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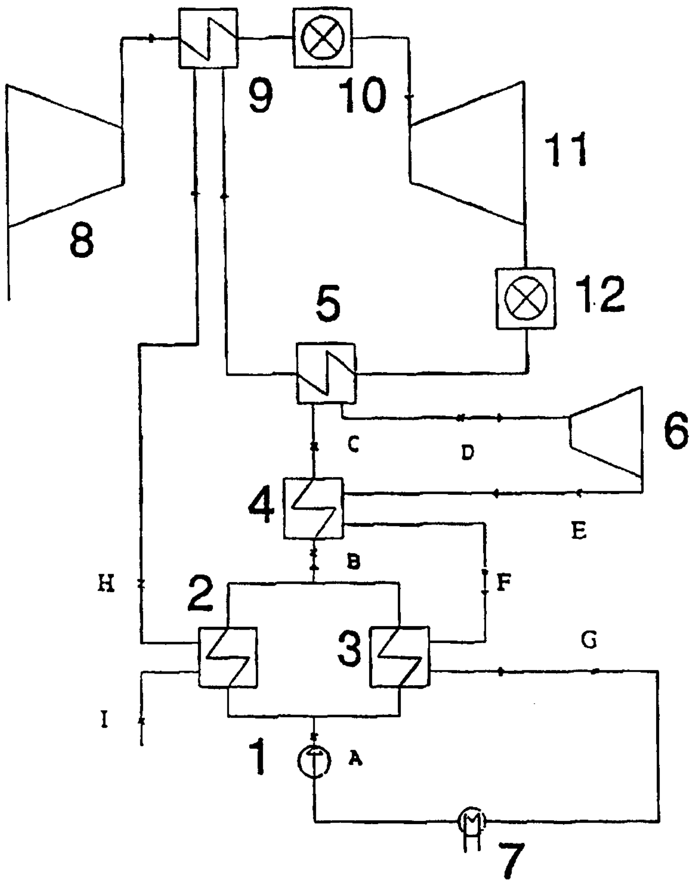
(57) Abstract

A method for exploiting waste thermal energy in power plants for accomplishing a better power production efficiency than at present, whereby the waste thermal energy of medium A and return medium B are used to heat, in parallel heat-exchangers (2, 3), medium B pressurized to a pressure higher than the critical pressure using the pump (1) of the process according to the invention. After this, mediums B are combined and heated in a heat-exchanger (4) by return medium B. Next, medium B is further heated in a boiler (5) by medium A of another process cycle and expanded in a turbine (6) to a pressure lower than the critical pressure, returning to the process to the heat-exchangers (4, 3). After this, it is condensed into liquid in the condenser (7) and a new cycle is started in which it is pressurized to a supercritical pressure using the pump (1), whereby an enthalpic difference corresponding to a certain temperature difference is higher than in the pressure subsequent to the turbine (6), and the difference can be equalized by the waste thermal energy of medium A. The process according to the invention makes it also possible to economically separate the carbon dioxide generated in the combustion by burning the combustible matter by oxygen in a closed carbon dioxide cycle.



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METHOD FOR EXPLOITATION OF WASTE THERMAL ENERGY IN POWER PLANTS

The object of the invention is a method for the exploitation of waste thermal energy in power plants, whereby warm medium A from a gas turbine process and return medium B heat medium B in parallel heat-exchangers, the pressure of medium B being higher than the critical pressure of the process according to the invention. Subsequently, mediums B are combined and further heated by return medium B in the heat-exchanger. After this medium B is further heated in a boiler by medium A subsequent to the turbine or combustion chamber and is expanded in the turbine to lower pressure than the critical pressure and returns to the process to the above-mentioned heat-exchangers. Then medium B is condensed into liquid in a condenser and pressurized to supercritical pressure by a pump, whereby the enthalpic difference corresponding to a certain temperature difference is higher than in the pressure subsequent to the turbine. The enthalpic difference can be equalized by waste thermal energy.

Electricity is presently produced in thermal power stations by fossil fuels or nuclear power and in more modern plants also by solar panels or geothermal energy. The basic process used in power plants is the gas turbine or steam power process or a combination thereof. Problems with nuclear power include radioactive waste and the high price of initial investment, and problems with fossil fuels include emissions causing acidification and the greenhouse effect. Furthemore, both plants have the problem of the risk of accidents and the consumption of non-renewable natural resources. All present thermal power stations in addition have a proportionally low efficiency because they are not able to exploit low-temperature energy for producing electricity. This is significantly improved by the plant according to the invention which is capable of achieving a very high efficiency of electricity production and numerous ensuing advantages. Examples of the advantages include lower fuel consumption, risk of accident, waste and emissions. In addition, an old plant is very easy to replace because it is easy to build a plant according to the invention to operate along with the old plant, utilizing the waste thermal energy. The waste thermal energy of the steam power process can also be exploited by increasing the number of tappings whereby the mass flow rate through the condenser can be reset to zero when needed. The invention is especially well adapted to utilizing natural gas because the condensing temperature of the water vapour generated in combustion can be exploited most effectively in a plant according to Fig. 8 because of the purity of natural gas.

The invention is based on the fact that a larger amount of energy is required - mostly in the low-temperature area - for heating medium B which is liquefied and compressed into supercritical pressure than what return medium B with lower pressure releases. This is a propery of real gases in the vicinity of the critical temperature. Thus the waste thermal energy of present thermal power stations can be exploited extremely effectively in parallel heat-exchangers. The invention differs from the ORC-process (for instance, US A 3 769 789) in that the enthalpic increase corresponding to evaporation requiring a lot of energy is mainly effected in the parallel heat-exchangers subsequent to the pump (1), because medium B is at a supercritical temperature after the parallel heat-exchangers (2, 3). Thus the external waste thermal energy can also be exploited by the process according to the invention. This means that the heat-exchanger (2, 3) is not bound to the boiler. The corresponding phase in the ORC-process is the preheating of liquid. Let us compare the invention with the gas turbine and steam power plant processes. A closed gas turbine process provided with an ideal heat-exchanger and a simple steam power plant process are selected as the objects of comparison. The difference between these two is that the power from the turbine in the gas turbine process is equally as high as the thermal power brought to the system. However, a major part of the power is used for pressurizing the medium by a compressor. In the steam power plant process, in turn, only a part of the thermal power can be exploited in the turbine because a large amount of energy is consumed by evaporation. The energy requirement for the pressurization is low, however. The reference process thus corresponds to the gas turbine process with respect to the efficiency of the turbine when the cooling demand of the blades of the turbine is taken into account. However, the energy requirement of the pressurization is considerably lower than the gas turbine process because part of the pressurization of the medium can be effected by a pump. The above is particularly true for the construction according to Fig. 4 (or 8).

A very suitable medium for the process, carbon dioxide, is harmless to the environment and there is plenty of it available. The required maximum pressure does not set too high technical requirements because a corresponding pressure is already in use in the steam power process at the moment. By suitably selecting medium B, the waste heat of the condenser can be exploited for district heating, for example, while the electricity production remains high at the same time. The invention is also well-adapted for the degassing of solid fuel because the process according to the invention can be used to exploit low-temperature energy better than in present processes as a double substance process, for instance. The waste heat generated in the cooling of the compressor can also be exploited very efficiently in the process according to the invention. The invention is also well-adapted to be used in a plant employing two different sources of heat. An advantage is also the lack of a compressor in the process according to the invention. The economically profitable size class of the plant is very wide as well. The small size due to the relatively high pressure of medium B of the plant is also significant.

Many advantages are achieved when burning combustible matter by oxygen in a closed carbon dioxide cycle. No oxides of nitrogen are generated in the combustion and the carbon dioxide generated in the combustion can be separated for practical application, decreasing the greenhouse effect. Nitrogen and argon from the air can be separated at the same time, and if so desired, also a part of the liquid oxygen. Considerably more thermal power (of high temperature) is obtained in maximum power production than at present (the thermal power per se can also be utilized in power production, when needed, by the plant according to the invention), whereby the energy loss is lower. Other advantages include the lack of water treatment, steam turbine (with associated generators) and a smokestack.

The operating time of the invention in the future is long because the possible heat generated in the fusion is well-adapted to be used in the plant according to Fig. 4, because there is thus no preheating of air. In the still longer run, the renewable energy resources, the sun and biomass, are also suitable for sources of heat in the process according to the invention. The main object of the invention is to provide a novel and more efficient exploitation method of waste thermal energy for power plants than at present, which at the same time makes it possible to economically separate the carbon dioxide generated in combustion. In order to accomplish this, the method according to the invention is characterized in what is disclosed in the characterizing clause of Claim 1.

The following is a detailed description of the drawings:
Fig. 1 is a flow diagram of the plant according to the invention (the gas turbine process as the source of waste thermal energy),
Fig. 2 is a flow diagram of the plant according to the invention (the steam power process as the source of waste thermal energy),
Fig. 3 is a flow diagram of the plant of the invention used for pressurizing natural gas,
Fig. 4 is a process according to the invention (the heat generated in the pressurizing of medium B as the source of waste thermal energy),
Fig. 5 is a table of condition point values of Fig. 1,
Fig. 6 is a h,T graph of the heat exchange of Fig. 1,
Fig. 7 is the flow diagram of a construction of the invention (the gas turbine process as the source of waste thermal energy),
Fig. 8 is a flow diagram of the plant in which the combustible matter is burned by oxygen in a closed carbon dioxide cycle,
Fig. 9 is a flow diagram of a plant according to Fig. 8 where the excess waste thermal energy is exploited by the process according to Fig. 1.

The plant according to Fig. 1 comprises a pump (1), heat-exchangers (2, 3, 4), a boiler (5), a turbine (6), a condenser (7), a compressor (8), a heat-exchanger (9), combustion chambers (10, 12) and a turbine (11). Medium B is carbon dioxide in this example. Medium A corresponds to the open gas turbine process. In principle, however, mediums A and B can be selected, as desired, so that they best suit the situation.

The pressurized air from the compressor (8) enters the heat-exchanger (9) to be preheated by the exhaust gases of the gas turbine process. Then it enters the combustion chamber (10) and the turbine (11). After the exhaust gases have expanded in the turbine (11) they go to the second combustion chamber (12) and after that to the boiler (5) and to the heat-exchanger (9) which is used for preheating air. All this is already well-known in practice. The novelty introduced by the invention is that the exhaust gases coming from the heat-exchanger (9) preheat, in the heat-exchanger (2), the carbon dioxide pressurized to supercritical pressure by the pump (1), while the return carbon dioxide heats the carbon dioxide also in the second parallel heat-exchanger (3). After this the carbon dioxides at supercritical pressure are combined and further heated in heat-exchanger (4) by the lower-pressure return carbon dioxide. After this the carbon dioxide is further heated in the boiler (5) and expanded in the turbine (6) to a lower pressure than the supercritical pressure. After expansion the carbon dioxide returns to the above-mentioned heat-exchangers (4, 3). After this the gaseous carbon dioxide enters the condenser (7) where it is condensed to liquid and pressurized by the pump (1) to supercritical pressure. Thus the process cycle of carbon dioxide is closed.

Fig. 2 represents the process according to the invention where waste thermal heat is obtained from the steam power process. The carbon dioxide cycle corresponds to the above-mentioned cycle but the boiler (5) is provided with an air preheater. In the water vapour cycle the water from decompression valve (15) enters feed water tank (16) where it is heated as the water vapour from the turbine (14) is mixed with it. After this the pump (17) pressurizes the water to the desired pressure, after which the water is heated in heat exchanger (18) by bleeding of the turbine (14), and further by the next bleeding in heat-exchanger (19). The return liquid from the heat exchangers (19, 18) flows to the feed water tank (16). After the heat-exchanger (19) the water cycle is devided while part of the water enters the boiler (5) where it is evaporated and superheated, and enters the turbine (14). The rest of the water enters the heat-exchanger (2) to preheat the carbon dioxide, after which the water goes to the decompression valve (15). The heating phase of carbon dioxide is also effected in the boiler (5).

Fig. 3 shows the flow diagram of a plant used for pressurizing natural gas. The process which uses carbon dioxide as a medium is like the one in Fig. 1, only the boiler (5) is provided with an air preheater. Natural gas is pressurized by compressor (20) with the aid of the energy produced by turbine (6), after which the heated natural gas heats the carbon dioxide in heat-exchanger (2) and is cooled at the same time. The process can be used, when desired, to produce electricity.

Fig. 4 shows a process consisting of a two-phase expansion. A part of the pressurizing of carbon dioxide is carried out by compressor (25), whereby the heat of the carbon dioxide heated in the compressor (25) can be exploited in heat-exchanger (2). The carbon dioxide cycle is otherwise similar to the one in Fig. 1, but boiler (5) is, when necessary, provided with an air preheater. Carbon dioxide is heated in boiler (5) before turbine (6) and also after that because the carbon dioxide is also expanded in turbine (23). The carbon dioxide returns from turbine (23) to heat-exchangers (4, 3) and is further cooled in precooler (24). Because carbon dioxide is expanded in turbine (23) to a pressure lower than the pressure corresponding to the achievable condensing temperature, it enters compressor (25) after this. The carbon dioxide heated in compressor (25) is cooled in the heat-exchanger (2), enters then condensor (7) where it is liquefied. After liquefaction the carbon dioxide is pressurized to supercritical pressure by pump (1).

Fig. 5 is a table of the values of the condition points of Fig. 1. For the sake of simplicity, plain air is used as medium A. 90% was used as the isentropic breeding ratio of the turbine, 3 % as the pressure drop in the heat-exchangers, and 90% as the recuperation rate of the heat-exchangers.

Fig. 6 is an h,T graph of points A, B, C and D of Fig. 1. Heat exchangers (2, 3, 4) and boiler (5) are converted into one heat-exchanger for the sake of clarity.

Fig. 7 shows one of the numerous different forms of application of Fig. 1. It differs from the process of Fig. 1 in that the boiler (5) corresponds to the combustion chamber of the gas turbine process. Thus boiler (5) naturally replaces combustion chamber (10) and combustion chamber (12) is not required. The connection actually corresponds to the connection of a water-cooled PFBC combi heating power plant.

Fig. 8 shows a basic process which is perhaps the most competitive construction of the invention. The oxygen required for the combustion is brought to a closed carbon dioxide cycle. This is a very natural means to increase the maximum temperature of the process because the gas turbine process can be used to achieve a higher maximum temperature of a process than processes based on heat-exchangers. This is because of the durability of the materials. In addition, the condensing heat of water vapour can be exploited in the process for power production and the advantages also include the lack of nitrogen oxides and a possibility to economically separate the carbon dioxide generated in the combustion. Naturally, the lost heat of the compressor is also exploited in the process for power production and a part of the pressurization of medium B, i.e. carbon dioxide, can be carried out by pump (1), whereby the energy requirement of the pressurization is decreased.

Present techniques can be used in the oxygen separation process. If the oxygen liquefied in the separation process is pressurized by the pump to the maximum pressure before the precooling phase of air is effected, part of the liquid oxygen can be separated from the process because the enthalpy difference corresponding to a certain temperature difference is higher in the pressure subsequent to the pump. The liquefied oxygen can be used in LNG-tankers, for instance, as combustion oxygen of a power source according to the invention (Fig. 8). This is partly associated with the so-called SNG-techniques (Substitute Natural Gas).

Subsequent to the condenser (7) in the carbon dioxide cycle, the carbon dioxide generated in the combustion is removed from the process through valve (26), after which the pump (1) pressurizes the carbon dioxide to supercritical pressure. Next, the carbon dioxide cycle is branched and the pressurized oxygen is combined with the carbon dioxide cycle of heat-exchanger (2). After this the carbon dioxide is heated in parallel heat-exchangers (2, 3). Next, the carbon dioxide cycles enter heat-exchanger (4). The oxygen brought to the cycle is burned in combustion chamber (10) by natural gas from compressor (28) while the rest of the carbon dioxide enters the cooling of combustion chamber (10). After expanding in turbine (6), the forward end of which is cooled by carbon dioxide from heat-exchanger (4), the carbon dioxide returns to heat-exchangers (4, 3). Next in the carbon dioxide cycle there is precooler (24), where heat can be recovered, if necessary, for district heating, for instance. The amount of district heat can be further increased by exploiting the heat generated in the air separation process. Next, the water generated in combustion is removed from the process. After this compressor (25) pressurizes the carbon dioxide to condensing pressure. The carbon dioxide returns from compressor (25) to heat-exchanger (2). At the end of the cycle the carbon dioxide is condensated into liquid in condenser (7) where the rest of the oxygen not burned is removed and conducted to the separation process of air subsequent to the compressor.

The carbon dioxide generated in the process can be removed any where in the process. The oxygen not combusted and separated in the condenser can also be pressurized by the compressor, treated by chemicals, or possibly dissolved in liquid carbon dioxide. The construction where the preheating of heat-exchanger (2) is carried out, for instance, using the waste thermal energy of the separation process of air, is also possible. The incombustible hydrocarbons and carbon monoxide can also be separated in the condenser (7), after which they can be recycled by mixing them with the combustible matter.

Fig. 9 is an application of the basic process according to Fig. 8. Excess waste thermal energy is exploited in it by the process according to Fig. 1. Because many components are the same, it is natural that the same components can be used, i.e., the plant can be integrated with respect to the number of the components. The process per se does not include further special inventive characteristics. The waste thermal energy of the air separation process is exploited in heat-exchanger (2).

The embodiments of the invention include a process in which medium B is not heated in boiler (5) after heat-exchanger (4). Thus the heating of medium B to the maximum temperature is carried out in a natural way by the waste thermal energy of medium A in heat-exchanger (4) which is thus actually a boiler. Some other components of the process can also be omitted, when necessary. Consequently, the carbon dioxide sides of heat-exchangers (2, 3, 4) can be combined, whereby the number of the heat-exchangers is decreased. The expansion in turbine (6) can also be effected in several phases as well as the compression in pump (1), whereby cooling is effected between the compression phases. The plant according to the invention also comprises, when necessary, components required for achieving a higher pressure level than the pressure of the surroundings of medium B. The plant according to Fig. 8 produces its own process mediums. The carbon dioxide of the process cycle is broken down at a sufficiently high temperature into carbon monoxide and oxygen which can be burned in a closed cycle before turbine (6). Thus the breeding ratio is improved with the increase of the maximum temperature of the process. Medium A or B can also consist of several substances whereby the desired heat-exchange properties can be accomplished by the mixture. For example, medium B can consist of carbon dioxide and water. The ideal case would be a medium consisting of two substances in which one of the mediums would not be required to be compressed by the compressor and/or it could be at least partly evaporated by excess waste thermal energy.

The process according to the invention can also be connected to the present combined power plant using the method of Fig. 2, for instance, by increasing the number of bleedings of the steam turbine, whereby an extremely high power production efficiency can be accomplished, especially if the condensing heat of water vapour generated in combustion is exploited in the process. In the plant according to Fig. 8 the heat-exchanger (4) can also comprise a water vapour cycle in addition to the carbon dioxide cycle. In practice, such a case would be the most competitive if the maximum temperature of the combustion chamber increased faster than the maximum temperature of the heat-exchangers. Likewise, two parallel heat-exchangers (2, 3) are not necessarily required if the condensing temperature of the water vapour generated in combustion is sufficient, for instance, or the temperature difference of the medium releasing the heat is higher than that of the recipient medium. The invention can naturally be used for other than power production purposes such as power sources for ships, for instance. In theory, the invention might be advantageous in the future as the power source for large propelling machines because the outside temperature is low.

The connection of a cooling apparatus to a power machine has been disclosed in theory in literature. This can also be applied in the plant according to the invention. Thus the condenser (7) is replaced by the evaporator of the cooling process and possible waste thermal energy of the cooling process is exploited in heat-exchanger (2). Especially the adsorption process (ammonia) might be well-adapted to be connected to the process according to the invention. Thus the process according to Fig. 8 would require no compressor (25). In the future, the possible so-called chemical combustion can be applied also to the plant according to the invention. The cooling of the combustion chamber and the turbine can be implemented also by applying the present technique.

The application examples of the invention are described only in order to illustrate the invention and they do not constitute a limitation to the use of the invention because the details, which are not necessary for comprehending the invention, are omitted for the sake of clarity. Thus the invention is not limited by the represented structural forms but it encompasses all that is included in the scope of the following Claims.

CLAIMS

1. A method for the exploitation of waste thermal energy in power plants, for instance, in which plants medium B of higher pressure than the critical pressure is heated in parallel heat-exchangers (2, 3) subsequent to a pump (1) using waste thermal energy, and in a turbine (6) by return medium B expanded to a pressure lower than the critical pressure, at least a part of return medium B being condensed to liquid in a condenser (7) and pressurized by the pump (1) to a pressure higher than the critical pressure, characterized in that medium B is heated to a supercritical temperature or in a supercritical temperature by parallel heat-exchangers (2, 3), whereby the enthalpic difference corresponding to a certain temperature difference is higher than in the pressure subsequent to the turbine (6), whereby the enthalpic difference is equalized by waste thermal energy.

2. A method according to Claim 1, characterized in that the increase in the temperature of medium B corresponding to the boiler (5) is implemented as desired by, for instance, burning the combustible matter by oxygen in a closed or semi-open cycle before the turbine (6).

3. A method according to Claims 1-2, characterized in that the condenser (7) serves as a heat-exchanger connected to the district heating network, for instance, or as the evaporator of an adsorption or another cooling process, whereby the waste thermal energy of the cooling process is exploited in the heat-exchanger (2), when desired.

4. A method according to Claims 1-3, characterized in that the waste thermal energy of medium A is obtained from the cooling of the compressor, from a combined power plant, from a steam power plant by increasing the number of bleedings of a turbine (14), for instance, or from another desired object, and that the number of different heat sources of the process is one or more.

5. A method according to Claims 1-4, c h a r a c t e r i z e d in that mediums A and B are selected as desired and consist of one or more substances, medium B being carbon dioxide, and when this is possibly broken down into carbon monoxide and oxygen at the high temperature of the process, the thus generated substances are allowed to react with one another burning in the closed process cycle.

6. A method according to Claims 1-5, c h a r a c t e r i z e d in that the heat-exchangers (2, 3, 4) are combined to each other with respect to medium B.

7. A method according to Claims 1-6, c h a r a c t e r i z e d in that the condensing temperature of the water vapour generated in the combustion is exploited in the heat-exchanger (2, 3), after which a heat-exchanger (4) is provided prior to a boiler (5) when desired, supercritical medium B being heated in the heat-exchanger (4) by return medium B.

8. A method according to Claims 1-7, c h a r a c t e r i z e d in that the expansion in the turbine (6, 23) is carried to a pressure lower than the pressure corresponding to the obtainable condensing temperature, whereby a compressor (25) is provided in the process before the condenser (7), in which compressor the heat of the heated medium B is exploited before the condenser (7) in the heat-exchanger (2), whereby more work is obtained from the turbines (6, 23), one or more bleedings being provided in the turbines or between them, when desired.

9. A method according to Claims 1-8, c h a r a c t e r i z e d in that the structural parts according to the method constitute a plant which operates as the power source of an SNG/LNG tanker or the plant according to Fig. 9, for instance.

10. A method according to Claims 1-9, c h a r a c t e r i z e d in that the number of the heat-exchangers (2, 3, 4), the boiler (5), the turbine (6), the pump (1), the condenser (7), the compressor (25), the combustion chamber (10), the precooler (24) and/or the process mediums is one or more, and that any of them

can be replaced by another device operating in a corresponding way.

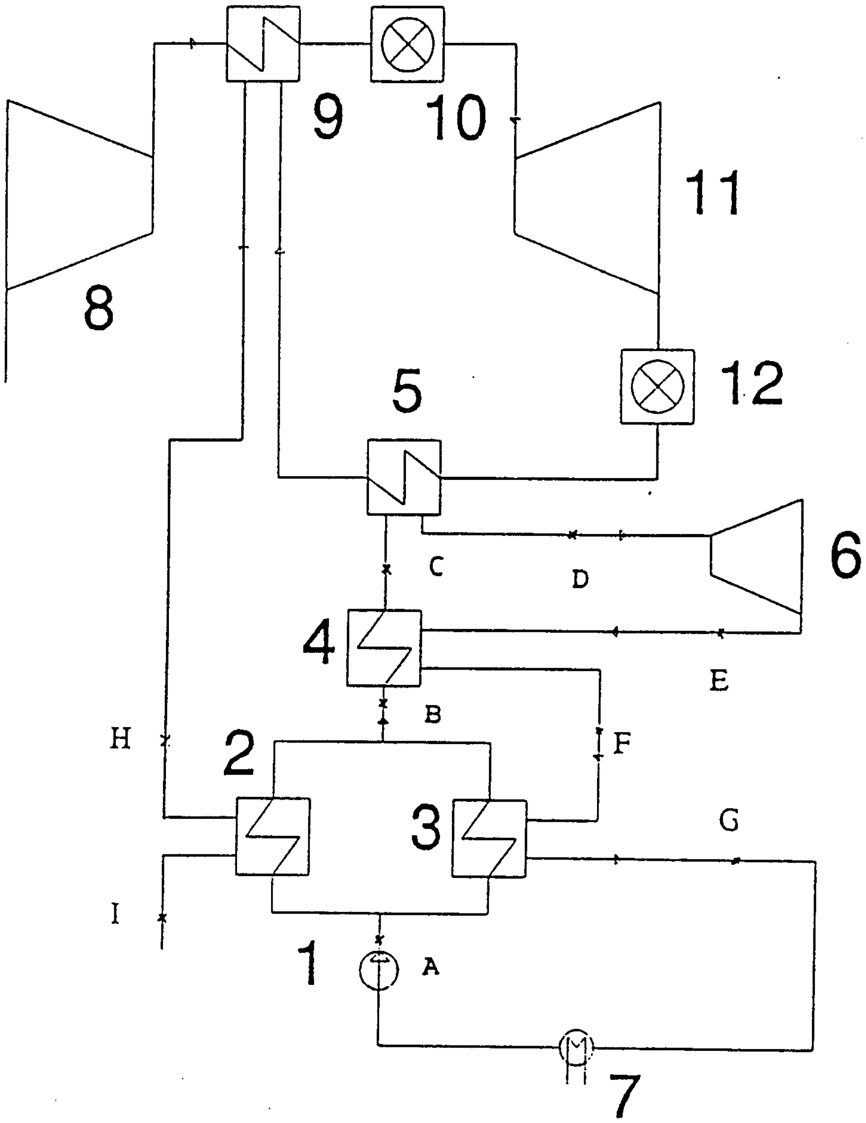

FIG. 1

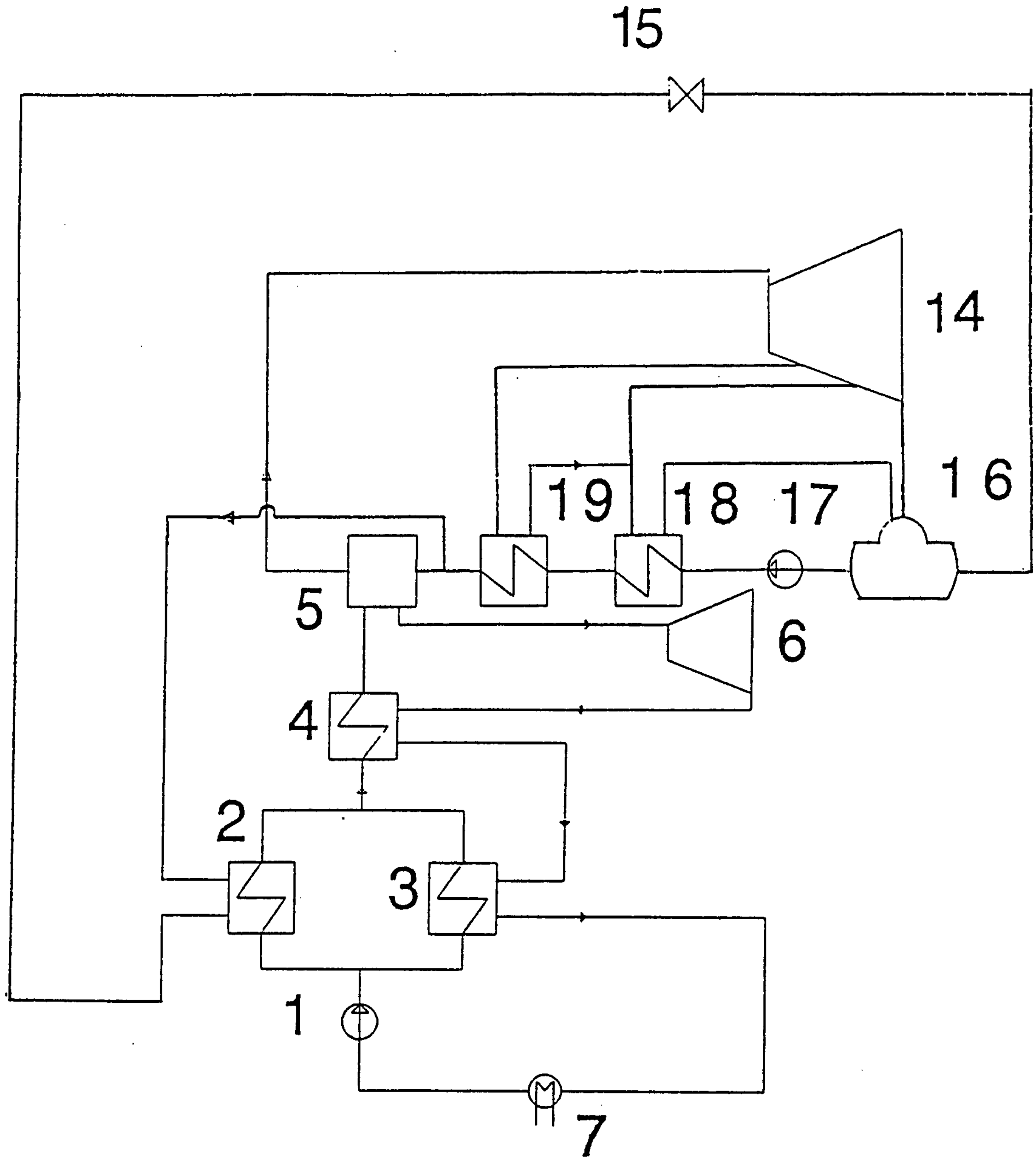

FIG. 2

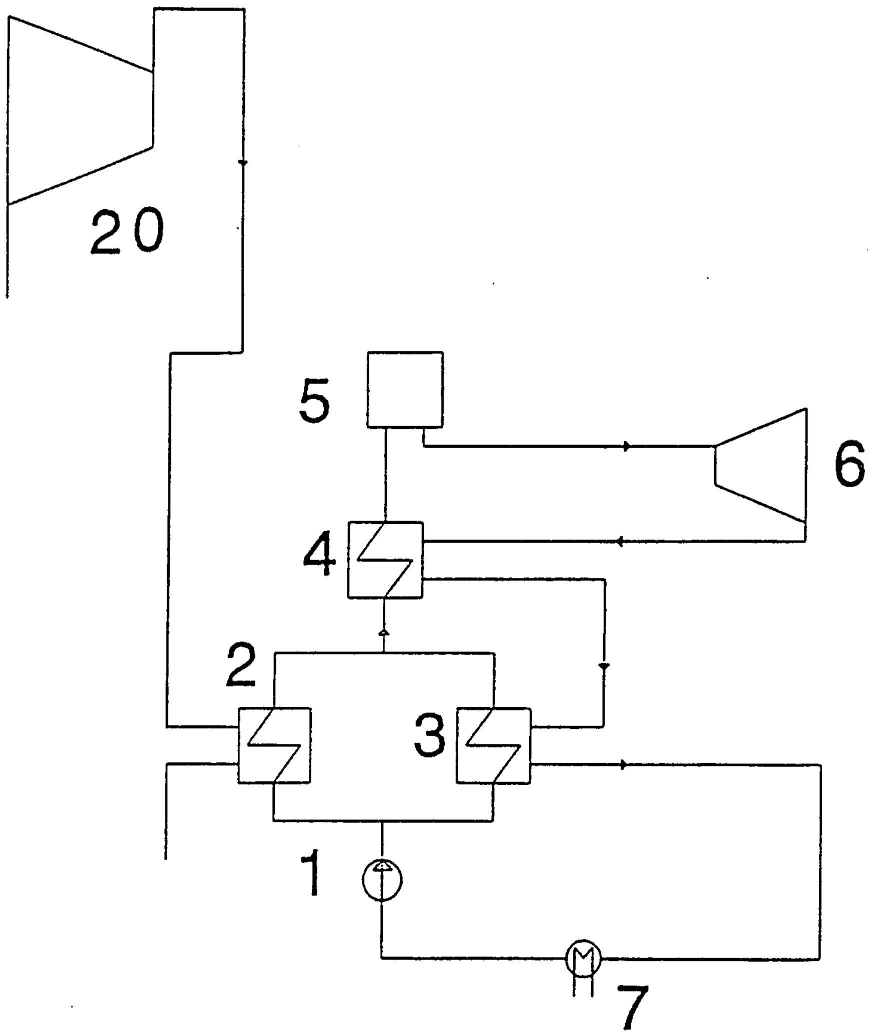

FIG. 3

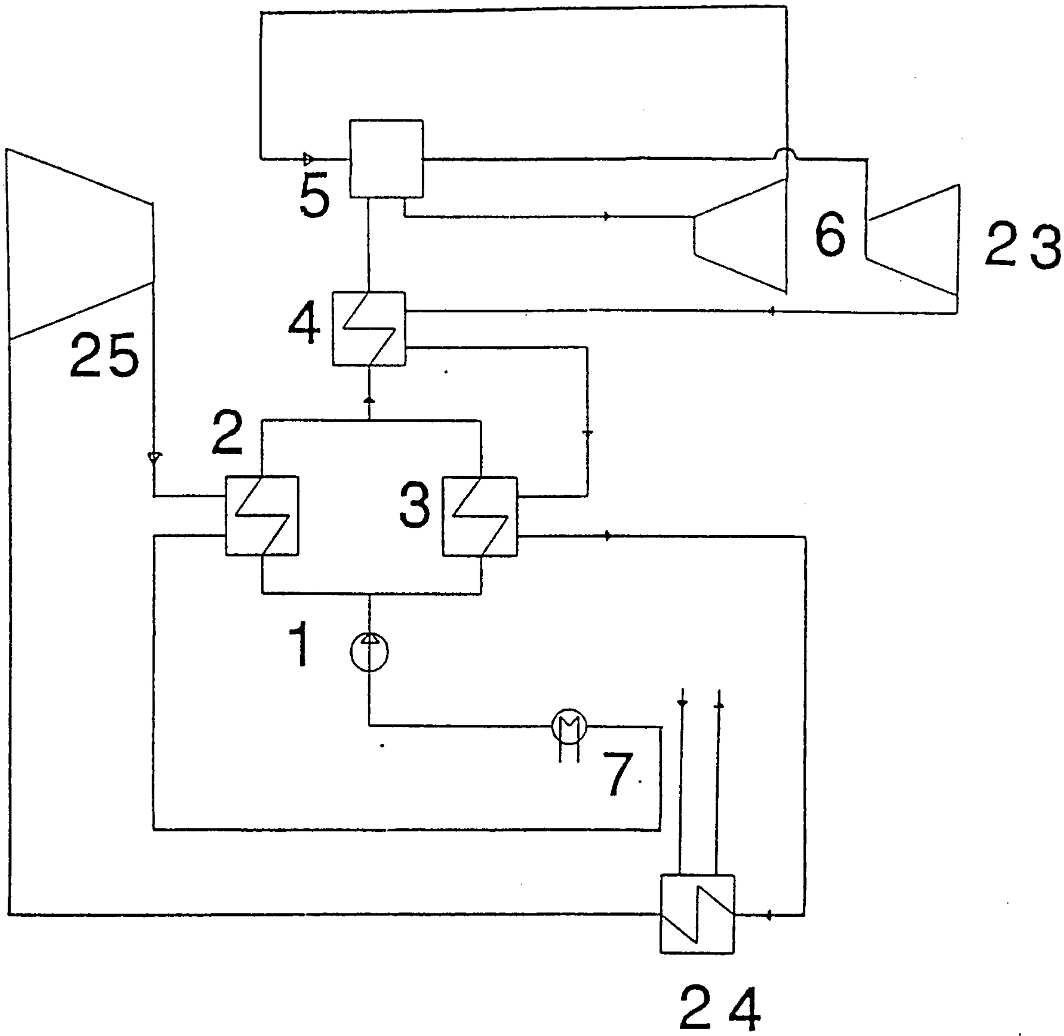

FIG. 4

Table 1. Values used in calculating condition points shown in FIG. 1. The mass flow rate of air is 60 kg/s and that of carbon dioxide 100 kg/s.

	T		*p*	*h*
	(K)	(°C)	(bar)	(kJ/kg)
A	304	31	235	178
B	528	255	228	591
C	950	677	221	1114
D	1200	927	214.5	1430
E	1020	747	53.6	1209
F	578	305	52	686
G	329	56	50	410
H	553	280	1	285
I	329	56	1	56

FIG. 5

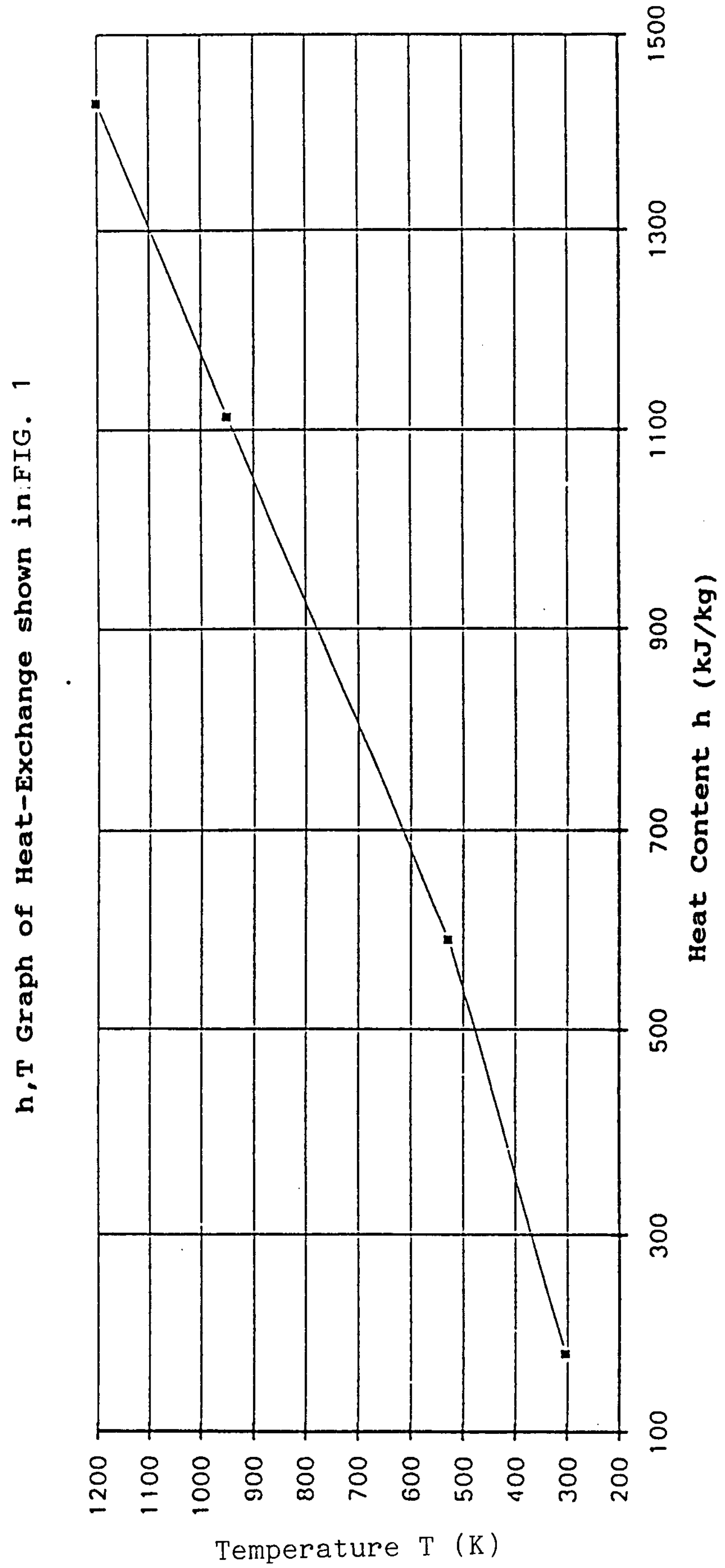
h,T Graph of Heat-Exchange shown in FIG. 1
Heat Content h (kJ/kg)
100
300
500
700
900
1100
1300
1500
Temperature T (K)
1200
1100
1000
900
800
700
600
500
400
300
200

FIG. 6

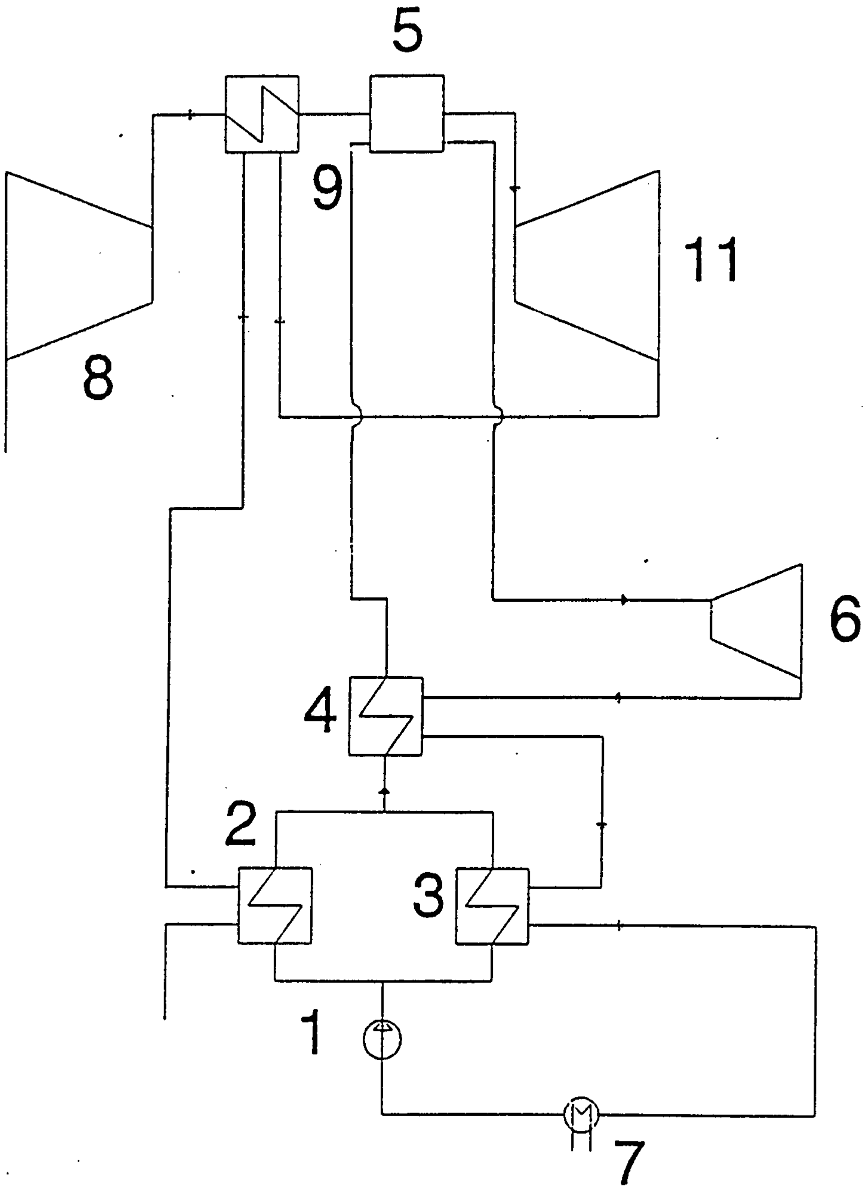

FIG. 7

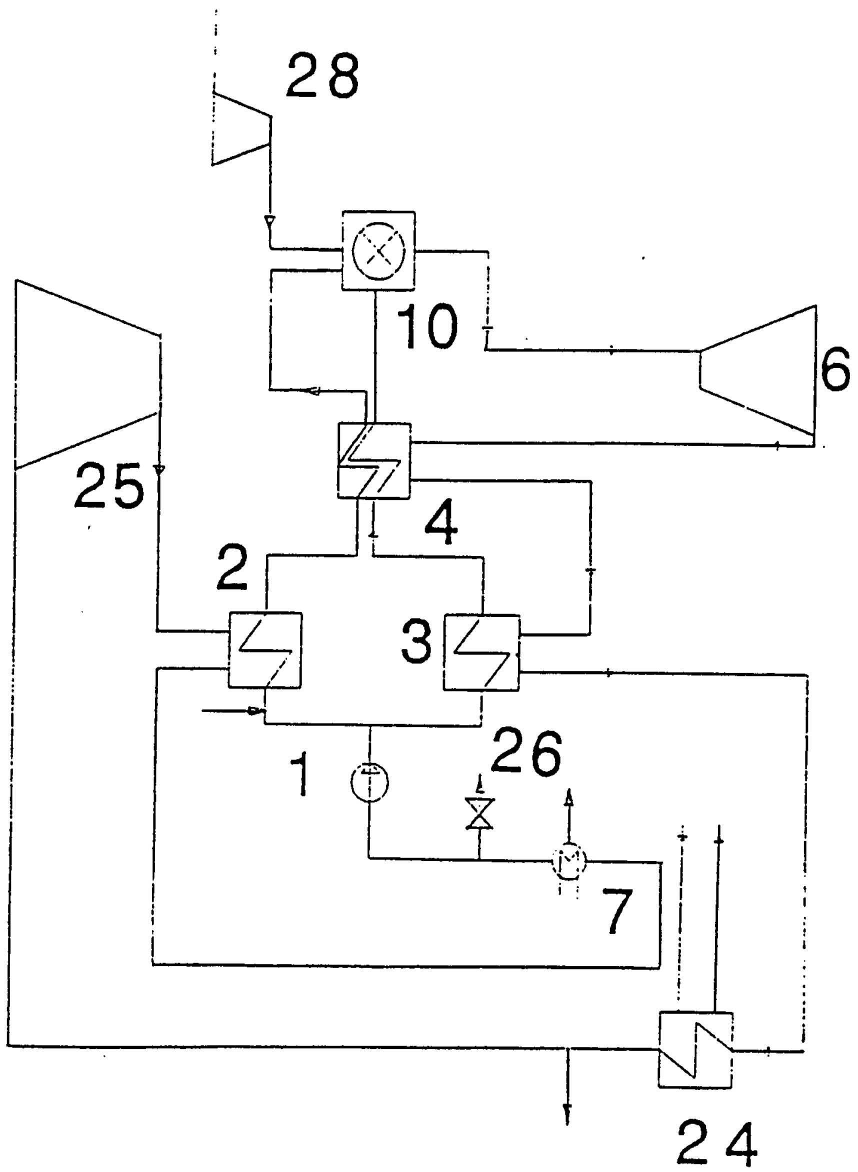

FIG. 8

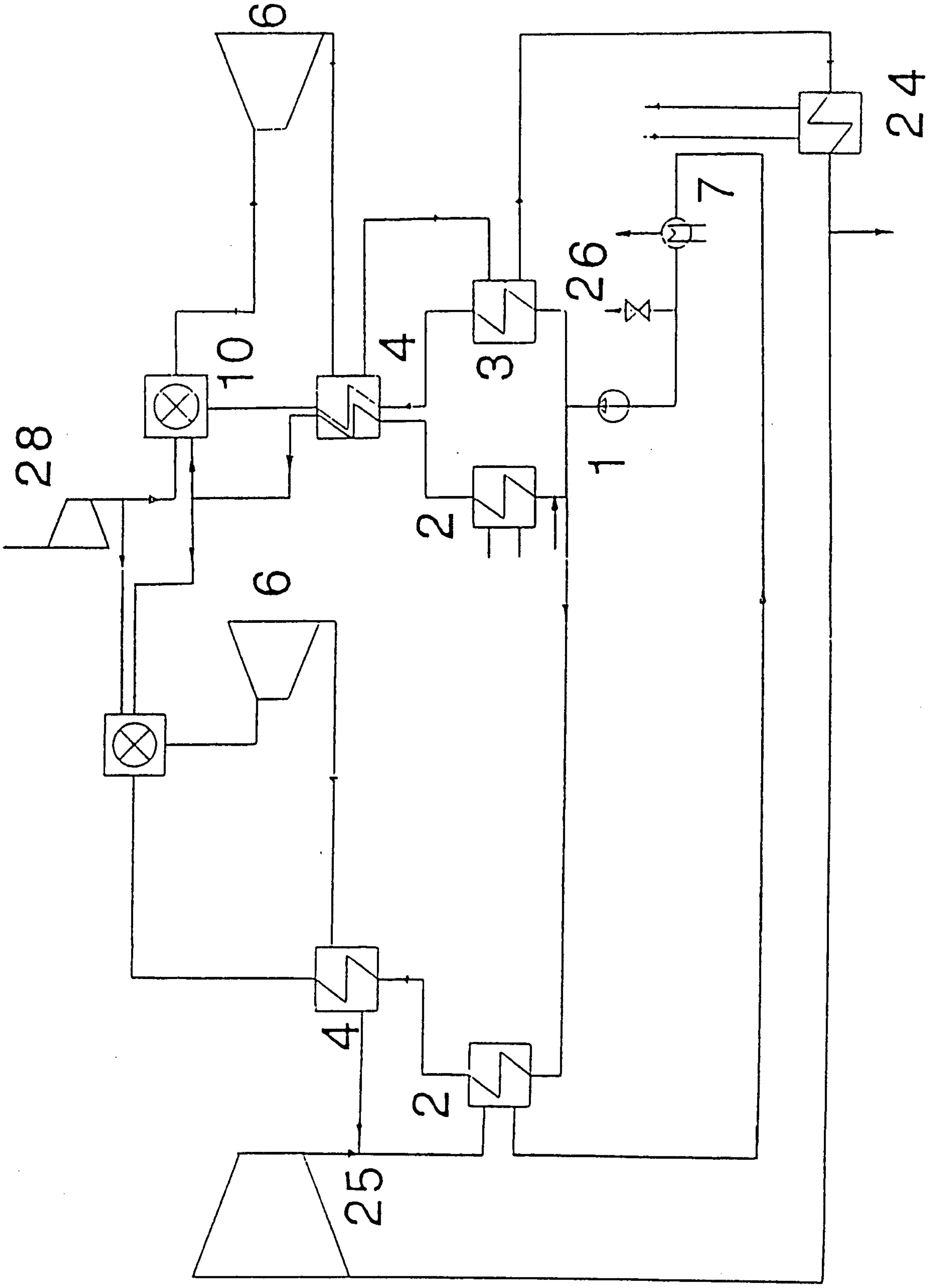

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI 94/00311

A. CLASSIFICATION OF SUBJECT MATTER

IPC 6 : F01K 23/06 // F01K 25/10

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)

IPC 6 : F01K

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)

WPI, CLAIMS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 3769789 (NIGGERMANN), 6 November 1973 (06.11.73), column 4, line 10 - line 26	1,2,6,7
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X	US, A, 3971211 (WETHE ET AL), 27 July 1976 (27.07.76), see for example fig 7; column 10, line 46 - column 12, line 13	1,2,4-7
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X	US, A, 4702081 (VINKO), 27 October 1987 (27.10.87), abstract	1,2,6,7
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☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search	Date of mailing of the international search report
5 October 1994	12 -10- 1994
Name and mailing address of the ISA/ Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Sune Söderling Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT
Information on patent family members

27/08/94

International application No.
PCT/FI 94/00311

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A- 3769789	06/11/73	DE-A- 2233327	18/01/73
		FR-A- 2145251	16/02/73
		GB-A- 1381126	22/01/75
US-A- 3971211	27/07/76	NONE	
US-A- 4702081	27/10/87	DE-C- 3509357	31/07/86
		EP-A,B- 0216835	08/04/87
		SE-T3- 0216835	
		JP-T- 62502209	27/08/87
		WO-A- 8605234	12/09/86

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