



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication: **18.07.2001 Bulletin 2001/29** (51) Int Cl.7: **F02G 1/044**

(21) Application number: **01200087.3**

(22) Date of filing: **12.01.2001**

(84) Designated Contracting States:
AT BE CH CY DE DK ES FI FR GB GR IE IT LI LU MC NL PT SE TR
 Designated Extension States:
AL LT LV MK RO SI

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(30) Priority: **17.01.2000 NL 1014087**

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(54) **Thermal-energy conversion device**

(57) The invention relates to a device (100) which comprises a cylinder (1) for a compressible medium with a displacement member (2) oscillating therein during operation, with a bypass line (3) through which the medium can flow back and forth during operation, and with cooling and heating means (4, 5), referred to as Stirling unit for short. A periodic pressure variation generated in the medium during operation results in a pressure difference between two vessels (6, 8) which are connected to the cylinder (1) via two non-return valves (7, 9). A load (L) is connected between the two vessels (6, 8).

A device (100) according to the invention comprises at least a further vessel (12) and at least a further Stirling unit (20) connected in series between the Stirling unit (10) and the second vessel (8), while a first end (21A) of a further cylinder (21) of the further Stirling unit (20) is connected to the first end (1A) of the cylinder (1) of the Stirling unit (10), and a further non-return valve (13) opening at an intermediate pressure is present at least between the Stirling unit (10) and the further vessel (12), through which further non-return valve the medium can flow from the cylinder (1) of the Stirling unit (10) to the further vessel (12). Preferably, the load (L) is a pneumatic motor. The displacement members (2, 22) of the Stirling units (10, 20) are preferably provided with a pneumatic drive (A).

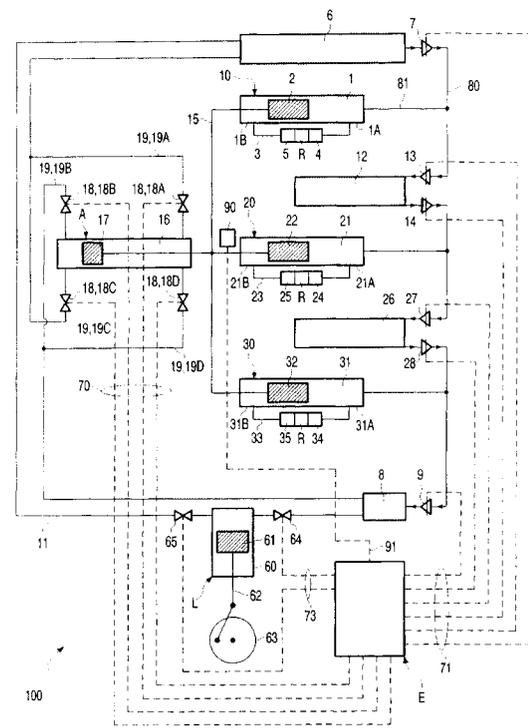


FIG. 1

EP 1 116 872 A1

Description

[0001] The invention relates to a device for converting thermal energy into especially mechanical energy, comprising a cylinder for a compressible medium with a displacement member smaller than the cylinder being arranged therein with sliding fit and oscillating between a first end and a second end of the cylinder, which ends are interconnected via a connection line through which the medium is capable of flowing back and forth during the oscillation of the displacement member, and comprising means for cooling the medium in the first end and further means for heating the medium in the second end such that a periodic pressure variation is generated in the medium during operation whereby a load can be driven, referred to as Stirling unit for short hereinafter, the first end of the cylinder being connected to a first vessel via a first non-return valve which opens at a low pressure and through which the medium can flow from the first vessel to the cylinder, and to a second vessel via a second non-return valve which opens at a high pressure and through which the medium can flow from the cylinder to the second vessel, while the load is arranged in a further connection line between the first and the second vessel. Energy in the form of heat is converted into pneumatic energy during operation in such a device. This takes place without internal combustion here, in contrast to so-called internal combustion engines.

[0002] Such a device is known from US Patent USP 3,782,859, published on January 1st, 1974. This describes a device - see Fig. 4 - with a Stirling unit which comprises two cylinders for a compressible medium arranged in parallel for the purpose of preventing vibrations and stalling in the Stirling cycle. Each cylinder comprises a displacement member and is provided with a so-called by-pass line for the medium which interconnects the ends of the cylinder and in which means for cooling the medium, a thermal regenerator, and further means for heating the medium are incorporated. A first, low-pressure vessel and a second, high-pressure vessel are connected to the cold ends of the two cylinders via a first non-return valve and a second non-return valve, respectively. A load which comprises, for example, a heart pump or some other pneumatic device is connected between the first and the second vessel

[0003] It is a disadvantage of the known device that the controllability of the known device leaves to be desired. The supply of different power levels in quick succession, in particular high powers, is in need of improvement. The limited controllability is connected with sub-optimal management possibilities of the thermodynamic cycle in the device.

[0004] It is accordingly an object of the present invention to provide a device which does not have the above disadvantages, or at least to a much lesser extent, which can supply a high output power, and which can be well controlled. In addition, the device should be easy to manufacture.

[0005] According to the invention, a device of the kind mentioned in the opening paragraph is for this purpose characterized in that it comprises at least a further vessel and at least a further Stirling unit which are coupled in series between the Stirling unit and the second vessel, while the first end of the cylinder of the further Stirling unit is connected to the first end of the cylinder of the Stirling unit, and a further non-return valve opening at an intermediate pressure is present at least between the Stirling unit and the further vessel, through which further non-return valve the medium can flow from the cylinder of the Stirling unit to the further vessel. The invention is based firstly on the far from obvious recognition that the use of at least a further vessel, a further Stirling unit, and a non-return valve renders it possible in a simple manner to obtain a device which achieves a higher pressure in the second vessel than does the known device. Thanks to this higher pressure, the device is not only capable of supplying a high output power, but the mechanical output power is also better controllable owing to the buffer effect of the second or high-pressure vessel. A pneumatic device coupled to the device will not readily stall for that same reason. A high pressure has the additional advantage that the adiabatic and flow losses are comparatively small. The device according to the invention is preferably coupled to a pneumatic motor. A major advantage of the device according to the invention then is that the power per unit mass can be freely chosen. The device comprises a thermal part which may be comparatively large and heavy, but this is counteracted by the fact that the pneumatic part can be positioned comparatively far away from the thermal part. Thus, if the device is used for driving a vehicle, the thermal part may be accommodated, for example, in the constructional parts of the vehicle. The pneumatic part of the device can be small, efficient, and high-speed. The power per unit mass ratio of the pneumatic part can thus be favorable.

[0006] The device according to the invention may be provided with a yet greater number of Stirling units and vessels in a simple manner. The final pressure in the second vessel can be comparatively high as a result of this. The number of units n required for a given application follows from the desired final pressure. $P_n = (T_1/T_2)^n \cdot P_1$, P_1 and P_n being the pressures in the first and the second vessel, respectively. T_1 and T_2 are the absolute temperatures of the medium in the second and the first end of the cylinder, respectively. It is assumed here that the Stirling units are identical. This is not necessary per se, but it does have practical advantages. A major further advantage of a device according to the invention is that a high final pressure can be achieved in this manner with a comparatively small temperature difference, i.e. with a comparatively low T_1 . The thermal requirements to be imposed on the materials used are accordingly mild, and the device may be manufactured, for example, from low-grade alloys. The efficiency does drop somewhat owing to the lower temperature T_1 , but

this is counteracted by the fact that low-grade heat can now be used, such as solar heat or heat evolved upon fermentation of biomass. The fact that the thermal part of a device according to the invention becomes comparatively large has the further advantage that the rate at which the medium is to change temperature is reduced. If this frequency can be kept low, mechanical problems in the thermal part will be comparatively small. A desired comparatively high final pressure means that the materials and construction used must be resistant thereto, but in a device according to the invention these problems for a major part do not arise simultaneously with the thermal problems. This is because the vessels and the lines used are present mainly at the cold side of the device.

[0007] In a major embodiment, the further vessel is connected to the further Stirling unit by means of a yet further non-return valve which opens at said intermediate pressure and through which medium can flow from the further vessel to the cylinder of the further Stirling unit. If the device comprises a cascade of n Stirling units in this embodiment, the total number of vessels will be equal to $n+1$, and the total number of non-return valves will be equal to $2n$.

[0008] In another favorable embodiment, the further vessel is at the same time the cylinder of the further Stirling unit. If the device comprises a cascade of n Stirling units, the total number of vessels required is no more than in the known device, i.e. 2. The number of non-return valves in this case is equal to $n+1$. This embodiment is particularly attractive on account of its comparatively great compactness and the small number of components.

[0009] In a further favorable modification, the device comprises a number of Stirling units whose displacement members move alternately in opposite directions. Such a device is comparatively stable and not liable to generate vibrations. In addition, the cold and the hot sides of the units may readily be jointly constructed.

[0010] In a preferred embodiment of a device according to the invention, the load comprises a pneumatically driven motor. The advantages inherent therein have been discussed above. Preferably, the volumes of the first, second, and further vessels are chosen such that during operation the product of the volume and the pressure in a vessel is approximately the same for all vessels. In the case of three Stirling units, for example, if a pressure ratio of 8 is desired between the first and the second vessel, the volume of the second vessel may be 8 times smaller than that of the first vessel. This also contributes to the compactness of the device.

[0011] In a particularly favorable modification, the displacement member of the Stirling unit, and preferably also the displacement member of the further Stirling unit, is connected to a piston rod which is provided with a pneumatic drive. The presence of such a piston rod enhances the controllability of the device further, as well as the controllability of the entire thermodynamic cycle

taking place therein. The device according to the invention remains comparatively simple in that the pneumatic energy already present is utilized for driving the piston rod. A major advantage of this modification is furthermore that the displacement member drive is independent of the operation of the load present. This is in contrast to the conventional Stirling motors, in which the frequency f_v of the displacement member is coupled to the motor frequency f_m . A high f_m is desired for supplying a high power to a crankshaft in the pneumatic part of the device. At a high f_v , however, the thermodynamic requirements imposed on the Stirling cycle are particularly stringent. Thus, for example, the medium has to be cooled down and heated up particularly quickly in that case. The effective decoupling of f_v and f_m provided in this modification renders possible a much better energy conversion efficacy, also at a high envisaged output power.

[0012] Preferably, the pneumatic drive of the piston rod comprises a cylinder which accommodates a piston connected to the piston rod and whose two ends are each connected to two conduits fitted with a valve, the one conduit being connected at both ends to the first vessel and the other conduit being connected to the second vessel, said valves being electronically operable and connected to an electronic control unit. Such a control unit may be a microprocessor, whereby not only the displacement member drive, but also other aspects of the thermodynamic Stirling cycle can be better controlled and optimized. Thus the non-return valves used in the device according to the invention may advantageously also be electronically operated valves which are coupled to the control unit. The same holds for the inlet and outlet valves of a pneumatic motor which is preferably used as the load. All valves may incorporate a pressure sensor.

[0013] The invention will now be explained in more detail with reference to three embodiments and the accompanying drawing, in which

Fig. 1 diagrammatically shows a first embodiment of a device according to the invention,

Fig. 2 diagrammatically shows a second embodiment of a device according to the invention,

Fig. 3 diagrammatically shows a third embodiment of a device according to the invention.

[0014] The Figures are not drawn true to scale. Corresponding parts have been given the same hatching and the same reference numerals as much as possible.

[0015] Fig. 1 diagrammatically shows a first embodiment of a device according to the invention. The device 100 for the conversion of energy comprises a Stirling unit 10 in this example. The unit comprises a cylinder 1 for a compressible medium which is inert with respect to the materials used, in which cylinder a displacement member 2 smaller than the cylinder is arranged with sliding fit so as to oscillate during operation of the device

100 between a first and a second end 1A, 1B of the cylinder 1, which ends 1A, 1B are interconnected via a connection line 3 through which the medium can flow back and forth during the oscillation of the displacement member 2. The unit 10 comprises means 4 for cooling the medium in or adjacent the first end 1A, further means 5 for heating the medium in or adjacent the second end 1B, and - in the present example - also a regenerator R. A periodic pressure variation is generated in the medium during operation of the device 100 whereby a load L can be driven. The first, cold end 1A of the cylinder 1 is connected to a first vessel 6 via a first non-return valve 7 which opens at a low pressure in the first vessel 6 and through which the medium can flow from the first vessel 6 to the cylinder 1. The first end 1A is also connected to a second vessel 8 via a second non-return valve 9 which opens at a high pressure in the cylinder 1 and through which the medium can flow from the cylinder 1 to the second vessel 8. The load L is positioned in a further connection line 11 between the first vessel 6 and the second vessel 8.

[0016] According to the invention, the device 100 comprises at least a further vessel 12 and at least a further Stirling unit 20 connected in series between the Stirling unit 10 and the second vessel 8, a first end 21A of a further cylinder 21 of the further Stirling unit 20 being connected to the first end 1A of the cylinder 1 of the Stirling unit 10, while a further non-return valve 13 is present at least between the Stirling unit 10 and the further vessel 12, which valve opens at a pressure lying between the high and the low pressure prevailing in the first 6 and the second vessel 8, respectively, and through which valve the medium can flow from the cylinder 1 of the Stirling unit 10 to the further vessel 12. The device 100 according to the invention thus comprises at least two Stirling units 10, 20, so that the pressure in the second vessel 8 can be substantially higher than in the known device. As a result, the device 100 supplies power at a higher pressure, and the power to be supplied is also better controllable, partly also owing to the high-pressure improved buffer action of the second vessel 8. The device 100 in this example also comprises a yet further Stirling unit 30 and a yet further vessel 26 in a series arrangement. Said yet further vessel 26 is connected between the further and the yet further Stirling units 20, 30 by means of two other non-return valves 27, 28 which open at a pressure lying between the pressure of the further vessel 12 and that of the second vessel 8. The volume of the first vessel 6 in this example is 24 l, that of the second vessel 3 l. The interposed vessels 12, 16 have volumes lying between these values such that the product of volume and pressure is approximately the same for all vessels 6, 8, 12, 26.

[0017] The device 100 in this example comprises as its load L a pneumatically driven motor L. The motor L here comprises a cylinder 60 with a piston 61 therein which is given a reciprocating motion through the consecutive opening and closing of two valves 64, 65

present in the connection line 11. This reciprocating motion is converted into a rotation of a wheel 63 by means of a transmission 62. This embodiment of the device 100 constitutes an attractive alternative to an internal combustion engine for driving a motor vehicle (not shown in the drawing). In this example, all displacement members 2, 22, 32 of the three Stirling units 10, 20, 30 are connected to a piston rod 15 which is provided with a pneumatic drive A. The work required for this is supplied by the pressure difference obtaining between the first and second vessels 6, 8, as is the work done the pneumatic motor L. The entire thermodynamic cycles of the Stirling units 10, 20, 30 can be better controlled and optimized thanks to the drive of the displacement members 2, 22, 32. An additional major advantage of this embodiment of the device 100 is that the displacement member frequency f_v can be chosen (and controlled) independently of the motor frequency f_m . As a result, for example, the motor L may have a high frequency f_m if it is to supply a high power, while at the same time the displacement member may have a low frequency f_v , which benefits the efficacy of the Stirling cycle.

[0018] The drive A of the displacement members 2, 22, 32 here comprises a cylinder 16 with therein a piston 17 which is connected to the piston rod 15 and whose two ends are each provided with two conduits 19 fitted with a valve 18. The one conduit 19A, 19C at each end of the cylinder 16 is connected to the first vessel 6, while the other conduit 19B, 19D is connected to the second vessel 8. The valves 18 are electronically operable and coupled to an electronic control unit E via electrical connection lines 70. Adjacent the piston rod 15 there is a position sensor 20 by means of which the position of the piston rod 15 is passed on to the electronic control unit E via an electrical connection line 91. In this example, the non-return valves 7, 9, 13, 14, 27, 28 are also electronically operated and are for this purpose connected to the electronic control unit E, a microprocessor E in this case, via electrical connection lines 71. The same is true for the inlet and outlet valves 64, 65 of the pneumatic motor L, which are coupled to the unit E via connection lines 73. In this example, moreover, all valves 7, 9, 13, 14, 27, 28, 18, 64, 65 are provided with respective pressure sensors (not shown in the drawing) which are connected to the control unit E by means of electrical connection lines (again, not shown at least individually in the drawing). The entire thermodynamic process can thus be better monitored and controlled, which benefits the performance of the device 100 according to the invention.

[0019] All connection lines 3, 23, 33 of the Stirling units 10, 20, 30 are provided with thermal regenerators R for the thermodynamic performance. These increase the efficacy of heating and cooling of the medium upon the passage thereof. The manufacture of the device 100 takes place with conventional techniques. A particular advantage of the device 100 according to the invention which should be noted is that the temperature difference

between the two ends of each cylinder of each Stirling unit 10, 20, 30 is allowed to be comparatively small thanks to the cascade of Stirling units 10, 20, 30. As a result, the materials used for the manufacture may comprise low-grade alloys which are not resistant to extremely high temperatures, and the device according to the invention may be comparatively inexpensive.

[0020] Fig. 2 diagrammatically shows a second embodiment of a device 100 according to the invention. The device 100 differs from the device 100 of the first embodiment firstly in that it now comprises a cascade of five Stirling units 10, 20, 30, 40, 50 instead of three. An even greater pressure difference between the first and the second vessel 6, 8 is made possible thereby, which benefits the performance of the device. A major difference, however, resides in the fact that the functions of all further and other vessels 12, 26 present in the previous example are performed here by the cylinders 21, 31, 41, 51 of the Stirling units 10, 20, 30, 40, 50. This makes the device 100 in this embodiment particularly compact, as it comprises no more than two separate vessels 6, 8. In addition, the device 100 in this embodiment has the important advantage that it requires not $2n = 10$ ($n = 5$) non-return valves (analogous to the first example, where 6 non-return valves were necessary), but only $n + 1 = 6$ ($n = 5$). Besides the first and second non-return valves 7, 9 only the further and other non-return valves 13, 27, 37, and 47 are necessary for a satisfactory operation. This renders this embodiment of the device 100 according to the invention comparatively simple and inexpensive. The connection line 80 connects not only the first and the second vessel 6, 8, but also all first ends 1A, 21A, 31A, 41A, 51A of the cylinders 1, 21, 31, 41, 51 of the Stirling units 10, 20, 30, 40, 50. The connection line 80 is for this purpose provided with branch lines 81 leading to the first, cold ends 1A ... 51A of the cylinders 1 ... 51. One of the further and other non-return valves 13, 27, 37, 47 is present between each pair of branch lines 81.

[0021] The Stirling units 10 ... 50 in this example are positioned relative to one another such that the mutually adjoining ends of the cylinders, for example the cylinders 1, 21, of two mutually adjoining Stirling units, for example the units 10, 20, are both either "cold" or "hot". The displacement members 2, 22, 32, 42, 52 are connected to a pneumatic drive A via a piston rod 15. The drive A is constructed in the same way as in the first example. Details of the drive A and the electrical connections to a control unit E have accordingly been left out in the drawing. The same holds for the pneumatic motor L and the electronic operation of the non-return valves 7, 9, 13, 27, 37, 47 used. It suffices to refer to Fig. 1 and the accompanying discussion for this.

[0022] Fig. 3 diagrammatically shows a third embodiment of a device according to the invention. The device 100 in this embodiment comprises a cascade of four Stirling units 10, 20, 30, 40. In contrast to the previous example, the displacement members 2, 22, 32, 42 of the

respective Stirling units 10, 20, 30, 40 move in opposite directions alternately. The piston rod 15A of the first and third Stirling units 10, 30 is for this purpose coupled to a first drive A1 and [the piston rod 15B on the second and fourth Stirling units 20, 40 to a second drive A2. This makes the operation of the device 100 in this example particularly stable. Another advantage over the second embodiment is that the Stirling units 10, 20, 30, 40- as in the first embodiment - all have the same orientation. That is to say, the means 5, 25, 35, 45 for heating the medium and the means 4, 24, 34, 44 for cooling the medium are all positioned at the same side of the Stirling units 10, 20, 30, 40, so that these means can each be jointly constructed. The remaining components of the device 100 in this embodiment are identical to those of the preceding examples. Reference is accordingly made here to these examples for a description thereof.

[0023] In a modification not shown in the drawing, only a single drive is used - as in the first and second embodiments - instead of two separate drives A1, A2. This drive is then coupled to the two piston rods 15A, 15B via a suitable transmission.

[0024] The invention is not limited to the embodiments described, since many modifications and variations are possible to those skilled in the art within the scope of the invention. The first and second vessels, and any further vessels, if present, are separately mounted vessels in the examples given here. Alternatively, however, the vessels may be accommodated one within the other, especially if the second vessel is (much) smaller than the first vessel. This renders possible a compact device.

[0025] It is expressly noted that the use of a device according to the invention is not limited to the drive of a vehicle (or ship), as in the examples. An application as a current generator for, for example, farms, camping grounds, and transmitter and/or receiver installations is equally possible. Another attractive application is found in buildings where the (residual) heat of central heating installations may be (partly) used for generating electric power by means of a device according to the invention. A further possibility is its use as a heat transformer which converts high-grade heat into low-grade heat for heating purposes and in addition into mechanical energy.

Claims

1. A device for converting thermal [energy into especially mechanical energy], comprising a cylinder (1) for a compressible medium with a displacement member (2) smaller than the cylinder (1) being arranged therein with sliding fit and oscillating between a first end (1A) and a second end (1B) of the cylinder (1), which ends are interconnected via a connection line (3) through which the medium is capable of flowing back and forth during the oscillation of the displacement member (2), and comprising means (4) for cooling the medium in the first end

- (1A) and further means (5) for heating the medium in the second end (1B) such that a periodic pressure variation is generated in the medium during operation whereby a load (L) can be driven, referred to as Stirling unit (10) for short hereinafter, the first end (1A) of the cylinder (1) being connected to a first vessel (6) via a first non-return valve (7) which opens at a low pressure and through which the medium can flow from the first vessel (6) to the cylinder (1), and to a second vessel (8) via a second non-return valve (9) which opens at a high pressure and through which the medium can flow from the cylinder (1) to the second vessel (8), while the load (L) is arranged in a further connection line (11) between the first (6) and the second vessel (8), characterized in that the device comprises at least a further vessel (12) and at least a further Stirling unit (20) which are coupled in series between the Stirling unit (10) and the second vessel (8), while a first end (21A) of the further cylinder (21) of the further Stirling unit (20) is connected to the first end (1A) of the cylinder (1) of the Stirling unit (10), and a further non-return valve (13) opening at an intermediate pressure is present at least between the Stirling unit (10) and the further vessel (12), through which further non-return valve the medium can flow from the cylinder (1) of the Stirling unit (10) to the further vessel (12).
2. A device as claimed in claim 1, characterized in that the further vessel (12) is connected to the further Stirling unit (20) by means of a yet further non-return valve (14) which opens at said intermediate pressure and through which medium can flow from the further vessel (12) to the cylinder (21) of the further Stirling unit (20).
3. A device as claimed in claim 1, characterized in that the further vessel (12) is at the same time the cylinder (21) of the further Stirling unit (20).
4. A device as claimed in claim 1, 2, or 3, characterized in that it comprises a number of Stirling units (10, 20, 30, 40) whose displacement members (2, 22, 32, 42) move alternately in opposite directions.
5. A device as claimed in claim 1, 2, or 3, or 4, characterized in that the load (L) comprises a pneumatic motor (L).
6. A device as claimed in any one of the preceding claims, characterized in that the volumes of the first, second, and further vessels (6, 8, 12) are chosen such that during operation the product of the volume and the pressure in a vessel (6, 8, 12) is approximately the same for all vessels (6, 8, 12).
7. A device as claimed in any one of the preceding claims, characterized in that the displacement member (2) of the Stirling unit (10), and preferably also a displacement member (22) of the further Stirling unit (20), is connected to a piston rod (15) which is provided with a pneumatic drive (A).
8. A device as claimed in claim 7, characterized in that the pneumatic drive (A) of the piston rod (15) comprises a cylinder (16) which accommodates a piston (17) which is connected to the piston rod (15) and whose two ends are each connected to two conduits (19) fitted with a valve (18), the one conduit (19A, 19C) being connected at each end to the first vessel (6) and the other conduit (19B, 19D) being connected to the second vessel (8), said valves (18) being electronically operable and connected to an electronic control unit (E).
9. A device as claimed in any one of the preceding claims, characterized in that the non-return valves (7, 9, 13, 14) can be electronically operated.
10. A device as claimed in any one of the preceding claims, characterized in that a thermal regenerator (R) is arranged in the connection line (3, 23) between the means (4, 24) for cooling the medium and the further means (5, 25) for heating the medium.

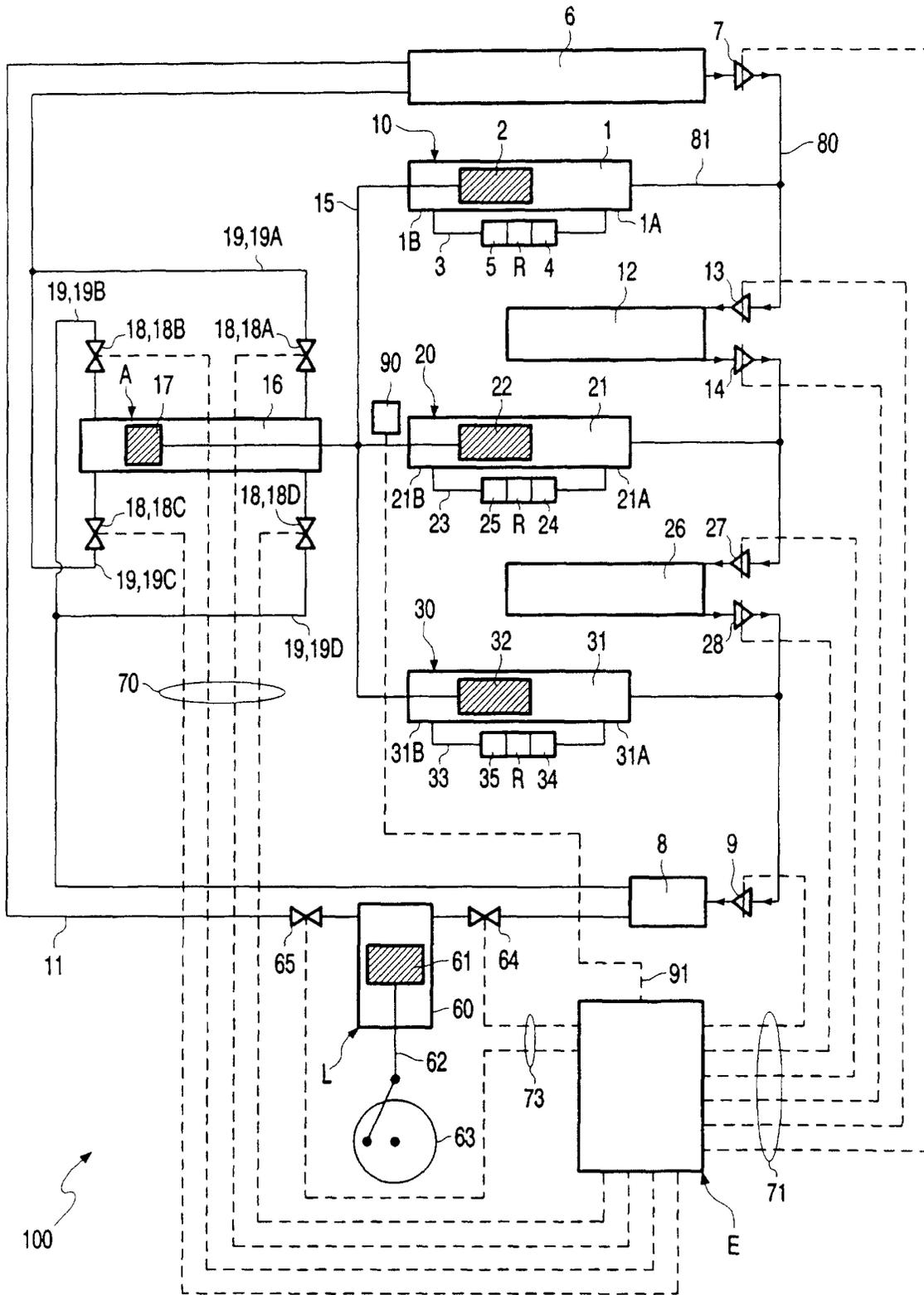


FIG. 1

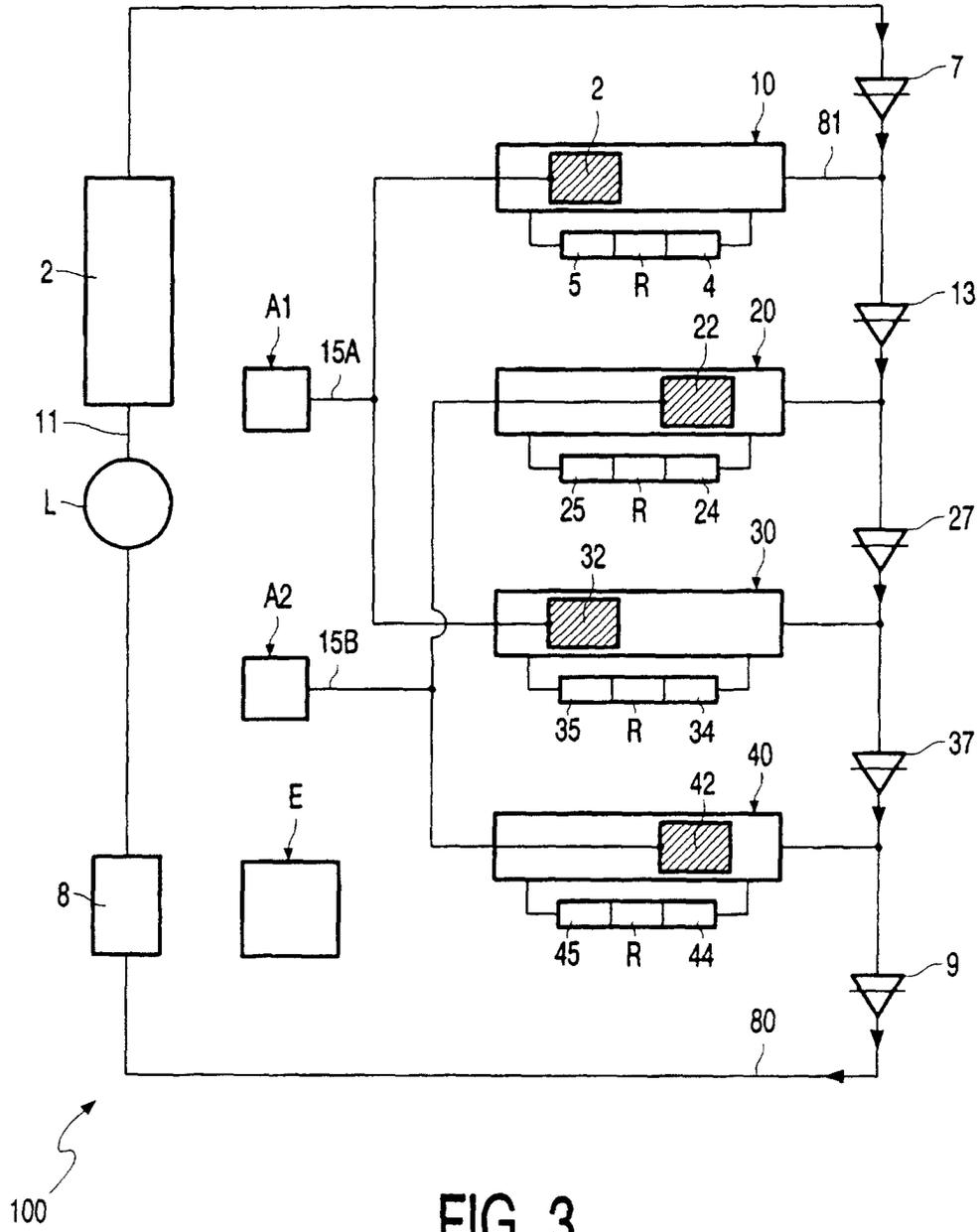


FIG. 3



European Patent Office

EUROPEAN SEARCH REPORT

Application Number
EP 01 20 0087

| DOCUMENTS CONSIDERED TO BE RELEVANT | | | |
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**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 01 20 0087

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
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