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(54) METHOD OF OPERATING AN OPEN CIRCUIT  
 GAS-TURBINE PLANT COOPERATING WITH  
 A VAPOUR POWER CIRCUIT

(71) We, SULZER BROTHERS LIMITED, a Company organised under the laws of Switzerland, of Winterthur, Switzerland, do hereby declare the invention, for which we pray that a patent may be granted to us, and the method by which it is to be performed, to be particularly described in and by the following statement:—

This invention relates to a method of operating an open circuit gas turbine plant cooperating with a vapour power circuit in which there flows a medium which consists of a hydrocarbon, a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide, and which is expanded to perform work, condensed and heated by recovery of the waste heat of the exhaust gases of the gas turbine plant, and to a plant suitable for performing the method.

Methods and plant of this kind are used when water vapour cannot be used as the vapour circuit medium. This is the case, for example, if a plant of this kind is used in cold zones where there is a risk of freezing-up or where appropriate monitoring of operation is possible only with uneconomic expenditure, or in areas where no water supply is available.

In such cases it is advantageous to use circuits containing a working medium consisting of a hydrocarbon, a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide. Media of this kind are thermally stable even at relatively high temperatures, e.g. in the range from 200°C to 400°C, i.e. there is no chemical decomposition. If traces of decomposition products are produced then these products are always other hydrocarbons which are not corrosive, i.e. these products do not interfere

with operation of the plant.

The object of the invention is to provide a method whereby such plant can be operated very economically and to ensure the operational reliability of remote-controlled plant, i.e. plant not controlled at the site of the plant.

According to one aspect, the present invention consists in a method of operating an open circuit gas turbine plant cooperating with a vapour power circuit in which there flows a medium which consists of a hydrocarbon, a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide and which is expanded to perform work, condensed and heated by recovery of waste heat from the exhaust gases of the gas turbine plant, the heating of the medium in the vapour power circuit being effected by transfer of heat from the exhaust gases via a forced-flow intermediate circuit in which a liquid heat carrier is circulated, in each complete passage around the circuit the heat carrier being repeatedly heated by heat-exchange with the exhaust gases and being cooled, between each heating, by heat-exchange with the vapour power circuit medium.

The method according to the invention is particularly suitable for delivering and cooling natural gas, especially in cold regions. In the case of natural gas pipes laid in regions where the soil may be frozen it is often desirable to dissipate compression heat from the natural gas in order to prevent the ice from melting in the soil in the region where the pipe is laid.

The natural gas pipeline system may comprise spaced stations with gas turbine and refrigerating plant, or a station located

actually at the natural-gas source, i.e. near the borehole, and intended to deliver the natural gas to the pipeline system and cool it.

5 In this connection, in a development of the invention, compression heat is withdrawn from the compressed natural gas by heat-exchange with the latter by means of a refrigerant circulating in a refrigerant circuit and consisting preferably of a hydrocarbon, 10 a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide, the drive power for the refrigerant compressor being provided by means of the vapour power circuit.

15 According to a second aspect of the present invention, a plant comprises: an open circuit gas turbine plant; a vapour power circuit including an expansion machine, a condenser, and a pump, and in which there 20 flows a medium which consists of a hydrocarbon, a mixture of hydrocarbons, or a mixture of one or more hydrocarbons and carbon dioxide; and a heat-exchange system comprising a forced-flow intermediate circuit 25 for a liquid heat carrier, the intermediate circuit including a heat exchanger in the exhaust gas passage of the gas turbine plant for transferring heat from the exhaust gas to the heat carrier and a heat exchanger in the 30 vapour circuit for transferring heat from the heat carrier to the medium in the vapour circuit.

35 With such a plant there is maximum reliability in transmitting heat from the hot exhaust gases of the gas turbine to the vapour circuit medium before the medium is expanded to perform work.

40 The vapour circuit medium should be stable within the range of the maximum temperatures of, for example, about 400°C occurring in the vapour power circuit. In the event of decomposition of the medium the decomposition products should not be corrosive. It is economically desirable to use the 45 cheapest possible medium. Propane and a mixture of butane and ethane meet these requirements. However, other unsubstituted or halogen-substituted hydrocarbons are possible as the vapour power circuit medium 50 provided they have the above-described properties.

55 The use of a forced-flow intermediate circuit for transferring the waste heat of the hot exhaust gases to the vapour power circuit medium gives a physical separation between these media and the exhaust gases. If the heat transfer from the exhaust gases to the vapour power circuit medium, e.g. propane, were to be effected, for example, directly in the gas turbine plant exhaust gas duct, then propane, 60 for example, might escape into the exhaust gas duct in relatively large quantities in the event of leakage of the heat-exchange passages in the exhaust gas passage, and result in 65 detonation and destruction of the plant since

it would form a highly explosive mixture with the exhaust gases. Propane might penetrate into the gas turbine plant combustion chamber, particularly in the event of shut-down of the plant, and result in an explosion on the next starting-up. This danger is 70 obviated with the invention.

75 The choice of heat carrier depends on the temperature range in which the heat transfer is carried out. The heat carrier should be as thermally stable as possible in that temperature range or, if decomposition products do occur to a slight degree, they should not be corrosive. In addition, the heat carrier used should be cheap and compatible with the 80 environment and have a low partial pressure (of the order of not more than 50 bar at 400°C), to ensure that the cost of the tubes of the forced-flow intermediate circuit remains within economic limits. In addition, the heat 85 carrier should not undergo any increase in volume in the event of freezing up. Suitable heat carriers include those consisting of or including a hydrocarbon, e.g. diphenyl ( $C_{12}H_{10}$ ) or a hydrocarbon oxide, e.g. diphenyl 90 oxide ( $C_{12}H_{10}O$ ) or a mixture of these two, or a silicone oil or a mixture of silicone oils.

95 The forced-flow intermediate circuit used for this heat-exchange system could be one in which the entire throughput is heated and cooled in a single pass. The maximum rate at which the heat carrier can escape into the waste gas duct in the event of a leakage in the tube system, e.g. through a material fault or 100 in the event of destruction of a weld seam due to temperature stresses, is equal to the rate of flow of the heat carrier. This rate of flow is determined by the amount of heat that has to be transferred from the exhaust 105 gases to the heat carrier. The leakage may form an explosive mixture with the ambient air or may only partially vaporise so that liquid heat carrier may accumulate in the gas turbine and subsequently completely vaporise and result in explosive mixtures. Preferably, 110 therefore, the heat exchanger in the exhaust gas passage has at least ten passes for the heat carrier. The rate of flow through each pass is the total rate of flow divided by the number of passes. If the number of passes 115 is made very large, the rate of escape in the event of a leakage in a tube will be limited accordingly. Thus, in the event of leakage of one of the tubes during operation, only a small quantity of heat carrier can escape into 120 the exhaust gas passage per unit of time so that there is no risk of an explosive mixture forming in the exhaust gas passage or in the gas turbine or in the atmosphere above the exhaust gas chimney. 125

130 Apart from the above-mentioned application of the invention to the delivery and cooling of natural gas in cold zones, in which case the load is the compressor of a refrigerating plant, the loads driven by the expan-

sion machine, e.g. an expansion turbine, in the vapour circuit and by the gas turbine, may, for example, be electricity generators, compressors or pumps for chemical processes or compressors or pumps for delivery of gases, e.g. natural gas, or liquids, e.g. petroleum.

The invention may be carried into practice in various ways but two plants and an intermediate circuit that may be used in either of the plants, together with the method of operation of the plants in accordance with the invention, will now be described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a flow diagram of a plant in which the loads are compressors for the delivery of natural gas;

Figure 2 is a detail showing a forced-flow intermediate circuit comprising a heater and heat exchange tubes in the exhaust gas duct; and

Figure 3 is a flow diagram of a plant coupled to a refrigerating plant and used for delivering and cooling natural gas in cold zones.

The plant shown in Figure 1 includes an open circuit gas turbine engine 14, 15, 16a, 16b having an exhaust gas passage 11 conveying exhaust gases from which heat is extracted and transferred to a working medium in a closed vapour power circuit.

The working medium, for example propane, passes around the vapour power circuit which includes an expansion turbine 1 in which the working medium is expanded with the performance of work. The turbine drives a compressor 2 for delivering natural gas. The working medium is then cooled in two heat-exchangers 3 and 4 and condensed in a condenser 5, in which heat is withdrawn from the medium by heat-exchange with a coolant, e.g. air, water or liquid gases required to be vaporised, more particularly liquid natural gas. The direction of entry and exit of the coolant is shown by arrows.

In addition to the expansion turbine, the condenser 5, a pump 6, and the heat-exchangers 3 and 4, the vapour power circuit contains heaters 7 and 8 in which heat-exchange systems 9 and 10 each having a forced-flow intermediate circuit are used to transfer heat from hot exhaust gases via the heat carrier fluid of the intermediate circuit to the working medium.

Figure 2 is a flow diagram of a heat-exchanger system which may be used in the plant shown in Figure 1.

A refrigerant fluid such as one of those listed above, is used as the heat carrier fluid in the forced-flow intermediate circuit 9, which comprises a pump 12 and a number of series-connected tubes 9a, 9'a; 9b, 9'b to 9x, 9'x, which extend through the heater 7 and the exhaust gas duct 11 of the gas turbine plant.

The greater the number of series connected tubes, the lower can be the rate of flow, so that the amount of heat carrier fluid escaping per unit of time in the event of a leak in the tube system is reduced. For example, there may be 80 passes in each of the heater 7 and the exhaust gas duct 11 of the heat-exchange system, of which the drawing shows only three, i.e. the first two 9a, 9'a and 9b, 9'b, and the last 9x and 9'x.

During operation, heat is transferred from the hot exhaust gases to the heat carrier fluid on each pass and during each heating in the heater 7 the working medium of the vapour power circuit, e.g. propane, is heated by heat-exchange with the heated heat carrier fluid, so that the latter cools.

Instead of the construction of heater shown in the drawing, the heater could alternatively be sub-divided into a number of individual parallel-connected, separately jacketed, tube exchange elements. Alternatively, each tube in the heater and in the exhaust gas duct would be replaced by a nest of tubes, the individual tubes of each nest being interconnected by heaters at their opposite ends. The heat-exchange system 10 in Figure 1 is of a similar construction to that shown in Figure 2.

In the plant shown in Figure 1, a load in the form of a natural gas compressor 13 is driven by a gas turbine plant. The latter is largely of conventional construction and comprises a compressor 14, a combustion chamber 15, a turbine 16a driving the compressor and a power turbine 16b.

When the plant is operating, the working medium expanded in the expansion turbine 1 is cooled in the heat-exchangers 3 and 4 and liquefied in the condenser 5.

The working medium is brought to either a sub-critical or super-critical pressure in the pump 6. It is then heated in the heat-exchanger 4 by heat-exchange with working medium which has been expanded to perform work and is then heated further in the heater 7 by heat-exchange with the heat carrier, and then in the heat-exchanger 3 and the heater 8 before the working medium is expanded to perform work.

In a plant of the construction shown in the flow diagram in Figure 3, natural gas is drawn by a compressor 21 through a pipe 20 laid in frozen ground and is delivered to the next station via a pipe 22 also laid in frozen ground. The compression heat is dissipated from the natural gas in a heat-exchanger 23 by heat-exchange with a refrigerant, e.g. propane. The heat-exchanger forms the evaporator of a refrigerant circuit. The evaporated refrigerant is compressed in a compressor 24, then liquefied in an air-cooled condenser 25, expanded in a throttle valve 26 and returned to the heat-exchanger 23. The compressor 24 is driven by an expansion

turbine 1 disposed in a vapour power circuit. In this embodiment, the working medium of this circuit is the same as the refrigerant, e.g. propane. All those parts of the plant which are equivalent to those of the plant shown in Figure 1 in respect of construction and function have been given like references.

The heat-exchange system shown in Figure 2 may be employed in the plant shown in Figure 3 as well as in that shown in Figure 1.

In the plant shown in Figure 3 there is a droplet separator 27 in the natural gas pipe downstream of the heat-exchanger 23. A droplet separator of this kind for separating heavy hydrocarbons, e.g.  $C_3H_8$ , from the flow of natural gas, is provided when the plant illustrated is not used for an intermediate station in the natural gas network, but when the station is located at the natural gas source, i.e. near the borehole.

A numerical example giving important variables and details of the throughput in the heat-exchanger system for a plant of the kind shown in Figure 1 will now be given.

#### Numerical Example

By way of example, 104 kg/s of propane were heated in a vapour circuit from 230°C to 309°C by means of 117.5 kg/s of combustion gases, the latter cooling from 461°C to 277°C. The heat carrier in the forced-flow intermediate circuit was a mixture of a hydrocarbon and a hydrocarbon oxide, and the circuit included eighty series-connected tube passes, the rate of flow of the heat carrier therein being 1.3 kg/s. In the event of a leak occurring in the forced-flow intermediate circuit tube system during operation, the circulation pump can thus only inject 1.3 kg/s of the heat carrier liquid into the exhaust gas duct. The bottom explosion limit of this liquid in air at 400°C is 3% by weight of the air. This would be equivalent to 3.4 kg/s of the liquid.

If a forced-flow intermediate circuit containing just a single passage through the exhaust gas duct and the heater were used instead of the described heat-exchange system construction comprising 80 tube passes, the liquid throughput and pump delivery in this system would be  $80 \times 1.3$  kg/s or 104 kg/s. In the event of a tube fracture in the system, this quantity of liquid, i.e. 104 kg/s, could escape into the exhaust gas duct and form an explosive mixture with the combustion gases there.

#### WHAT WE CLAIM IS:—

1. A method of operating an open circuit gas turbine plant cooperating with a vapour power circuit in which there flows a medium which consists of a hydrocarbon, a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide and which is expanded to perform work, condensed and

heated by recovery of waste heat from the exhaust gases of the gas turbine plant, the heating of the medium in the vapour power circuit being effected by transfer of heat from the exhaust gases via a forced-flow intermediate circuit in which a liquid heat carrier is circulated, in each complete passage around the circuit the heat carrier being repeatedly heated by heat-exchange with the exhaust gases and being cooled, between each heating, by heat-exchange with the vapour power circuit medium.

2. A method as claimed in Claim 1 in which the gas turbine plant drives a compressor for delivering natural gas and in which compression heat is withdrawn from the compressed natural gas by heat-exchange with a refrigerant circulating in a refrigerant circuit which includes a compressor the drive power for which is provided by the vapour power circuit.

3. A method as claimed in Claim 2 in which the refrigerant is a hydrocarbon or a mixture of hydrocarbons or a mixture of one or more hydrocarbons and carbon dioxide.

4. A method as claimed in Claim 1 or Claim 2 or Claim 3 in which the heat exchange between the vapour power circuit medium and the heat carrier and the heat exchange between the exhaust gases and the heat carrier are effected in counter-current.

5. A method as claimed in any of the preceding claims in which, before heat-exchange with the heat carrier, the medium is heated by heat-exchange with the medium expanded to perform work.

6. A method as claimed in any of the preceding claims in which the heating of the vapour power circuit medium takes place successively in at least two stages, heat being transferred from the medium which has been expanded to perform work and to the medium at higher pressure before heat-exchange with the heat carrier of the forced-flow intermediate circuit.

7. A plant comprising: an open circuit gas turbine plant; a vapour power circuit including an expansion machine, a condenser, and a pump, and in which there flows a medium which consists of a hydrocarbon, a mixture of hydrocarbons, or a mixture of one or more hydrocarbons and carbon dioxide; and a heat-exchange system comprising a forced-flow intermediate circuit for a liquid heat carrier, the intermediate circuit including a heat exchanger in the exhaust gas passage of the gas turbine plant for transferring heat from the exhaust gas to the heat carrier and a heat exchanger in the vapour circuit for transferring heat from the heat carrier to the medium in the vapour circuit.

8. A plant as claimed in Claim 7 in which the gas turbine plant drives a natural gas compressor, and the plant includes a refrigerating plant comprising a heat-exchanger for

- the transfer of heat from the natural gas downstream of the compressor to the refrigerant of the refrigerating plant, a compressor, a condenser and a throttle, the compressor being connected to be driven by the vapour power circuit expansion machine.
9. A plant as claimed in Claim 8 in which the refrigerant is the same as the vapour power circuit medium.
10. A plant as claimed in Claim 7 or Claim 8 or Claim 9 in which the heat exchanger in the vapour power circuit is formed by a plurality of individual parallel-connected separately jacketed tube exchange elements.
11. A plant as claimed in Claim 7 or Claim 8 or Claim 9 in which the heat exchanger in the vapour power circuit and the heat exchanger in the exhaust gas passage each consist of a tube bundle.
12. A plant as claimed in any of Claims 7 to 11 in which the heat exchanger in the exhaust gas passage has at least ten passes for the heat carrier.
13. A plant as claimed in any of Claims 7 to 12 which includes a further heat-exchanger upstream of the heat-exchanger in the vapour power circuit with respect to the direction of flow of the medium in the vapour power circuit connected to provide heat-exchange between the vapour power circuit medium passing to the heat-exchanger in the vapour power circuit and vapour power circuit medium expanded in the expansion machine.
14. A plant as claimed in any of Claims 7 to 13 comprising a second forced-flow intermediate circuit for a liquid heat carrier, the second intermediate circuit including a heat exchanger in the exhaust gas passage of the gas turbine plant for transferring heat from the exhaust gas to the heat carrier and a heat exchanger in the vapour power circuit for transferring heat from the heat carrier to the medium in the vapour power circuit.
15. A plant as claimed in Claim 14 which includes an additional heat-exchanger upstream of the heat-exchanger of the second intermediate circuit in the vapour power circuit with respect to the direction of flow of the medium in the vapour power circuit connected to provide heat exchange between the vapour power circuit medium passing to the heat exchanger of the second intermediate circuit in the vapour power circuit and the vapour power circuit medium expanded in the expansion machine.
16. A plant as claimed in any of Claims 7 to 15 in which the heat carrier consists of or includes a hydrocarbon.
17. A plant as claimed in Claim 16 in which the heat carrier is diphenyl.
18. A plant as claimed in any of Claims 7 to 15 in which the heat carrier consists of or includes a hydrocarbon oxide.
19. A plant as claimed in Claim 18 in which the heat carrier is diphenyl oxide.
20. A plant as claimed in any of Claims 7 to 15 in which the heat carrier is a mixture of diphenyl and diphenyl oxide.
21. A plant as claimed in any of Claims 7 to 15 in which the heat carrier is a silicone oil or a mixture of silicone oils.
22. A method of operating an open circuit gas turbine plant substantially as described herein with reference to Figure 1 or to Figures 1 and 2 of the accompanying drawings.
23. A method of operating an open circuit gas turbine plant substantially as described herein with reference to Figure 3 or to Figures 3 and 2 of the accompanying drawings.
24. A plant constructed and arranged to operate substantially as described herein with reference to Figure 1 or to Figures 1 and 2 of the accompanying drawings.
25. A plant constructed and arranged to operate substantially as described herein with reference to Figure 3 or to Figures 3 and 2 of the accompanying drawings.

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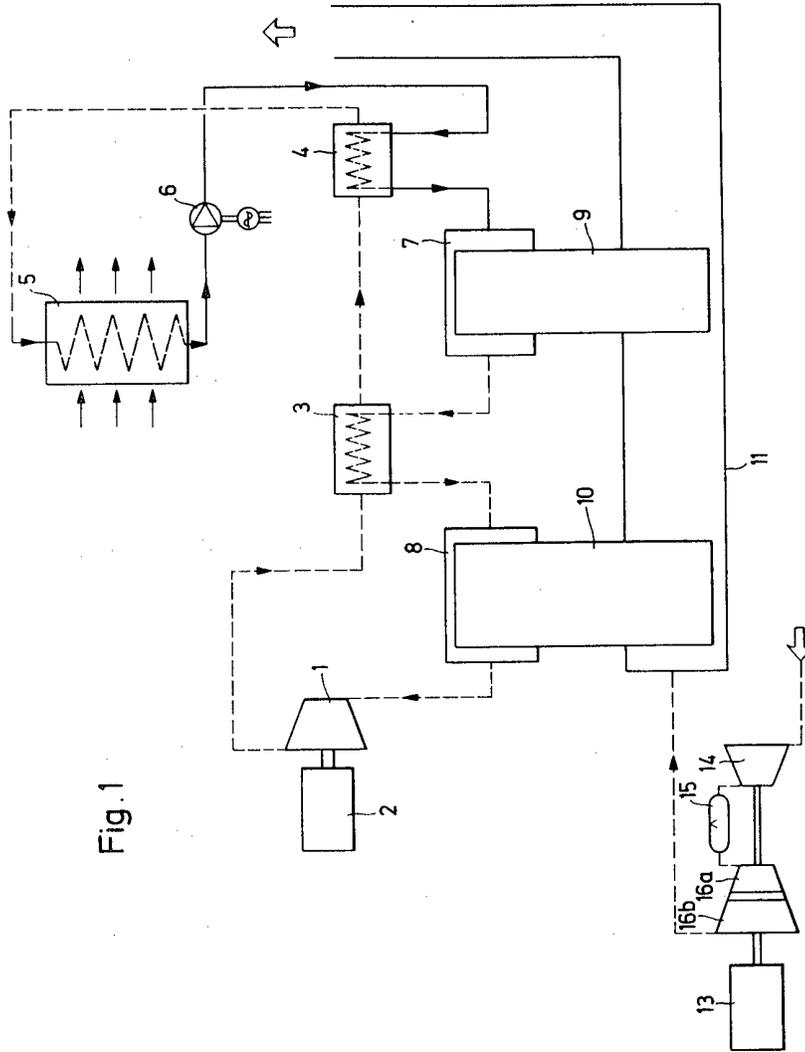
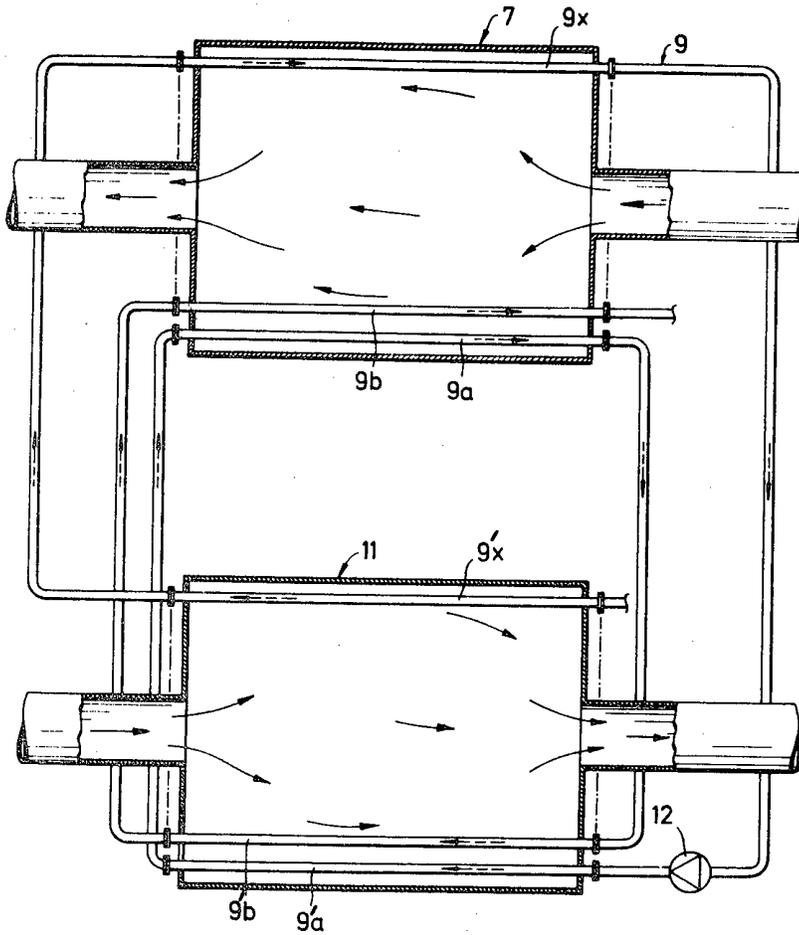


Fig. 1

Fig. 2



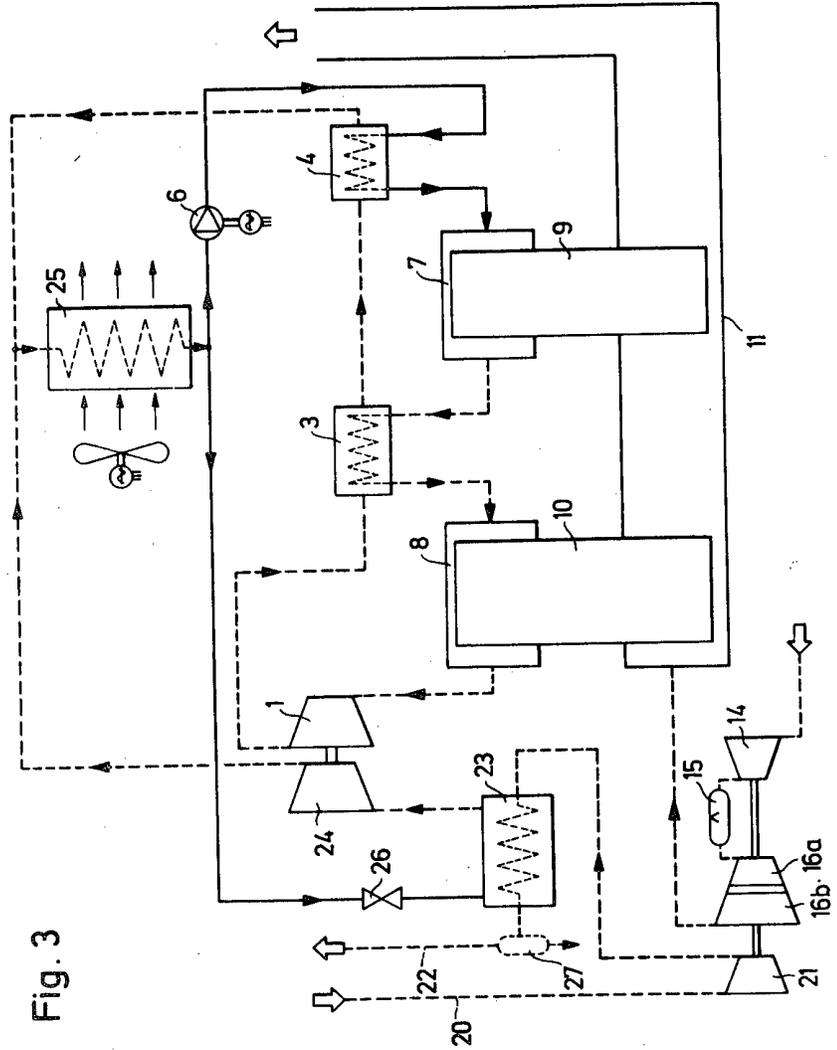


Fig. 3