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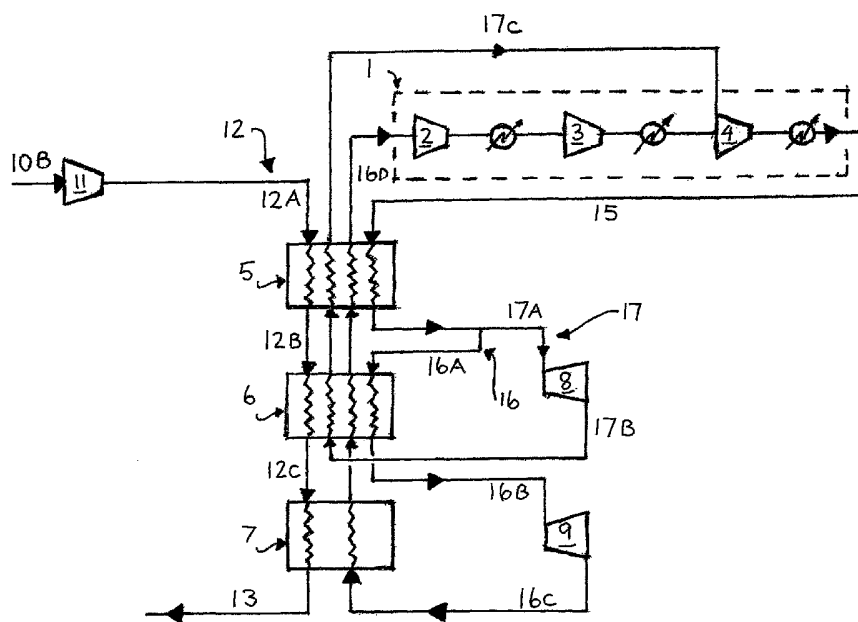
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(54) Title: METHOD FOR RE-LIQUEFACTION OF BOIL-OFF GAS



(57) Abstract: A method for re-liquefaction of a stream of boil-off gas (12), wherein the boil-off gas is being cooled and liquefied in a closed-loop refrigeration system before being returned (13) to a storage vessel (20). The refrigeration comprises splitting a coolant stream (15) into a first stream (16) and a second stream (17) and isentropically expanding (8, 9) said first and second streams, and selectively heat exchanging (5, 6, 7) the streams before merging said first and second streams. With the invented method, complete re-liquefaction is achieved for a boil-off gas having up to 30% nitrogen by volume.

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*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

### Method for re-liquefaction of boil-off gas

The invention relates to the field of re-liquefaction of boil-off gases from liquid natural gas (LNG), as set out in the introduction to the independent claim 1.

5

A common technique for transporting natural gas from its extraction site, is to liquefy the natural gas at or near this site, and transport the LNG to the market in specially designed storage tanks, often placed aboard a sea-going vessel.

10 The process of liquefying the natural gas involves compression and cooling of the gas to cryogenic temperatures (e.g.  $-160^{\circ}\text{C}$ ). The LNG carrier may thus transport a significant amount of liquefied gas to its destination. At this destination, the LNG is offloaded to special tanks onshore, before it is either transported by road or rail on LNG carrying vehicles or re-vaporized and transported by e.g. pipelines.

15

LNG boils at slightly above  $-163^{\circ}\text{C}$  at atmospheric pressure, and is usually loaded, transported and offloaded at this temperature. This requires special materials, insulation and handling equipment in order to deal with the low temperature and the boil-off vapor. Due to heat leakage, the cargo (LNG) surface is constantly boiling, generating va-  
20 porized natural gas ("boil-off") – primarily methane – from the LNG.

25

Plants for the continuous re-liquefaction of this boil-off gas are well known. The re-liquefaction of boil-off gases on LNG carriers results in increased cargo deliveries and allows the operator to choose the most optimal carrier propulsion system. LNG carriers  
25 have traditionally been driven by steam turbines, and the boil-off gases from the LNG cargo have been used as fuel. This has been considered a costly solution.

One such alternative to using the boil-off gas as fuel is the Moss RS<sup>TM</sup> Concept, wherein the boil-off gas is liquefied and the resulting LNG is pumped back to the cargo tanks.

30 The Moss RS<sup>TM</sup> Concept, described in Norwegian Patent No. 305525 B1, is based on a closed nitrogen expansion cycle, extracting heat from the boil-off gas. Boil-off gas (BOG) is removed from the cargo tanks by two conventional LD compressors operating in series. The BOG is cooled and condensed to LNG in a cryogenic heat exchanger ("cold box"), to a temperature between the saturation temperature for compressed  $\text{CH}_4$   
35 and  $\text{N}_2$  before being fed into a separator vessel where certain non-condensibles (mainly  $\text{N}_2$ ) is removed. The LNG coming out of the separator is pumped back to the cargo tanks, while the non-condensibles (i.e. gases) are sent to a flare or vent stack.

It has, however, been discovered that the boil-off gas temperature fluctuates considerably, and values far outside the above range are not uncommon. This is particularly the case during the ballast voyage, where the cargo tanks are virtually empty and easily pick up high temperatures. During ballast voyage, an LNG-ship normally carries between 5 1% and 1.5% of its overall available cargo volume. Normally, when the ship is off-loaded, an amount of LNG is deliberately left in some (e.g. one or two) tanks, in order to keep the tanks' temperatures at a lowered level. The tanks' temperatures gradually increase during the ballast voyage, and this residual liquid is then used to cool the tanks 10 at regular intervals, such that the tanks will be sufficiently cold for receiving a new load of LNG when the ship reaches port. Each tank comprises a number of nozzles which are used for this cooling process. All the tanks' nozzles are connected via a common pipe system, such that a pump may supply all nozzles with LNG from any given tank. Normally, each tank comprises a pump capable of performing this function.

15 An LNG ship normally holds four or five LNG storage tanks, each tank having a dome penetrated by the necessary pipes. These pipes are used for loading and offloading of LNG, as well as for the handling of boil-off. Pipes connecting the tanks, run along each tank dome and terminate at the ship's manifold (used for loading and offloading). This 20 network of pipes comprises a number of flexible bellows, fitted at certain points. These bellows are necessary for taking up movements of the pipes due to the ship's movements. These bellows may be as long as four meters and are not insulated. A considerable part of the heat leaking into the boil-off gases takes place through these bellows.

25 In order to reduce the overall numbers of pipes on a vessel, it is quite common that a given pipe is designed for several functions. This is possible when the various functions are not being performed simultaneously. For example, the pipe connecting the gas phase of all the tanks is dimensioned for the gas volume coming out of the tanks when these are heated, prior to e.g. inspection or repair. In this state, the gas volume flow may be 30 more than ten times the volume flow produced by regular boil-off.

As stated above, the vapor header running from each of the cargo tanks have some un-insulated areas that cause a significant temperature increase in the boil-off gas. The vapor header is designed for a vapor flow significantly larger than the boil-off gas flow, 35 thus the resident time of the boil-off gas is high in the vapor header and consequently the heat transfer to the gas is accordingly high.

For example, temperatures as high as  $-40^{\circ}\text{C}$  have been recorded at the compressor inlet. Such high temperatures are unfortunate, given that the compressors are designed for much lower temperatures. It is therefore desirable to control the temperature of the boil-off gas prior to its entry into the compressor, to a greater extent than what thus far has  
5 been possible and considered necessary.

Norwegian Patent Application No. 2003 5047, by the same inventor and filed by the present applicant on 13 November 2003, discloses an apparatus and method for controlling temperature in a boil-off gas in a liquefaction plant prior to compression. Boil-off  
10 gas originating from an LNG storage tank is compressed and at least partially condensed, and the condensed boil-off gas (LNG) is being returned to the storage tank. A heat exchanger is connected to the boil-off gas feed line upstream of the compressor, and a first conduit fluidly connects the line for returning LNG to the storage tank and the heat exchanger. A second conduit fluidly connects the heat exchanger to the boil-off  
15 gas feed line at a point upstream of said heat exchanger. Boil-off gas is heat exchanged against said cooler prior to being fed into said compressor. Thus, the boil-off gas temperature is lowered downstream of said heat exchange, and a selected temperature or range of temperatures - for example determined by the compressor characteristics - may be used as a controlling parameter for the choke valve in order to control the flow  
20 through the cooler and into the boil-off gas feed line upstream of the heat exchanger.

One problem with the prior art systems is that the boil-off is not completely re-liquefied or starts boiling on its way to the tanks, as described above. This significantly reduces the tank nozzles' capacity. Also, the aforementioned pumps are necessary in order to  
25 transfer the partly re-liquefied boil-off to the tanks.

A number of systems and methods for re-liquefaction of boil-off gases are known. For example, United States Patent No. 4,486,862 discloses a system and an improved process for the re-liquefaction of boil-off gas containing up to 10% nitrogen resulting from  
30 the evaporation of liquefied natural gas contained in a storage vessel. In this process, a closed-loop refrigeration cycle is utilized, where an isenthalpically expanded stream is heat exchanged against an initially cooled boil-off stream. United States Patent No. 4,843,829 discloses a similar process. Both these publications disclose processes where compressed nitrogen is used as a working fluid in a closed-loop refrigeration system,  
35 and where the working fluid is split into a first and a second stream, and where the first stream is expanded isenthalpically whereas the second stream is expanded isentropi-

cally. The described systems are capable of re-liquefying a boil-off gas having a nitrogen content of up to 10% per volume.

It is therefore an object of the invention to obtain complete re-liquefaction of the boil-off gas, even for higher nitrogen contents, and being able to provide the subcooled liquid to the tanks, in order to effectively cool the tanks.

The present invention meets the above needs, in that it provides a method for re-liquefaction of a stream of boil-off gas resulting from the evaporation of LNG contained in a storage vessel, wherein the boil-off gas is being cooled and liquefied in a closed-loop refrigeration system before being returned to a storage vessel, said closed-loop refrigeration being characterized by the following steps:

- a) compressing a coolant as a working fluid in said refrigeration system to form a compressed coolant stream;
- b) heat exchanging said compressed coolant stream and said boil-off stream against first and second coolant streams;
- c) splitting said coolant stream into a first stream and a second stream;
- d) isentropically expanding said second stream;
- e) heat exchanging the first stream and the boil-off stream against said expanded second stream and an expanded and further heat exchanged first stream;
- f) said expanded and further heat exchanged first stream being achieved by isentropically expanding said heat exchanged first stream, followed by heat exchanging said expanded first stream against said boil-off stream;
- g) following said heat exchange in step b), compressing said first stream;
- h) following said heat exchange in step b), merging said second stream with said compressed first stream to form said compressed coolant stream;
- i) compressing said stream,

wherein complete re-liquefaction is achieved for a boil-off gas having up to 30% nitrogen by volume.

Preferred embodiments of the invented method are described in the dependent claims 2 - 15.

An embodiment of the invention will now be described in more detail, with reference to the accompanying drawings, where like parts have been given like reference numbers.

Figure 1 is a principle flow diagram illustrating the closed-loop process according to the invention.

Figure 2 is the principle flow diagram of figure 1, incorporated in an LNG re-  
5 liquefaction plant according to the invention.

The system according to the invention is shown in its most principle form in figure 1. A boil-off gas stream 10 from a reservoir (not shown) is compressed in a regular fashion in the compressor 11. The boil-off stream 12 is thus routed through a compact heat exchanger (visualized in the figures as three separate heat exchangers) 5, 6, 7 and heat  
10 exchanged against the closed-loop refrigeration system as will be described below. The stream 13 exiting the heat exchanger (or series of heat exchangers) is completely re-liquefied with a careful tuning of the refrigeration system. The person skilled in the art will appreciate that the heat exchangers 5, 6, 7 as shown in the figures, may be com-  
15 bined into one compact heat exchanger.

Turning now to the refrigeration system, figure 1 shows a compressor system 1 comprising three in-line compressors 2, 3, 4. In a practical application, the compression may be achieved by one compression unit comprising three compressor wheels and two ex-  
20 pander wheels connected via a common gear box. The compressor system compresses the coolant, normally nitrogen, and feeds this stream 15 into the first heat exchanger stage 5 where, together with the boil-off gas, it is heat exchanged against the other coolant streams. After the first heat exchanger step 5, the coolant stream 15 is split into a first stream 16 and a second stream 17. The first stream 16 is heat exchanged together  
25 with the boil-off stream in the second heat exchanger stage 6 against the other coolant streams, before the first stream is expanded isentropically in the expander 9. The expanded first stream 16 is then heat exchanged in the third heat exchanger 7 against the boil-off gas and again heat exchanged through second and first heat exchanger 6 and 5 before it is routed back into the compressor system 1.

30 The second coolant stream 17 is expanded isentropically in the expander 8 before being heat exchanged as stream 17B together with the first stream 16C in the second heat exchanger 6 against the boil-off stream 12B and the first stream 16A. Then the expanded second coolant stream 17B is further heat exchanged together with the first stream 16C  
35 in the first heat exchanger 5, against the boil-off stream 12A and the coolant stream 15, before said second coolant stream 17B is routed back to the compressor system.

In the compressor system, the second coolant stream 17 is merged with the first coolant stream 16 between the second 3 and third 4 compressors before the coolant stream 15 once more is routed through the closed-loop cycle.

5 Figure 2 shows the same system as in figure 1, incorporated in an LNG re-liquefaction plant according to the invention. Here liquefied boil-off is routed back to a heat exchanger 24 from a take-off point 22, where it is utilized as described in Norwegian Patent Application No. 2003 5047. The boil-off stream 10A is fed from the tanks 20, into a separator 25, before it is heat exchanged against the re-liquefied boil-off and the heat  
10 exchanger 24 and enters the re-liquefaction process as stream 10B.

Referring to the figures, the table below illustrates the invention by providing exemplary numerical values and data for the various streams:

<u>Stream</u>	<u>Phase</u>	<u>Pressure</u> (kPa)	<u>Temp</u> (°C)	<u>Flow</u> (Kgmole/hr)	<u>Composition</u>	
					<u>Methane</u> (Mole %)	<u>Nitrogen</u> (Mole %)
10A	Vapour	106	-80	203.7	70	30
10B	Vapour	101	-121	236.7	69	31
12A	Vapour	450	-29	236.7	69	31
12B	Vapour	443	-80	236.7	69	31
12C	Vapour	435	-118	236.7	69	31
13	Liquid	428	-171	236.7	69	31
15	Vapour	5384	41	3141.4	0	100
16A	Vapour	5377	-80	1427.9	0	100
16B	Vapour	5369	-118	1427.9	0	100
16C	2 Phase	801	-172.6	1427.9	0	100
16D	Vapour	779	35	1427.9	0	100
17A	Vapour	5277	-80	1713.5	0	100
17B	Vapour	2829	-111.6	1713.5	0	100
17C	Vapour	2814	35	1713.5	0	100
23	Liquid	428	-171	29.4	69	31

15

Thus, the invented method comprises the following steps:

- a) compressing 2, 3, 4 a coolant as a working fluid in said refrigeration system to form a compressed coolant stream 15;

- b) heat exchanging 5 said compressed coolant stream 15 and said boil-off stream 12 against first 16C and second 17B coolant streams;
- c) splitting said coolant stream 15 into a first stream 16A and a second stream 17A;
- d) isentropically expanding 8 said second stream 17A;
- 5 e) heat exchanging 6 the first stream 16A and the boil-off stream 12 against said expanded second stream 17B and an expanded and further heat exchanged first stream 16C;
- f) said expanded and further heat exchanged first stream 16C being achieved by isentropically expanding 9 said heat exchanged first stream 16B, followed by
- 10 heat exchanging 7 said expanded first stream 16C against said boil-off stream 12C;
- g) following said heat exchange in step b), compressing 2, 3 said first stream 16D;
- h) following said heat exchange in step b), merging said second stream 17C with said compressed first stream 16D to form said compressed coolant stream 15;
- 15 i) compressing 4 said stream 15.

In the heat exchange 5 in step b), said first 16 and second 17 coolant streams may be obtained by the splitting in step c), and subsequently heat exchanged and expanded prior to the heat exchange in step b).

20

In the heat exchange 5 in step b), said previously heat exchanged and expanded first coolant stream 16 may be a medium pressure coolant stream.

25

In the heat exchange 5 in step b), said previously heat exchanged and expanded second coolant stream 17 may be a low pressure coolant stream.

The compression may comprise at least three compression stages and the second stream may be merged with said first stream between the second and third compression stage.

30

The coolant may comprise nitrogen.

A selected amount of said re-liquefied boil-off 13 may be used in the heat exchange 24 of said boil-off stream 10 prior to said compression 11.

35

The coolant stream 15 to be used as a working fluid may be compressed 2, 3, 4 to a pressure in the range of 5000 kPa to 6000 kPa.

The compressed coolant stream 15 in the heat exchange 5 of step b) may be cooled to a temperature in the range of -70 °C to -90°C.

5 The heat exchanged second stream 17A may be isentropically expanded 8 to a pressure in the range of 2500 kPa to 3000 kPa.

The second stream 17A may in said isentropic expansion 8 be cooled to a temperature in the range of -105 °C to -125 °C.

10 The first stream 16 in the heat exchange 6 in step e), may be cooled to a temperature in the range of -110 °C to -125 °C.

The heat exchanged first stream 16B may be isentropically expanded 9 to a pressure in the range of 500 kPa to 1200 kPa.

15

The first stream 16B may in said isentropic expansion 9 be cooled to a temperature in the range of -165 °C to -175 °C.

20 The re-liquefied boil-off 13 may have a temperature in the range of -160 °C to -173 °C and a pressure in the range of 350 kPa to 600 kPa.

25 By subcooling the liquid and obtaining complete liquefaction as described above, the liquid may be used for cooling the tanks without the need for pumps, as described in the introduction as being a requirement in the prior art systems. With the invention, the tank nozzles capacities are maintained. The subcooled liquid may be fed directly to the nozzles without having to use pumps. The invention makes redundant the pumps for feeding the liquid back to the storage tanks. Such pumps are necessary in the prior art systems.

30 In the executing the invented method, it may be convenient to use a plate-fin heat exchanger, known in the art as a PFX heat exchanger.

P a t e n t C l a i m s

1.

A method for re-liquefaction of a stream of boil-off gas (12) resulting from the evapora-  
5 tion of LNG contained in a storage vessel (20), wherein the boil-off gas is being cooled  
and liquefied in a closed-loop refrigeration system before being returned (13) to a stor-  
age vessel (20), said closed-loop refrigeration being c h a r a c t e r -  
i z e d b y the following steps:

- 10 a) compressing (2, 3, 4) a coolant as a working fluid in said refrigeration system to  
form a compressed coolant stream (15);
- b) heat exchanging (5) said compressed coolant stream (15) and said boil-off  
stream (12) against first (16) and second (17) coolant streams;
- c) splitting said coolant stream (15) into a first stream (16) and a second stream  
15 (17);
- d) isentropically expanding (8) said second stream (17);
- e) heat exchanging (6) the first stream (16) and the boil-off stream (12) against said  
expanded second stream (17) and an expanded and further heat exchanged first  
stream (16);
- 20 f) said expanded and further heat exchanged first stream (16) being achieved by  
isentropically expanding (9) said heat exchanged first stream (16), followed by  
heat exchanging (7) said expanded first stream (16) against said boil-off stream  
(12);
- g) following said heat exchange in step b), compressing (2, 3) said first stream (16);
- 25 h) following said heat exchange in step b), merging said second stream (17) with  
said compressed first stream (16) to form said compressed coolant stream (15);
- i) compressing (4) said stream (15),

wherein complete re-liquefaction (13) is achieved for a boil-off gas having up to 30%  
30 nitrogen by volume.

2.

The method of claim 1, c h a r a c t e r i z e d i n t h a t  
in the heat exchange (5) in step b), said first (16) and second (17) coolant streams are  
35 obtained by the splitting in step c), and subsequently heat exchanged and expanded  
prior to the heat exchange in step b).

3.

The method of claim 1, characterized in that in the heat exchange (5) in step b), said previously heat exchanged and expanded first coolant stream (16) is a medium pressure coolant stream.

5

4.

The method of claim 1, characterized in that in the heat exchange (5) in step b), said previously heat exchanged and expanded second coolant stream (17) is a low pressure coolant stream.

10

5.

The method of claim 1, characterized in that said compression comprises at least three compression stages and that said second stream is merged with said first stream between the second and third compression stage.

15

6.

The method of claim 1, characterized in that said coolant comprises nitrogen.

20

7.

The method of claim 1, characterized in that a selected amount of said re-liquefied boil-off (13) is used in the heat exchange (24) of said boil-off stream (10) prior to said compression (11).

25

8.

The method of claim 1, characterized in that the coolant stream (15) to be used as a working fluid is compressed (2, 3, 4) to a pressure in the range of 5000 kPa to 6000 kPa.

30

9.

The method of claim 1, characterized in that said compressed coolant stream (15) in the heat exchange (5) of step b) is cooled to a temperature in the range of -70 °C to -90°C.

10.

The method of claim 1, characterized in that the heat exchanged second stream (17A) is isentropically expanded (8) to a pressure in the range of 2500 kPa to 3000 kPa.

5

11.

The method of claim 10, characterized in that said second stream (17A) in said isentropic expansion (8) is cooled to a temperature in the range of -105 °C to -125 °C.

10

12.

The method of claim 1, characterized in that the first stream (16) in the heat exchange (6) in step e), is cooled to a temperature in the range of -110 °C to -125 °C.

15

13.

The method of claim 1, characterized in that the heat exchanged first stream (16B) is isentropically expanded (9) to a pressure in the range of 500 kPa to 1200 kPa.

20

14.

The method of claim 13, characterized in that said first stream (16B) in said isentropic expansion (9) is cooled to a temperature in the range of -165 °C to -175 °C.

25

15.

The method of claim 1, characterized in that the re-liquefied boil-off (13) has a temperature in the range of -160 °C to -173 °C and a pressure in the range of 350 kPa to 600 kPa.

30

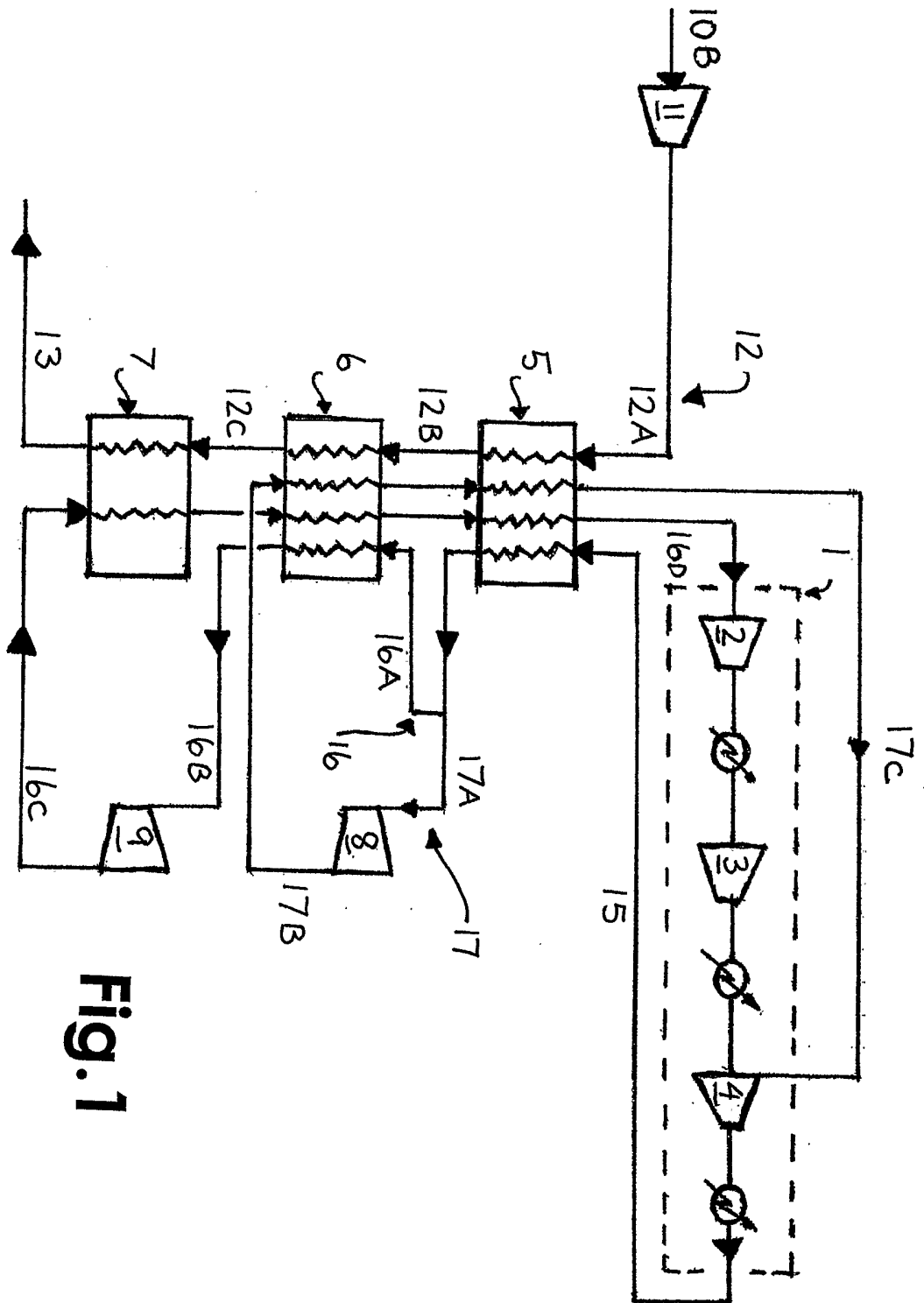


Fig. 1

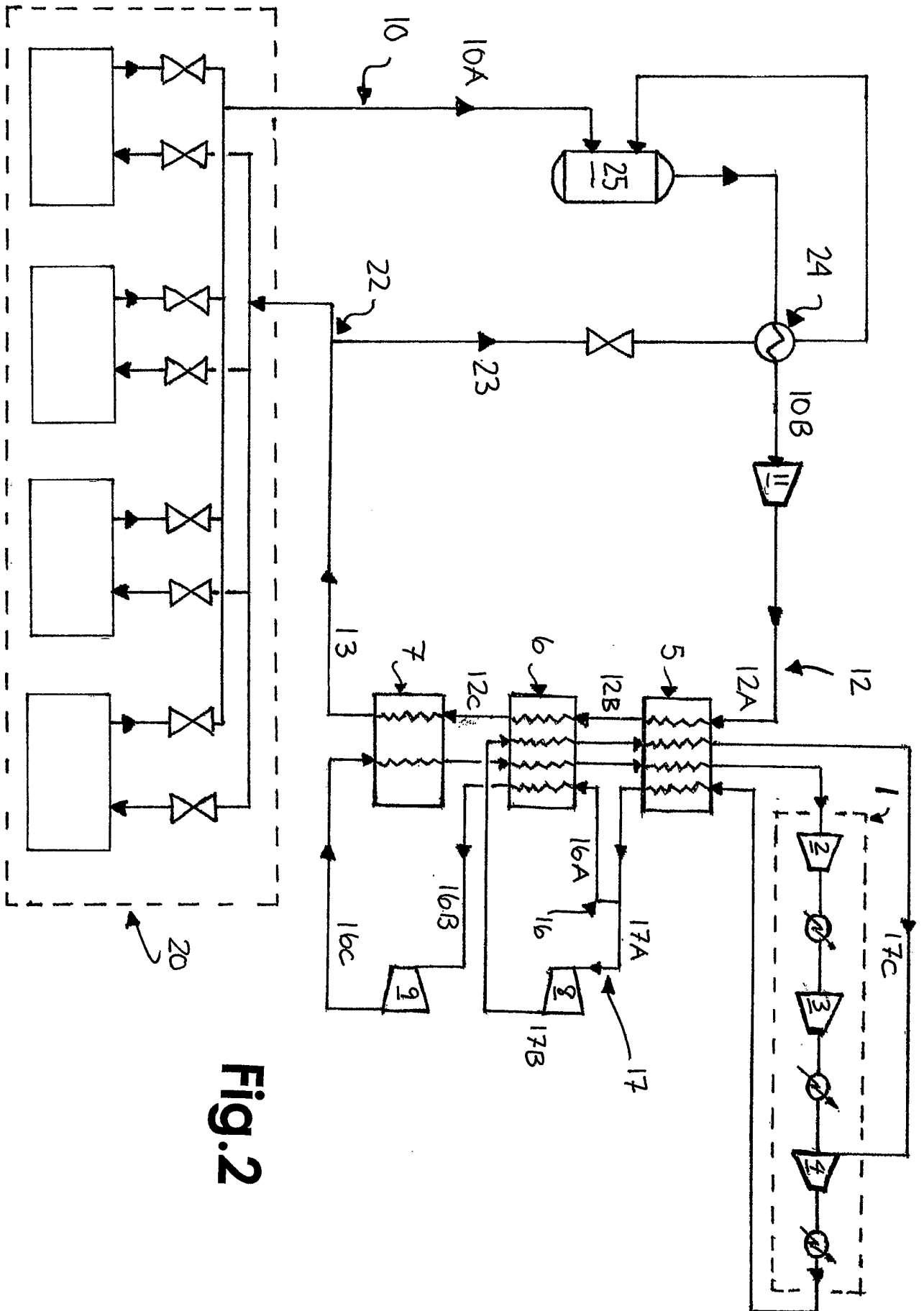


Fig. 2

## INTERNATIONAL SEARCH REPORT

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## A. CLASSIFICATION OF SUBJECT MATTER

IPC7: F25J 1/02

According to International Patent Classification (IPC) or to both national classification and IPC

## B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: F25J, B01D, F17C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-INTERNAL, WPI DATA, PAJ

## C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 4846862 A (COOK), 11 July 1989 (11.07.1989), whole document --	1-5,7,9
A	US 4843829 A (STUBER ET AL), 4 July 1989 (04.07.1989), whole document --	1-15
A	US 3874185 A (ETZBACH), 1 April 1975 (01.04.1975), whole document --	1-15
A	GB 2069119 A (PETROCARBON DEVELOPMENTS LTD.), 19 August 1981 (19.08.1981), whole document --	1-15

 Further documents are listed in the continuation of Box C. See patent family annex.

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## C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 1120615 A2 (CRYOSTAR-FRANCE SA), 1 August 2001 (01.08.2001), whole document  ---	1-15
A	US 20030182947 A1 (KIMBLE ET AL), 2 October 2003 (02.10.2003), whole document  -- -----	1-15

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