

(19)



Europäisches Patentamt

European Patent Office

Office européen des brevets



(11)

EP 0 826 935 A2

(12)

EUROPEAN PATENT APPLICATION

(43) Date of publication:
04.03.1998 Bulletin 1998/10

(51) Int. Cl.⁶: **F25B 30/02**, F04B 39/00,
F04C 18/063

(21) Application number: **97202616.5**

(22) Date of filing: **26.08.1997**

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

(30) Priority: **27.08.1996 NL 1003887**

(71) Applicant:
**N.V. Nederlandsche Apparatenfabriek NEDAP
NL-7141 DE Groenlo (NL)**

(72) Inventor:
**Hogen Esch, Johannes Harm Lukas
7122 ZN Aalten (NL)**

(74) Representative:
**Smulders, Theodorus A.H.J., Ir. et al
Vereenigde Octrooibureaux
Nieuwe Parklaan 97
2587 BN 's-Gravenhage (NL)**

(54) Heat pump

(57) A heat pump comprises a tubular member (6; 18) forming a substantially closed loop with a compression and an expansion section for a working medium. Each of said sections cooperates with a heat exchanger (12, 16). In the operational state at least two floating plugs (10; 19) of a magnetic material are provided in the tubular member (6; 18), said plugs (10; 19) enclosing a gas bubble and/or liquid sample of the working medium.

The heat pump further comprises electromagnetic means along at least a part of said tubular member (6; 18) for generating a moving magnetic field to control the movement of the plugs (10; 19) in said tubular member (6; 18). The plugs (10; 19) are formed by a magnetic fluid.

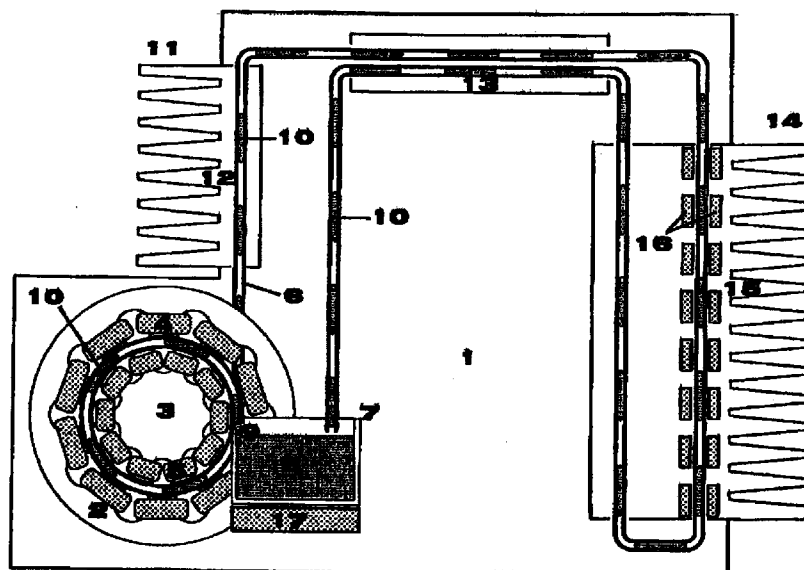


Figure 2

EP 0 826 935 A2

Description

The present invention relates to a heat pump comprising a tubular member forming a substantially closed loop with a compression and an expansion section for a working medium, each of said sections cooperating with a heat exchanger, in which tubular member in the operational state at least two floating plugs of a magnetic material are provided, said plugs enclosing a gas bubble and/or liquid of the working medium, the heat pump further comprising electromagnetic means along at least a part of said tubular member for generating a moving magnetic field to control the movement of the plugs in said tubular member.

Such a heat pump is known from DE-A-3607976 and may be used in e.g. household refrigerators. In said document the plugs are formed by plungers, which have the disadvantage that they are relatively heavy, induce vibrations, are noisy, wear out, are difficult to regulate and have efficiency losses because of friction and leakage of the working medium.

Other known heat pumps which may be used in e.g. household refrigerators are based upon the so called Rankine evaporation principle, where fluor-hydrogen compounds and nowadays more environmental-friendly compounds are used as heat transport media. The disadvantages of these systems is that the "coefficient of performance (COP)", i.e. the amount of removed heat divided by the required energy, for this removal is rather low, varying from 1,2 to 1,4 at the existing operating temperature-differences. A preferable COP for a temperature-difference of about 30° C. in the order of 3 can be obtained by applying Stirling coolers, which however are rarely used because of complexity and cost reasons. Also in the latter type of heat pumps moving mechanical parts are used with the above mentioned disadvantages.

The present invention aims to obviate or at least to mitigate the above mentioned disadvantages.

Therefore, according to the invention, the heat pump as described in the opening paragraph is characterized in that the plugs are formed by a magnetic fluid. By applying such plugs moving mechanical parts with the disadvantages thereof are avoided. The term "magnetic fluid" is generally known and relates to a fluid which is not magnetic of itself, but which is a magnetic flux conducting fluid.

From the Dutch patent specification No. 31163, the application of a liquid metal drivable by means of a movable electromagnetic field and providing for the compression of a working medium in a refrigerator is known per se. The document however does not describe a heat pump of the type as described in the opening paragraph.

The invention will now be described with reference to the accompanying drawing wherein:

Fig. 1 shows an example of a P-V diagram followed

by a working gas that is used as heat transport medium and where the regeneration phase is isobaric;

Fig. 2 schematically shows a first embodiment of a heat pump according to the invention using a driven compression and a throttle with e.g. air as a working medium;

Fig. 3 shows an example of a P-V diagram followed by a working gas that is used as heat transport medium and where the regeneration phase is isochoric;

Fig. 4A and 4B schematically show a second embodiment of a heat pump according to the invention using a driven expansion with e.g. helium as a working medium.

The principle of the heat pump according to the invention is based upon the compression, the propulsion and the expansion of a working medium, such as air or helium, separated in a tubular member, such as a tube or pipe, by means of magnetic fluid plugs, whereby these plugs are driven by an electromagnetically induced moving magnetic field. The diameter and the material of the tubular member is chosen in such a way that the surface-tension of the magnetic fluid is capable to separate the successive gas bubbles of the working medium, so that the magnetic fluid plugs provide for an appropriate sealing effect in the tubular member. Magnetic fluids have been disclosed in e.g. US-A-5,147,573, US-A-5,064,550 and US-A-4,938,886 and are commercially available.

In the present invention a magnetic liquid is used which preferably is constituted by an appropriate emulsion of iron oxide dust in an oil or ester. However, in order to further increase the flux density of the magnetic liquid and the performance of the heat pump, according to the invention magnetic flux conducting bodies in the form of e.g. metal balls may be supplied thereto. Particularly these metal balls will have a diameter of about 10 to 30%, preferably about 20%, of the inner diameter of the tubular member. With the magnetic liquid according to the invention, i.e. with the addition of magnetic flux conducting bodies, the sealing of a working medium sample in the tubular member will be improved, while the pressure difference over the fluid plugs can further be increased.

Because of the effect that the commercially available, so called super-paramagnetic fluids have relatively low magnetic saturation values, the force that can be generated by a magnetic field and thus the pressure difference that can be obtained over the fluid plugs in a tubular member, without the addition of the magnetic flux conducting bodies, is relatively low and amounts to a maximum of about 20 kPa. To obtain a larger pressure difference between compression and expansion, in the heat pump according to the invention a large number of magnetic fluid plugs are present in series inside the tubular member, separated by gas bubbles of the work-

ing medium and all these plugs are driven simultaneously by the electromagnetically induced moving magnetic field. In such a manner a pressure difference of 300 to 400 kPa between compression and expansion can easily be achieved. To increase the total pumping volume a number of tubular members can be placed in parallel, if desired.

In the embodiment of fig. 2 and as indicated in the P-V diagram of the so called Ericsson cycle of fig. 1, for each gas bubble between two fluid plugs the compression takes place on the isotherm trajectory A-B, whereby heat is transferred from the gas to the environment. Thereupon the gas is lowered isobarically in temperature on the trajectory B-C, whereby the volume decreases and the generated heat is transferred to the returning gas bubbles inside a regenerator as will be further explained below. At the trajectory C-D heat is absorbed through isothermic expansion of the gas bubbles of the working medium, e.g. by means of a magnetic throttle. Finally on the trajectory D-A the expanded returning gas bubbles are heated isobarically again to the original temperature in the regenerator whereas also the volume increases to the starting volume.

The embodiment schematically shown in fig. 2 includes a closed circuit 1 largely provided by a tube 6 wherein the working gas, e.g. air, is brought under an increased pressure of about 2-3 MPa. For the induction of a moving magnetic field statically mounted multiple pole shoes 2 and 3 are located along an number of windings of the tube 6. On outer pole shoes 2 and inner pole shoes 3 respectively coils 4 and 5 are wound and successively activated in e.g. four phases to generate a circular moving magnetic field with a field strength that is close to the saturation value of superparamagnetic fluid plugs 10 provided in the tube 6. A first section of tube 6 that is partly wound between the pole shoes starts inside a container 7 containing a small volume of a magnetic fluid 8, but just above the liquid level. When by means of one or more coils 5 at the beginning of the tube 6 a magnetic field is generated, then a certain amount of magnetic liquid 8 will be sucked inside the tube 6 as indicated at position 9, because the magnetic liquid tends to fill areas with the highest magnetic flux density.

When in e.g. four phases the coils 4 and 5 are successively activated, the tube 6 will be successively filled with fluid plugs 10 and gas bubbles of the working medium which is present in the container 7 above the fluid level. For each winding of the tube 6 the fluid plugs 10 are in phase, whereby all fluid plugs 10 inside the different windings of the tube 6 and between the pole shoes 2 and 3 are propelled, whereby a small increase of pressure inside the gas bubble in front of each fluid plug 10 is induced. Because a small compression of the gas bubbles takes place, also a small correction of the relative distance between the pole shoes 2 and 3 in relation to the tube 6 is necessary. This can be achieved by decreasing the winding-pitch of the tube 6 between

the poleshoes 2 and 3 or by changing the shape of the tube 6 to reduce the surface of the bore of the tube 6 in relation to the increase of pressure inside the tube 6. Further, it may be noticed that is also possible to give the pole shoes 2 and 3 a conical form, whereby the diameter of the tube gradually increases.

During the compression cycle of the gas bubbles in the compression section of the tube 6 heat is transferred to the "hot" side 11 of the heat pump through the pole shoes 2 and 3 and a heat exchanger 12. Via a, preferably isolated, regenerator 13 the compressed gas bubbles together with fluid plugs 10 are transferred to the "cold" side 14 of the heat pump.

In the regenerator 13 heat from the gas bubbles and the fluid plugs 10 is transferred to a return section of the tube 6 and to the returning gas bubbles and fluid plugs and is used to bring the temperature thereof back to the level of the "hot" side 11. At the "cold" side 14 a throttle comprising in this embodiment a number of permanent magnets 16 is installed, by which a force is exerted on the magnetic fluid plugs 10 to build up the required compression pressure. It may be noticed that with such a throttle helium cannot be used as working medium; therefore in this embodiment preferably air is used as working medium. After the fluid plugs 10 have passed the throttle, the working gas bubbles expand in the expansion section of the tube 6 in accordance with the pressure inside the closed system 1, whereby heat is absorbed from the "cold" side through a heat exchanger 15. After the returning gas bubbles and the magnetic fluid plugs 10 are warmed up inside the regenerator 13 the magnetic fluid plugs 10 are dispensed into the container 7 where the fluid is used to form new fluid plugs for further compression/expansion cycles.

An extra permanent magnet 17 can be located under the container 7 to allow the heat pump to operate in any orientation.

Fig. 3 shows an example of a P-V diagram where isotherm compression of the gas bubbles between fluid plugs 10 takes place on the trajectory E-F, whereby heat is transferred from the gas to the environment. Thereupon the gas is lowered isochorically in temperature on a regeneration trajectory F-G, whereby the pressure decreases and whereby generated heat is transferred to the returning gas bubbles inside a regenerator. At the trajectory G-H heat is absorbed through the driven isotherm expansion of the gas bubbles of the working gas. A suitable working gas would be e.g. helium. Finally on the trajectory H-E the expanded returning gas bubbles are heated isochorically again to the original temperature in the regenerator where also the pressure increases to the original starting pressure.

Fig. 4A and 4B schematically show another embodiment of the heat pump in accordance with the invention wherein the working gas follows the P-V diagram of fig. 3. This embodiment is provided with a closed circuit tube 18, wherein a working gas, e.g. helium, separated

by magnetic fluid plugs 19, is brought under an increased pressure of about 2-3 MPa. The induction of the moving magnetic fields takes place in a similar way as shown in fig. 2 with statically mounted multiple pole shoes 20 and 21. The tube 18 in this embodiment is wound in two layers back and forth between the pole shoes 20 and 21. On the outer pole shoes 20 and the inner pole shoes 21 respectively the coils 22 and 23 are wound and successively activated in e.g. four phases to generate a circular moving magnetic field with a field strength that is close to the saturation value of the super-paramagnetic fluid plugs 19. The central part of the wound tube functions as a regeneration section 24. The total system can be encapsulated inside a close housing similar to the system of fig. 2, filled with the working gas under an averaged pressure P_m of 2-3 MPa. At two positions in the loop of tube 18 the pressure will be equal to the average pressure P_m , where, if necessary, the forming of the fluid plugs 19 can be restored from a liquid container in a similar way as described for the system in fig. 2 or just by allowing the working gas to fill up the space between the fluid plugs 19.

For each winding of the tube 18 in both directions the fluid plugs 19 are in phase, whereby all fluid plugs inside the different windings of the tube 18 and between the pole shoes 20 and 21 are driven in the expansion section 25. Thereby in the "hot" compression section 26 a small increase of pressure inside the gas bubble in front of each fluid plug 19 is induced. Because a small compression of the gas bubbles takes place, also a small correction of the relative distance between the pole shoes in relation to the fluid plugs 19 is necessary, since the distance between the fluid plugs 19 remains constant. In the example system of fig. 4 this is achieved e.g. by increasingly giving the tube 18 a more oval shape between the pole shoes 20 and 21 in relation to the increase of pressure inside the tube 18 in the compression section 26. In this way the surface-area of the cross-section of the tube 18 is gradually reduced in the compression section, causing a pressure increase in the working gas between the fluid plugs 19. It may be noticed that in this embodiment the sum of the diameters of the tubes located above each other is a constant.

During the isotherm compression cycle of the gas bubbles heat is transferred to the "hot" side 26 of the heat pump. Through the regenerator section 24 the compressed working gas bubbles together with the fluid plugs 19 are also propelled and transferred isochorically to the "cold" side 25 of the heat pump. The heat content of the magnetic fluid plugs 19, mainly consisting out of mineral oil or ester, also has to be transferred inside the regenerator section 24.

In the regenerator section 24 heat of the working gas and the fluid plugs 19 is transferred to the returning gas bubbles and fluid plugs 19 and is used to bring the temperature thereof to the level of the "hot" side 26. Because of the isochoric cooling in the regenerator section 24 the pressure drops as indicated by trajectory F-

G of fig. 3. At the "cold" side 25 driven isotherm expansion takes place e.g. by changing the oval shape of the tube 18 gradually back to the original more round shape, by which a force is induced on the magnetic fluid plugs 19 to achieve the required expansion pressure. Due to the expansion, heat is absorbed from the "cold" side 25 of the heat exchanger. On the way to the compression side the returning gas bubbles and the magnetic fluid plugs 19 are heated isochorically inside the regenerator section 24, resulting in a pressure increase as indicated by trajectory H-E of fig. 3.

Of course modifications of the described system are possible within the fundamentals of its working principle. E.g. linear (in one or more rows) positioned pole shoes and a more or less straight tubular member instead of circular or helical positioned pole shoes or conical pole shoes and a wound tubular member are possible. The moving magnetic field can also be generated by means of permanent magnets in the form of a rotor or by fixed permanent magnets, in which case the tubular members have to be rotated. Also a different throttle mechanism like a tube section of reduced diameter can be used. Further there is a possibility to use a combination of driven compression and expansion or regeneration. Also a discontinuous up and down pumping instead of a continuous closed loop pump system could be used and a combination of an isochoric and an isobaric regeneration. Instead of an ideal gas as a working medium, gas mixtures or a non-condensing vapour, or even a condensing vapour or liquid, could be used to increase the heat capacity of the working medium.

Further it may be noticed that by the expansion of the working medium the fluid plugs are subjected to an additional acceleration by means of which a varying magnetic field is generated. This magnetic field may be used to generate an electric current in coils, which current may further be applied in the heat pump. The recovery of electrical energy leads to a system in which mainly an amount of energy has to be supplied equal to the frictional energy of the system, so that an ideal heat pump can be obtained.

Claims

1. Heat pump comprising a tubular member forming a substantially closed loop with a compression and an expansion section for a working medium, each of said sections cooperating with a heat exchanger, in which tubular member in the operational state at least two floating plugs of a magnetic material are provided, said plugs enclosing a gas bubble and/or liquid of the working medium, the heat pump further comprising electromagnetic means along at least a part of said tubular member for generating a moving magnetic field to control the movement of the plugs in said tubular member, characterized in that the plugs (10; 19) are formed by a magnetic fluid.

2. Heat pump as claimed in claim 1, characterized in that the magnetic fluid is provided with magnetic flux conducting bodies in the form of e.g. metal balls with a diameter of about 10 to 30%, preferably about 20%, of the inner diameter of the tubular member (6; 18) 5
3. Heat pump as claimed in claim 1 or 2, characterized in that the moving magnetic field is generated by means of successively positioned pole shoes (2, 3; 20, 21) which are electromagnetically energized successively in different phases. 10
4. Heat pump as claimed in claim 3, characterized in that the pole shoes (2, 3; 20, 21) are positioned in a circular form. 15
5. Heat pump as claimed in claim 4, characterized in that the tubular member (6; 18) containing the fluid plugs (10; 19) separated by gas bubbles and/or liquid of the working medium has been wound with one or more windings between the circular positioned pole shoes (2, 3; 20, 21), whereby in each winding the fluid plugs (10; 19) are driven in phase by means of the relevant electromagnetically driven pole shoes (2, 3; 20, 21). 20 25
6. Heat pump as claimed in claim 4, characterized in that the pitch of the tubular member (6; 18) wound between the pole shoes (2, 3; 20, 21) decreases in relation to the increase of pressure inside the gas bubbles and/or liquid of the working medium between two fluid plugs (10; 19), whereby the relative position of the fluid plugs (10; 19) in relation to the pole shoes (2, 3; 20, 21) in front of the respective fluid plugs (10; 19) remains constant. 30 35
7. Heat pump as claimed in claim 4, characterized in that the shape of the tubular member (6; 18) is changed to reduce the surface of the bore of the tubular member (6; 18) in relation to the increase of pressure inside the tubular member (6; 18). 40
8. Heat pump as claimed in claim 3, characterized in that the pole shoes (2, 3; 20, 21) are positioned linear, possibly in more than one row. 45
9. Heat pump as claimed in any one of the preceding claims, characterized in that by the expansion of the working medium the fluid plugs (10; 19) are subjected to an additional acceleration by means of which a varying magnetic field is generated, the expansion section being provided with coils wherein an electric current is generated by said varying magnetic field, which current may further be applied in the heat pump. 50 55
10. Heat pump as claimed in any one of the preceding claims, characterized in that the fluid plugs (10; 19) are driven in the compression section.
11. Heat pump as claimed in any one of the claims 1-8, characterized in that the fluid plugs are driven in the expansion section.
12. Heat pump as claimed in any one of the claims 1-8, characterized in that the fluid plugs (10; 19) are driven in both the compression section and the expansion section.
13. Heat pump as claimed in any one of the preceding claims, characterized in that the pressure difference between compression and expansion is realized by means of a throttle in the expansion section.
14. Heat pump as claimed in claim 13, characterized in that the throttle consists of a restriction in the tubular member (6; 18).
15. Heat pump as claimed in any one of the claims 1-12, characterized in that the pressure difference between compression and expansion is realized by means of permanent magnets (16), located in a row along the tubular member (6; 18) and inducing a force on the fluid plugs (10) in front of the permanent magnets (16) and thus for each fluid plug (10) creating a pressure difference in the working medium in front of these fluid plugs (10).
16. Heat pump as claimed in claim 12, characterized in that a linear or circular pumping system is used in which the working medium is transported isochorically instead of isobarically in the regenerator section (24) from the "hot" side (26) to the "cold" side (24) and vice versa.
17. Heat pump as claimed in any one of the preceding claims, characterized in that a regenerator (13; 24) is provided to transfer the heat of the working medium and the fluid plugs (10; 19) transported from the "hot" side to the "cold" side of the heat pump to the working medium and the fluid plugs (10; 19) transported from the "cold" side to the "hot" side of the heat pump to minimise the heat leakage of the heat pump.
18. Heat pump as claimed in any one of the preceding claims, characterized in that a number of tubular members (6; 18) is provided, located and working parallel to each other.
19. Heat pump as claimed in any one of the preceding claims, characterized in that the heat pump is provided with a container (7) for a magnetic fluid.
20. Heat pump as claimed in claim 19, characterized in

that the heat pump is provided with one or more permanent magnets (17) located at the container (7), the said one or more permanent magnets (17) preventing the fluid to drop out of the container (7) such that the heat pump can operate in any orientation. 5

21. Heat pump as claimed in any one of the preceding claims, characterized in that a two-phase working medium is used and an additional cooling capacity is obtained from the evaporation phase change of the working medium. 10

15

20

25

30

35

40

45

50

55

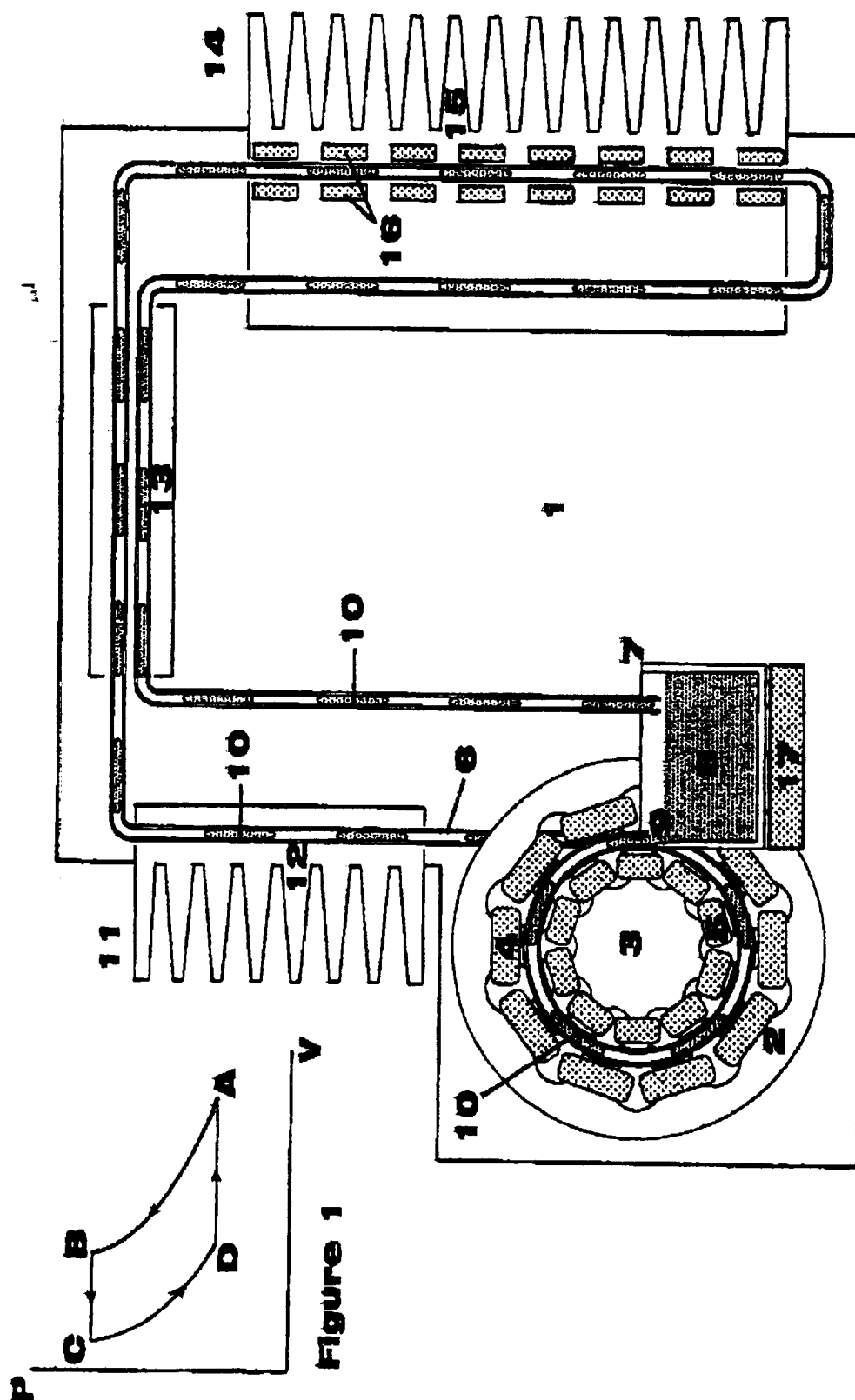


Figure 2

