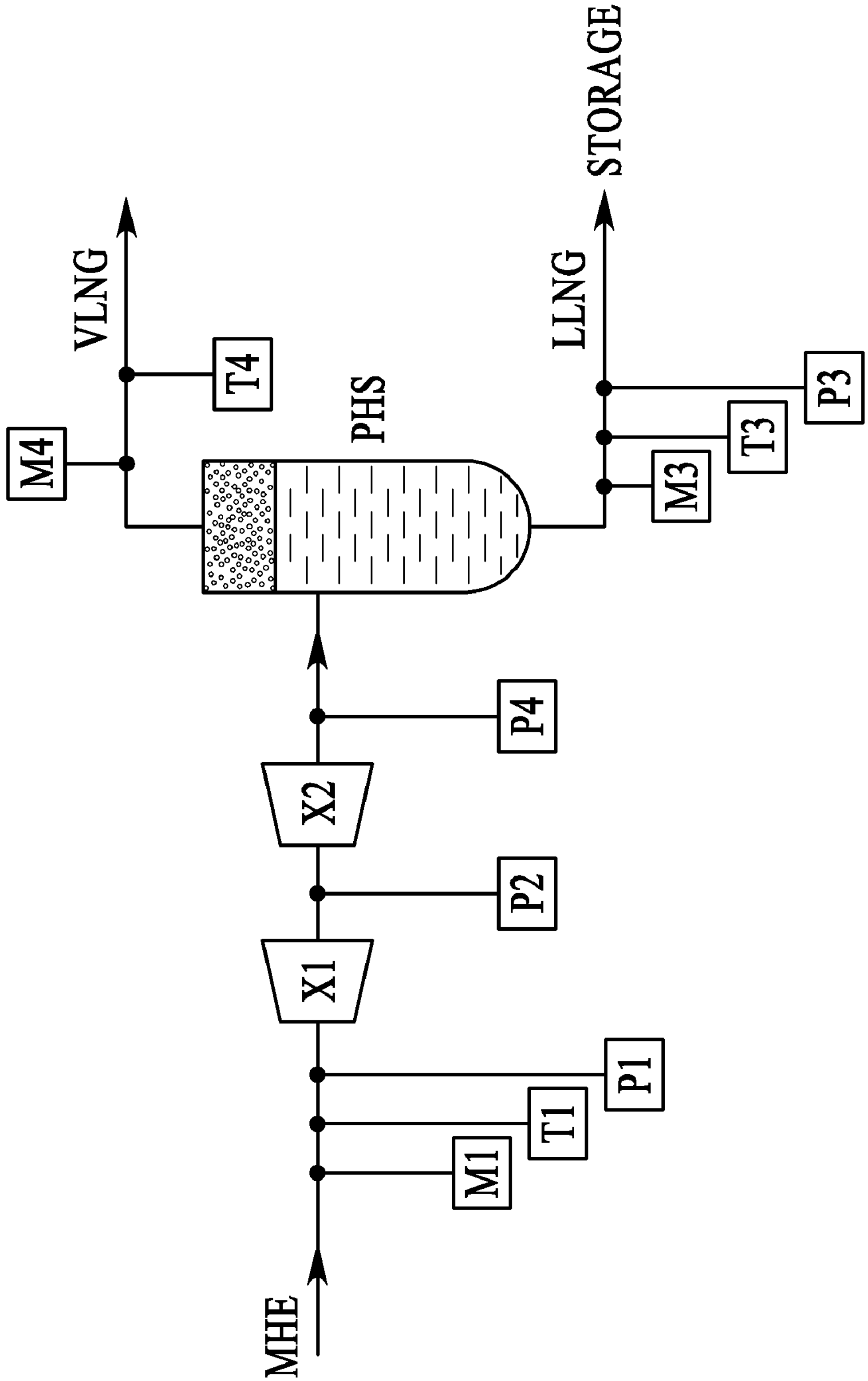


FIG.3

NATURAL GAS LIQUEFACTION PROCESS TO EXTEND LIFETIME OF GAS WELLS

FIELD OF THE INVENTION

[0001] The present invention relates to the method of production of natural gas (LNG), and more particularly to extension of the lifetime of gas wells by utilization of variable speed liquid LNG expander in series with a variable speed 2-phase LNG expander such that amount of liquid LNG produced to the feed gas supply is maximized and the amount of vapor and boil-off downstream is minimized.

BACKGROUND OF THE INVENTION

[0002] The depletion of natural gas wells is the subject of increasing technical and economic interest. There are several reasons for this growing interest:

- **[0003]** It is difficult to predict the time when the natural gas well starts to deplete and to estimate the remaining time until the well is completely exhausted.
- **[0004]** Upgrading the facility to an advanced technology is too expensive in relation to the risk connected with the depletion.
- **[0005]** Reduced pressure in the gas well requires injection with nitrogen gas and increases the overall liquefaction costs.

[0006] Dr William Cullen, Professor in Chemistry at the Universities of Glasgow and Edinburgh formulated in 1765 his theory of heat and combustion. In 1775 he developed a simple method for producing ice by simply evaporating the air and water vapor from a tank filled with liquid water. Today this refrigeration process is known as evaporation or vacuum cooling.

[0007] Evaporation cooling occurs at the liquid-vapor interface. A liquid-to-vapor phase change process requires vaporization heat, which is extracted from the remaining liquid part. Consequently any partial vaporization of a liquid cools the remaining part of the liquid.

[0008] Evaporation cooling is applied in gas liquefaction plants, particularly for natural gas liquefaction, to reduce the temperature of the liquefied gas below the condensation temperature. The necessary equipment to introduce evaporation cooling to the LNG liquefaction process is a two-phase LNG expander.

[0009] "New Cryogenic Two-Phase Expanders in LNG Production" by Kikkawa et al., "Two-Phase Expanders Increase Capacity of LNG Liquefaction Trains" by Iviukaiboh et al. and "Two-Phase LNG Expanders Replace Two-Phase Joule-Thomson Valves" by Chiu et al. describe the principle of single-phase and two-phase LNG expanders in their referred publications.

[0010] FIG. **1** (PRIOR ART) shows a cross section of the design of a two-phase LNG expander such as that manufactured and installed by Ebara International Corporation at the Krio Nitrogen Rejection Plant in Odolanow, Poland. "Improvements in Nitrogen Rejection Unit Performance with Changing Gas Compositions" by Cholast et al. and "Two-Phase LNG Expanders" by Kociemba et al. presented a detailed report on the performance of two-phase LNG expanders at the Krio site in Odolanow/Poland. The above mentioned articles are all hereby incorporated herein by reference in their entirety, without limitations.

[0011] There are some important differences in the performance of single-phase and two-phase LNG expanders. Two-phase LNG expanders vaporize a certain amount of LNG to sub-cool the remaining LNG. The reduction of pressure in two-phase expanders is relatively small compared to the pressure difference across a single phase LNG expander, as described in "LNG Expander for Extended Operating Range in Large-Scale Liquefaction Trains" by Kimmel et al. which is hereby incorporated herein by reference in their entirety, without limitations. The performance of single-phase expanders depend only on the mass flow, differential pressure and rotational speed, while the performance of two-phase expanders depends on the composition, temperature, inlet and outlet pressure, volumetric flow and rotational speed. Therefore, changes in the performance characteristic of two-phase expanders have to be adjusted to the momentary process data.

[0012] Depleting gas wells are in many cases events which are very difficult to predict in time. Once known, the possible solutions to be applied for depleting gas wells are the same as for new gas wells: To reduce the overall energy consumption for the liquefaction process to a minimum. Each existing equipment of the liquefaction plant has to be analyzed for possible energy savings, and eventually be replaced by more advanced equipment. The costs for upgrades are different for each piece of equipment and some improvements may not be economical for existing plants while other improvements are feasible solutions.

[0013] Single-phase and two-phase LNG expanders replacing Joule-Thomson valves increase the LNG production without increasing the energy consumption and are investments that have a payback time of less than six months. In addition, LNG expanders produce electrical energy that reduces the overall energy consumption, to gain the most benefits using LNG expanders.

OBJECTS AND ADVANTAGES OF THE PRESENT INVENTION

[0014] The paper presents a new approach to extend the lifetime of depleting gas fields. As used herein the term "LNG" refers to natural gas (primarily methane) which has been liquefied by refrigeration below the boiling point (e.g. −161.5° C., 111.7K depending on constituents of the gas) for storage and transport.

[0015] The installation and operation of two-phase LNG expanders reduces the required feed gas supply in existing liquefaction plants, thus extending the lifetime of the gas well. In addition, for nitrogen injected gas wells, or nitrogen rich feed gas, two-phase LNG expanders can handle such feed gas, resulting in sub-cooling the remaining LNG and reducing the entire boil-off downstream of the expander. The investment payback time for LNG expanders is less than six months. The overall plant profit increases by using two-phase LNG expanders in a base-load LNG plant despite the gas well depletion.

[0016] It is an object and advantage of the present invention to provide one variable speed liquid LNG expander (X**1**) and downstream one variable speed two-phase LNG expander (X**2**) in line. The rotational speed of both expanders can be controlled and changed independent from each other.

[0017] It is a further object and advantage of the present invention to describe a method to optimize the output of two expanders in series by varying the rotational speed of each one independently, to obtain the most and the coldest liquid LNG possible. The speed of the expander X**1** and the expander X**2** is determined in such way that the amount of liquid LNG compared to the feed gas supply is maximized and the amount of vapor and boil-off downstream of X2 is minimized.

[0018] It will be understood that in the present invention, there is no need to have a Joule Thompson valve (JT valve) if a two-phase expander is installed. There are essentially three ways to expand pressurized LNG: A. If liquefied LNG is expanded only across a JT valve without an expander, then there will be some vapor formation. B. If the LNG is expanded across a single phase, liquid only expander, then the outlet pressure of the expander has to be high enough not to allow the formation of vapor. The remaining pressure with vapor formation is then expanded across an additional JT valve. This solution is necessary to avoid vapor in the expander. C. If the LNG is expanded across a two-phase (liquid+vapor) expander, then there is no need to provide a JT valve because the two-phase expander expands to relieve the full pressure. Two-phase expanders tolerate vapor in the machine.

[0019] As described, it is an object and advantage of the present invention to extend the lifetime of gas wells by decreasing boil-off gas, essentially requiring less gas from the well to maintain the same level of production. Additionally, it is yet a further object and advantage of the present invention is to reduce the importance of lifetime of the gas well, since the same method can be applied to increase production from the gas well. Thus, essentially the same amount of feed gas from the well produces more liquid output.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] FIG. **1** (PRIOR ART) shows a cross section of a design of a two-phase LNG expander such as that manufactured and installed by Ebara International Corporation at the Krio Nitrogen Rejection Plant in Odolanow, Poland.

[0021] FIG. **2** shows a possible assembly of the present invention consisting of one single-phase expander and one two-phase expander operating in series and mounted together in tandem configuration.

[0022] FIG. **3** shows a liquefaction process of the present invention for optimum sub-cooling of LNG using one single-phase X**1** and one two-phase X**2** LNG expander both operating on variable rotational speed.

DETAILED DESCRIPTIONS OF THE VARIOUS EMBODIMENTS

[0023] The description that follows is presented to enable one skilled in the art to make and use the present invention, and is provided in the context of a particular application and its requirements. Various modifications to the disclosed embodiments will be apparent to those skilled in the art, and the general principals discussed below may be applied to other embodiments and applications without departing from the scope and spirit of the invention. Therefore, the invention is not intended to be limited to the embodiments disclosed, but the invention is to be given the largest possible scope which is consistent with the principals and features described herein.

[0024] It will be understood that while numerous preferred embodiments of the present invention are presented herein, numerous of the individual elements and functional aspects of the embodiments are similar. Therefore, it will be understood that structural elements of the numerous apparatus disclosed herein having similar or identical function may have like reference numerals associated therewith.

[0025] FIG. **2** shows a possible assembly **100** of the present invention consisting of one single-phase expander and one two-phase expander operating in series and mounted together in tandem configuration. The single-phase expander X**1** for larger pressure differences and two-phase expander X**2** for smaller pressure differences are able to operate independently on different rotational speeds.

[0026] To comply with the differences in the performance of single-phase and two-phase LNG expanders, U.S. Patent Application No. 60/705,800 filed Aug. 6, 2005 entitled "Compact Configuration for Cryogenic Pumps and Turbines" by Madison, which is hereby incorporated herein by reference in their entirety without limitations, presented an assembly of one single-phase expander X**1'** and one two-phase expander X**2'** operating in series and mounted together in tandem configuration within one pressure vessel **110**.

[0027] It will be understood that while FIG. **2** shows expander X**1'** in series with expander X**2'** and both contained within a single surrounding vessel, the present invention is not limited thereby. The present invention is directed to optimization of two or more expanders operating in series, either within a single reactor or surrounding enclosure **110** or not.

[0028] FIG. **3** shows a liquefaction process of the present invention for optimum sub-cooling of LNG using one single-phase X**1** and one two-phase X**2** LNG expander both operating on variable rotational speed. The phase separator PHS is installed downstream and close to the two-phase expander X**2**. To gain the most benefits from the evaporation cooling process it is necessary to separate the LNG liquid and vapor immediately after the vaporization takes place. During this transitional non-steady state at the exit of the two-phase expander X**2** the liquid portion of the LNG is much colder than the vapor portion, and immediate phase separation prevents re-heating of the liquid portion.

[0029] The pressurized condensed LNG from the main heat exchanger MHE enters the liquid expander X**1** under the inlet condition T**1** (temperature), P**1** (inlet pressure) and M**1** (mass flow). The rotational speed of X**1** is set to expand the LNG to the outlet pressure P**2**, which is also the inlet pressure for X**2**. The rotational speed of X**2** is set to optimize the ratio between LNG liquid (LLNG) and vapor (VLNG) under certain conditions. Dependent on the existing process the preferred condition is to produce the most and the coldest LNG. This is achieved through the optimization of a parameter V, where V is one of seven specific ratios of temperature and mass flow rate measured at various locations within the process.

[0030] By optimizing the operation of X**1** and X**2** for the production of the most and coldest LNG, expressed by the value of V, reduces the energy costs and feed gas consumption of the liquefaction plant. The produced LNG vapor is partially re compressed, used as fuel for the gas turbines, or used as cooling medium in heat exchangers.

[0031] The variable speed liquid expander X**1** and the variable speed two-phase expander X**2** are in line, whereas X**2** is downstream of X**1**. From the Main Heat Exchanger of a regular liquefaction process the condensed LNG flows into X**1**, then into X**2** and then into the Phase Separator PHS. X**1**, X**2** and PHS are mounted close together to avoid unnecessary losses in the piping system.

[0032] The Phase Separator separates the liquid LNG portion from the vapor LNG portion. The vapor LNG (VLNG) is extracted on top of the PHS and the liquid LNG portion (LLNG) is extracted from the bottom of the PHS.

[0033] At the inlet of X1 are equipment to measure the mass flow M1, the temperature T1 and the pressure P1 of the incoming LNG.

[0034] At the outlet of X1 and the inlet X2 is the equipment to measure the pressure P2.

[0035] At the outlet of the PHS for the liquid portion LLNG but located as close as possible to the LLNG storage are equipment to measure the mass flow M3, the temperature T3 and the pressure P3.

[0036] At the outlet of PHS for the vapor portion VLNG is the equipment to measure the mass flow M4 and the temperature T4 of the LNG vapor.

[0037] The operation of X1 and X2 is determined by a central process control. The purpose is to obtain and maintain a maximum liquid temperature difference between T3 (temperature of LLNG) and T1 (temperature of LNG at inlet to X1) while keeping as close to constant the mass flow rates M1, M3, and M4. Therefore, the object is to optimize one of the following values V1, V2, V3, V4, V5, V6, or V7.

$V1=(T1-T3)/(M1-M3)$>>>search for maximum value

$V2=M3/M1$>>>search for maximum value

$V3=(T1-T3)M3/M1$>>>search for maximum value

$V4=M1-M3$>>>search for minimum value

$V5=(T1-T3)\times(M3-M4)$>>>search for maximum value

$V6=(T1-T3)\times M3-(T1-T4)\times M4$>>>search for maximum value

$V7=(T1-T3)\times M3/((T1-T4)\times M4)$>>>search for maximum value

To Search for Optimum Values:

[0038] Step 1: For a certain flow M1 the rotational speed of X1 parameter S is a first chosen and will produce a pressure difference P2−P1. The rotational speed R of X2 is determined by the pressure difference P3−P2.

[0039] Step 2: The corresponding values of M1, M3, M4, T1, T3 and T4 are measured and at least one of the values V1 through V7 is calculated.

[0040] Step 3: Based on the value calculated in Step 2, the parameter S (S=rotational speed of X1) is varied by a small amount, thus the rotational speed R of X2, and measured values M1, M3, M4, T1, T3, and T4 change.

[0041] Then Step 2 and 3 are repeated, The new value of V is compared to the previous value and the speed of X1 is adjusted. By measuring, calculating and comparing values and adjusting speed parameter S results in a more or less optimized value.

[0042] By repeating the steps until the optimum of at least one of the values V1 through V7 is found, the purpose of the invention is achieved: to minimize the feed gas supply by reducing the LNG vaporization and the LNG boil-off downstream the expanders. Reducing the feed gas supply for a given output of liquid LNG extends the lifetime of the gas well.

[0043] For every change of the composition, temperature and pressure of the LNG this procedure has to be repeated, because the optimum performance of the two-phase expander depends on these values and any change in the plant condition will effect the optimization. A frequent or continuous search for the optimum is proposed.

[0044] The maximum design pressure for X1 is greater than the maximum pressure difference (P2−P1), and for a preferred embodiment the maximum design pressure difference is approximately $(P2-P1)+0.5\times(P4-P2)$.

[0045] P4 is the outlet pressure at X2.

[0046] In another embodiment and in addition to the maximum design pressure for X1 as described above, the maximum design pressure for X2 is greater than the maximum pressure difference (P4−P2). These embodiments allow the operation of X1 and X2 in such a manner that one expander is expanding a higher pressure difference than the other. In any operational case the total pressure difference will not exceed the difference (P4−P1).

Extension of Lifetime of Gas Well Vs. Increase in Production of Gas Well

[0047] As described above, the present invention can extend the lifetime of gas wells by decreasing boil-off gas, essentially requiring less gas from the well to maintain the same level of production. Additionally, the present invention is a method to increase production from the gas well. Thus, essentially the same amount of feed gas from the well produces more liquid output. The same methodology can be used to either extend the lifetime of the gas well or used to increase production from the gas well, depending upon plant economics or other plant operating policy.

[0048] Both increasing the life time for a given output and increasing production for a given input are analog goals in the present invention. The proposed method reduces the temperature of the produced LNG. Causing this reduction in temperature has the following benefit: Downstream of the expander and phase separator the LNG can be transferred to other locations and stored either in fixed storage tanks or in mobile tanker ships.

[0049] During these transfer and storage operations, heat from the environment is conducted to the LNG and warms up the LNG, thus vaporizing a volume of LNG. This vaporized LNG, also named boil-off, is usually lost and has to be resupplied by the feed gas. The amount of heat supplied by the environment is directly related to the volume of LNG vaporized by the heat.

[0050] Thus, reducing the boil-off of liquid LNG downstream of the expander and phase separator reduces the feed gas supply rate requirement for a given LNG output and extends the life time of the well. However, reducing the boil-off of liquid LNG downstream of the expander and phase separator for a given feed gas supply rate increase results in an increase in production. It will be understood that a balancing of these outcomes can be achieved in order to optimize the plant economics. Driving the system in one direction or another will depend upon the goals set by the operating engineers, design engineers and plant management.

CONCLUSION

[0051] Installation and use of a variable speed two-phase LNG expanders in combination with variable speed single-phase LNG expander in conjunction with the above described optimization method, presents the most advantageous solution for improving existing and new liquefaction plants, reducing the overall feed gas supply by reducing the overall energy consumption and extending the lifetime of gas wells.

With its short payback time of less than six months LNG expanders are economical solutions for existing and new liquefaction plants.

[0052] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which the present invention belongs. Although any methods and materials similar or equivalent to those described can be used in the practice or testing of the present invention, the preferred methods and materials are now described. All publications and patent documents referenced in the present invention are incorporated herein by reference.

[0053] While the principles of the invention have been made clear in illustrative embodiments, there will be immediately obvious to those skilled in the art many modifications of structure, arrangement, proportions, the elements, materials, and components used in the practice of the invention, and otherwise, which are particularly adapted to specific environments and operative requirements without departing from those principles. The appended claims are intended to cover and embrace any and all such modifications, with the limits only of the true purview, spirit and scope of the invention.

We claim:

1. A method of producing liquefied natural gas (LNG) consisting of the steps of installing and operating a single phase LNG expander in series with a two-phase LNG expanders and optimizing the system to produce a maximum amount of liquid LNG at the coldest temperature.

2. The method of claim **1** further comprising the following step:

Reducing the boil-off of liquid LNG downstream of the expander and phase separator to reduce the feed gas supply rate requirement for a given LNG output and extend the life time of the well.

3. The method of claim **1** further comprising the following step:

Reducing the boil-off of liquid LNG downstream of the expander and phase separator for a given feed gas supply rate increase to increase overall LNG production.

4. The method of claim **1** further comprising the following steps:

Reducing the boil-off of liquid LNG downstream of the expander and phase separator to reduce the feed gas supply rate requirement for a given LNG output and extend the life time of the well; and

Reducing the boil-off of liquid LNG downstream of the expander and phase separator for a given feed gas supply rate increase to increase overall LNG production.

5. The method of claim **4** further comprising the following step:

Balancing the outcomes of extending the lifetime of the well and increasing the overall LNG production rate to optimize the plant economics.

6. A method of extending the lifetime of a depleting natural gas well consisting of the steps of installing and operating a single phase LNG expander in series with a two-phase LNG expander and optimizing the system to produce a maximum amount of liquid LNG at the coldest temperature.

7. A method to extend the lifetime of depleting nitrogen rich natural gas fields, the method consisting of the following steps:

installing two-phase LNG expanders in existing liquefaction plants;

operating the expanders to process such nitrogen rich feed gas; and

sub-cooling the remaining LNG, thereby reducing the entire boil-off downstream of the expander.

8. The method of claim **7** in which the nitrogen rich natural gas fields are nitrogen injected prior to processing the feed gas.

9. The method of claim **7** further comprising the step of controlling the rotational speed of the expanders.

10. The method of claim **7** in which the step of installing two-phase LNG expanders further comprises operating one variable speed liquid LNG expander (**X1**) and one variable speed two-phase LNG expander (X**2**) in series.

11. The method of claim **9** further comprising the step of independently controlling the rotational speed of the expanders.

12. The method of claim **10** further comprising the step of controlling the rotational speed of the expanders.

13. The method of claim **12** further comprising the step of independently controlling the rotational speed of the expanders.

14. The method of claim **10** further comprising the step of controlling the rotational speed of expander X**1** and expander X**2** such that the amount of liquid LNG downstream from the expanders compared to the feed gas supply is maximized.

15. The method of claim **10** further comprising the step of controlling the rotational speed of expander X**1** and expander X**2** such that the amount of vapor LNG and boil-off downstream of X**2** is minimized.

16. A system for use in liquefaction plants for extending the lifetime of a depleting natural gas well, the system comprising a plurality of controllable variable speed LNG expanders in series.

17. The system of claim **16** which the plurality of controllable variable speed liquid LNG expanders comprises a controllable variable speed liquid LNG expander X**1** and a controllable variable speed two-phase LNG expander X**2**.

18. The system of claim **16** which the output of X**1** is fluidically coupled to the inlet of the X**2**.

19. The system of claim **16** in which X**1** and X**2** are independently controllable.

20. The system of claim **17** in which X**1** and X**2** are independently controllable.

21. The system of claim **17** in which the speeds of X**1** and X**2** are determined such that the amount of liquid LNG downstream from X**2** compared to the feed gas supply to X**1** is maximized.

22. The system of claim **17** in which the speeds of X**1** and X**2** are determined such that the amount of vapor LNG and boil-off downstream of X**2** is minimized.

23. The system of claim **16** further comprising a nitrogen injector for enriching the natural gas well with nitrogen.

24. A system for processing condensed LNG, such as that produced from a main heat exchanger (MHE) at a liquefaction plant, which extends the lifetime of a depleting natural gas well, the system comprising:

a controllable variable speed liquid LNG expander (X**1**) downstream of the MHE, X**1** in series with a controllable variable speed two-phase LNG expander (X**2**) wherein X**2** is downstream from X**1**; and

a phase separator (PHS) for separating the liquid LNG (LLNG) portion from the vapor LNG (VLNG) portion.

25. The system of claim **24** in which the VLNG is extracted on top of the PHS and the LLNG is extracted from the bottom of the PHS.

26. The system of claim **24** in which X**1**, X**2** and PHS are mounted as close together as possible to avoid unnecessary losses in the piping system.

27. The system of claim **24**, further comprising:

Equipment to measure the mass flow rate M**1**, the temperature T**1** and the pressure P**1** of the incoming LNG, the equipment located at the inlet of X**1**.

28. The system of claim **24**, further comprising:

Equipment to measure the pressure P**2** at the outlet of X**1** and the inlet X**2**.

29. The system of claim **24**, further comprising:

Equipment to measure the mass flow M**3**, the temperature T**3** and the pressure P**3** at the outlet of the LLNG stream of the PHS.

30. The system of claim **29** in which measuring equipment M**3**, T**3** and P**3** are located as close as possible to LLNG storage area equipment at a liquefaction plant.

31. The system of claim **24**, further comprising:

Equipment to measure the pressure P**4** at the outlet of X**2**.

32. The system of claim **24**, further comprising:

Equipment to measure the mass flow M**4** of the VLNG at the outlet of the PHS.

33. The system of claim **24**, further comprising:

Equipment to measure the temperature T**4** of VLNG at the outlet of PHS.

34. A system for use in liquefaction plants for extending the lifetime of a depleting natural gas well, the system comprising:

a controllable variable speed liquid LNG expander (X**1**) fluidically coupled to a stream of condensed LNG such as that produced by a main heat exchanger (MHE) in a liquefaction plant, X**1** downstream of the MHE, X**1** in series with a controllable variable speed two-phase LNG expander (X**2**) wherein X**2** is downstream from X**1**;

a phase separator (PHS) for separating the liquid LNG (LLNG) portion from the vapor LNG (VLNG) portion, the VLNG optionally is extracted from the top of the PHS and the LLNG extracted from the bottom of the PHS, wherein X**1**, X**2** and PHS are mounted as close together as possible to avoid unnecessary losses in the piping system;

equipment to measure the mass flow rate (M**1**), the temperature (T**1**) and the pressure (P**1**) of the incoming LNG, the equipment located at the inlet of X**1**;

equipment to measure the pressure (P**2**) at the outlet of X**1** and the inlet X**2**;

equipment to measure the mass flow (M**3**), the temperature (T**3**) and the pressure (P**3**) at the outlet of the LLNG stream of the PHS, wherein measuring equipment M**3**, T**3** and P**3** are located as close as possible to LLNG storage area equipment at the liquefaction plant;

equipment to measure the pressure (P**4**) at the outlet of X**2**;

equipment to measure the mass flow (M**4**) of the VLNG at the outlet of the PHS; and

equipment to measure the temperature (T**4**) of VLNG at the outlet of PHS.

35. A method for optimum sub-cooling of LNG comprising the following steps:

Introducing the pressurized condensed LNG from a main heat exchanger or other supply source (MHE) to an initial liquid expander (X**1**) under inlet temperature (T**1**), inlet pressure (P**1**) and mass flow (M**1**);

Setting the rotational speed of X**1** to expand the LNG to the outlet pressure (P**2**); and

Setting the rotational speed of X**2** to optimize the ratio between liquid LNG (LLNG) and vapor (VLNG), whereby the process is optimized to produce the greatest volume of LNG and the coldest LNG.

36. A method for optimum sub-cooling of LNG comprising the following steps:

Introducing the pressurized condensed LNG from a main heat exchanger or other supply source (MHE) to an initial liquid expander (X**1**) under inlet temperature (T**1**), inlet pressure (P**1**) and mass flow (M**1**);

Setting the rotational speed of X**1** to expand the LNG to the outlet pressure (P**2**);

Setting the rotational speed of X**2** to optimize the ratio between liquid LNG (LLNG) and vapor (VLNG), whereby the process is optimized by either maximizing one of the following values:

$$V1=(T1-T3)/(M1-M3);$$

$$V2=M3/M1;$$

$$V3=(T1-T3)M3/M1;$$

$$V5=(T1-T3)\times(M3-M4);$$

$$V6=(T1-T3)\times M3-(T1-T4)\times M4;$$

$$V7=(T1-T3)\times M3/((T1-T4)\times M4);$$

or minimizing the following value V**4**:

$$V4=M1-M3;$$

with temperature T**1** at the inlet to X**1**, temperature T**3** of the liquid outlet of the PHS, temperature T**4** of the vapor leaving PHS, mass flow M**1** into X**1**, liquid mass flow M**3** out of the PHS, vapor mass flow M**4** out of the PHS and pressure P**3** at the LNG liquid outlet.

37. In a system comprising:

a. X**1**, a variable-speed liquid LNG expander;

b. X**2**, a variable-speed, two-phase LNG expander;

c. MHE, a main heat exchanger or other source of liquid LNG;

d. PHS, a phase separator in which liquid LNG is separated from the vapor LNG, the liquid LNG is extracted from the bottom of the PHS and piped to storage, and the vapor LNG is extracted from the top of the PHS;

e. M**1**, T**1** and P**1**, equipment to measure the mass flow rate, temperature and pressure at the inlet of X**1**;

f P**2**, equipment to measure pressure between X**1** and X**2**;

g. P**4**, equipment to measure pressure at outlet of X**2**;

h. M**3**, T**3** and P**3**, equipment to measure the mass flow rate, temperature and pressure of the liquid LNG extracted from the PHS; and

i. M**4** and T**4**, equipment used to measure the mass flow rate and temperature of the vapor LNG at the outlet of the PHS;

the method comprising the following steps:

1. Setting a rotational speed of X**1**, thereby producing an initial pressure differential P**2**−P**1**;
2. Determining the rotational speed of X**2** based on the resulting pressure differential P**3**−P**2**;

3. Measuring M**1**, M**3**, M**4**, T**1**, T**3** and T**4** data and performing optimization calculations thereon;
4. Adjusting rotational speeds X**1** and X**2** to adjust the pressure differentials; and
5. Repeating steps 2-4, until optimization of the system is achieved and maintained.

38. The method of claim **37** in which the maximum design pressure for X**1** is greater than P**2**−P**1** and is preferred to be P**2**−P**1**+0.5(P**4**−P**2**), further comprising the following step:

fluctuating the pressure differential across X**1** to maintain significant pressure differential across X**2**.

39. The method of claim **37** in which one expander is operating at a higher pressure differential than the other, but the total pressure differential across both expanders will not exceed P**4**−P**1**.

40. A method for both extending the life time of a gas well for a given output of LNG and increasing production of LNG for a given input, the method comprising the following steps:

Reducing the temperature of the produced LNG; and

Transferring the LNG to other locations downstream of the expander and phase separator such as for storage or transportation of the LNG in tanks;

Allowing heat transfer during liquid transfer operations from the environment to the LNG thereby resulting in warming up the LNG and thus boil-off of a volume of LNG;

Optionally reducing the boil-off of liquid LNG downstream of the expander and phase separator to reduce the feed gas supply rate requirement for a given LNG output and extend the life time of the well; and

Optionally reducing the boil-off of liquid LNG downstream of the expander and phase separator for a given feed gas supply rate increase to increase overall LNG production.

41. The method of claim **40** in which a balancing of the outcomes can be achieved in order to optimize the plant economics.

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