

ROTICULATING THERMODYNAMIC APPARATUS

The present disclosure relates to a roticulating thermodynamic apparatus.

- 5 In particular the disclosure is concerned with a thermodynamic apparatus operable as a heat pump and/or heat engine.

Background

- 10 Conventional heat pumps and heat engines that compress and expand a working fluid often comprise a pump to pressurise the working fluid and a turbine to expand the fluid. This is because the most efficient conventional thermodynamic expanders tend to be of a rotational type (e.g. turbines) and are typically limited to a single stage expansion ratio of 3:1.

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In order to optimise performance of the system, the running speed of the turbine is generally higher than the running speed of the pump. Hence the pump and turbine tend to be of different types and rotate independently of one another to allow them to run at different speeds.

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Additionally, conventional pump and turbine arrangements require consistent running speeds in order to maximise their efficiency. The very nature of most systems means they tend to be optimised for a relatively narrow operating range, and running outside of this range may result in high inefficiencies or unacceptable wear on components.

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This means that for a conventional heat pump or conventional heat engine a large differential in temperature is required to achieve sufficiently high running speeds, which means such devices cannot operate in environments where only lower temperature differentials are available. This limits the effectiveness of such
30 conventional devices.

Hence a heat pump or motor which may operate over a wide range of running speeds and/or temperature differentials with fewer limitations, fewer losses and of higher efficiency is highly desirable.

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Summary

According to the present disclosure there is provided an apparatus and method as set forth in the appended claims. Other features of the invention will be apparent from the dependent claims, and the description which follows.

Accordingly there may be provided a roticulating thermodynamic apparatus (100) having a first fluid flow section (111) comprising : a first shaft portion (118) which defines, and is rotatable about, a first rotational axis (130); a first axle (120) defining a second rotational axis (132), the first shaft portion (118) extending through the first axle (120); a first piston member (122a) provided on the first shaft portion (118), the first piston member (122a) extending from the first axle (120) towards a distal end of the first shaft portion (118); a first rotor (119) carried on the first axle (120); the first rotor (119) comprising : a first chamber (134a), the first piston member (122a) extending across the first chamber (134a); a first casing wall adjacent the first chamber (134a), a first port (114a) and second port (114b) provided in the housing wall and each in flow communication with the first chamber (134a); whereby : the first rotor (119) and first axle (120) are rotatable with the first shaft portion (118) around the first rotational axis (130); and the first rotor (119) is pivotable about the axle (120) about the second rotational axis (132) to permit the first rotor (119) to pivot relative to the first piston member (122a) as the first rotor (119) rotates about the first rotational axis (130); such that the first fluid flow section (111) is configured for the passage of fluid between the first port (114a) and second port (114b) via the first chamber (134a); the apparatus further comprising a second fluid flow section (115), which comprises : a second chamber (134b, 234b), a second housing wall adjacent the second chamber (134b, 234b), a third port (116a) and a fourth port (116b) provided in the second housing wall and each in flow communication with the second chamber (134b, 234b), such that the second fluid flow section (115) is configured for the passage of fluid between the third port (116a) and fourth port (116b) via the second chamber (134, 234b); the second port (114b) being in fluid communication with the third port (116a) via a first heat exchanger (302a).

The second rotational axis (132) may be substantially perpendicular to the first rotational axis (130).

The first rotor (119) may comprise the second chamber (134b). The first piston member (122a) may extend from one side of the first axle (120) along the first shaft portion (118). A second piston member (122b) may extend from the other side of the first axle (120) along the first shaft portion (118), across the second chamber (134b) to permit the first rotor (119) to pivot relative to the second piston member (122b) as the first rotor (119) rotates about the first rotational axis (130).

The fourth port (116b) may be in fluid communication with the first port (114a) via a second heat exchanger (306a).

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The volumetric capacity of the first rotor first chamber (134a) may be substantially the same, less, or greater than the volumetric capacity of first rotor second chamber (134b).

15 The first shaft portion (118), first axle (120) and first piston member(s) (122a, 122b) may be fixed relative to one another.

The apparatus (200) may further comprise : a second rotor (219) comprising the second chamber (234b), a second shaft portion (218) rotatable about the first rotational axis (130); and the second shaft portion (218) is coupled to the first shaft portion (118) such that the first shaft portion (118) and second shaft portion (218) are rotatable together around the first rotational axis (130). There may also be provided a second axle (220) defining a third rotational axis (232), the second shaft portion (218) extending through the second axle (220); a second piston member (222b) provided on the second shaft portion (218), the second piston member (222b) extending from the second axle (220) towards a distal end of the second shaft portion (218); the second rotor (219) carried on the second axle (220); the second piston member (222b) extending across the second chamber (234b); whereby : the second rotor (219) and second axle (220) are rotatable with the second shaft portion (218) around the first rotational axis (130); and the second rotor (219) is pivotable about the second axle (220) about the third rotational axis (232) to permit the second rotor (219) to pivot relative to the second piston member (222) as the second rotor (219) rotates about the second rotational axis (130).

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The third rotational axis (232) may be substantially perpendicular to the first rotational axis (130).

The first rotor (119) may comprise : a first rotor second chamber (134b), the first piston member (122a) extending from one side of the first axle (120) along the first shaft portion (118); and a second piston member (122b) extends from the other side of the first axle (120) along the first shaft portion (118), across the first rotor second chamber (134b) to permit the first rotor (119) to pivot relative to the second piston member (122b) as the first rotor (119) rotates about the first rotational axis (130). The second rotor (219) may comprise : a second rotor first chamber (234a), the second piston member (222b) extends from one side of the second axle (220) along the second shaft portion (218); and a second rotor first piston member (222a) extends from the other side of the second axle (220) along the second shaft portion (218), across the second rotor first chamber (234a) to permit the second rotor (219) to pivot relative to the second rotor first piston member (222a) as the second rotor (219) rotates about the first rotational axis (130). The first rotor second chamber (134b) may be in flow communication with : a fifth port (114c) and a sixth port (114d); to thereby form part of the first fluid flow section (111), and configured for the passage of fluid between the fifth port (114c) and sixth port (114d) via the first rotor second chamber (134b); the second rotor first chamber (234a) is in flow communication with a seventh port (116c) and an eighth port (116d); to thereby form part of the second fluid flow section (115), and configured for the passage of fluid between the seventh port (116c) and eighth port (116d) via the second rotor second chamber (234b); wherein the sixth port (114d) is in fluid communication with the seventh port (116c) via the first heat exchanger (302a).

The eighth port (116d) may be in fluid communication with the fifth port (114c) via a second heat exchanger (306a).

The fourth port (116b) may be in fluid communication with the first port (114a) via the second heat exchanger (306a).

The first chamber (134a) and second chamber (134b) of the first rotor (119) may have substantially the same volumetric capacity; the first chamber (234a) and second chamber (234b) of the second rotor (219) have substantially the same volumetric capacity; the volumetric capacity of the first rotor chambers (134a, 134b) are

substantially the same, less, or greater than the volumetric capacity of the second rotor chambers (234a, 234b).

5 The first shaft portion (118) may be directly coupled to the second shaft portion (218) such that the first rotor (119) and second rotor (219) are operable to only rotate at the same speed as each other.

10 The second shaft portion (218), second axle (220) and second piston member(s) (222a, 222b) may be fixed relative to one another.

The first heat exchanger (302a) may be operable as a heat sink to remove heat energy from fluid passing through it.

15 The second heat exchanger (306a) may be operable as a heat source to add heat energy to fluid passing through it.

20 The first heat exchanger (302a) may comprise a chamber (810) operable to permit fluid flow between the first fluid flow section (112) and the second fluid flow section (115); and an injector (812) configured to inject a cryogenic medium into the chamber (810) such that heat energy is transferred from the fluid to the cryogenic media.

25 The first heat exchanger (302a) may be operable as a heat source to add heat energy to fluid passing through it.

The second heat exchanger (306a) may be operable as a heat sink to remove heat energy from fluid passing through it.

30 The first heat exchanger (302a) may comprise : a combustion chamber operable for continuous combustion.

35 The or each chamber (134a, 134b, 234a, 234b) may have an opening (36); and the or each respective piston member (122a, 122b, 222a, 222b) extends from its respective axle (20) across its corresponding chamber towards the corresponding opening (36).

The apparatus may further comprise : a pivot actuator operable to pivot the rotor (119, 219) about the axle (120, 220); wherein the pivot actuator comprises : a first guide feature (52) provided on the rotor (119, 219); and a second guide feature (50) provided on the housing (112); the first guide feature (52) operable to co-operate with
5 the second guide feature (50) to pivot the rotor (119, 219) about the axle (120, 220).

At least one of the first guide feature (52) and second guide feature (50) may comprise an electro-magnet operable to magnetically couple to the other of the first guide feature (52) and second guide feature (50).

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The apparatus may further comprise : a pivot actuator operable to pivot the rotor (119, 219) about the axle (120, 220); wherein the pivot actuator comprises : a first guide feature (52) on the rotor (119, 219); and a second guide feature (50) on the housing (112); the first guide feature (52) being complementary in shape to the
15 second guide feature (50); and one of the first or second guide features defining a path (50) which the other of the first or second guide feature (52), is constrained to follow; the other of the first or second guide feature (52) comprising a rotatable member (820) which is operable to engage the path (50) and rotate as it moves along the path (50).

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The heat source may further comprises a substance passing through a duct (303) in the first heat exchanger 302a, wherein the apparatus (1000) provides cooling to the substance.

25 The fluid passing through the apparatus may comprise air.

In some examples, the apparatus comprises a motor (308) coupled to the first shaft portion 118 configured to drive the rotor (119) around the first rotational axis (130).

30 The motor (308) may be reversible, such that when the motor is configured to drive the rotor (119) around the first rotational axis (130) in a first direction, the first heat exchanger (302a) is operable to act as a heat source to transfer heat from the substance to the fluid, and wherein when the motor is configured to drive the rotor (119) around the first rotational axis (130) in a second direction, opposite to the first
35 direction, the first heat exchanger (302a) is operable to act as a heat sink to transfer heat from the fluid to the substance.

The second guide feature (550) may comprises a slewing ring (527) configured to hold at least part of a bearing (529) that is coupled with the housing.

- 5 The first guide feature (552) may comprise a stylus configured to be received in the slewing ring (527).

In one embodiment, there is provided a roticulating thermodynamic apparatus (100) having a **first fluid flow section (111)** comprising : a first shaft portion (118) which
10 defines, and is rotatable about, a first rotational axis (130); a first axle (120) defining a second rotational axis (132), the first shaft portion (118) extending through the first axle (120); a first piston member (122a) provided on the first shaft portion (118), the first piston member (122a) extending from the first axle (120) towards a distal end of the first shaft portion (118); a first rotor (119) carried on the first axle (120); the first
15 rotor (119) comprising : a first chamber (134a), the first piston member (122a) extending across the first chamber (134a); a first casing wall adjacent the first chamber (134a), a first port (114a) and second port (114b) provided in the housing wall and each in flow communication with the first chamber (134a); whereby : the first rotor (119) and first axle (120) are rotatable with the first shaft portion (118) around
20 the first rotational axis (130); and the first rotor (119) is pivotable about the axle (120) about the second rotational axis (132) to permit the first rotor (119) to pivot relative to the first piston member (122a) as the first rotor (119) rotates about the first rotational axis (130); such that the **first fluid flow section (111)** is configured for the passage of fluid between the first port (114a) and second port (114b) via the first chamber (134a);
25 the apparatus further comprising a **second fluid flow section (115)**, which comprises : a second chamber (134b, 234b), a second piston member (122b) extending from the other side of the first axle (120) along the first shaft portion (118); the second piston member (122b) extending across the second chamber (134b); to permit the first rotor (119) to pivot relative to the second piston member (122b) as the first rotor (119) rotates about the first rotational axis (130), a second housing wall adjacent the second
30 chamber (134b, 234b), a third port (116a) and a fourth port (116b) provided in the second housing wall and each in flow communication with the second chamber (134b, 234b), such that the **second fluid flow section (115)** is configured for the passage of fluid between the third port (116a) and fourth port (116b) via the second chamber
35 (134, 234b); wherein the first fluid flow section (111) and the second fluid flow section (115) are two sides of the first rotor (119) and wherein one of the first fluid flow section

(111) and the second fluid flow section (115) is operable as a compressor and the other one of the first fluid flow section (111) and the second fluid flow section (115) is operable as an expander, the second port (114b) being in fluid communication with the third port (116a) via a first heat exchanger (302a).

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Hence there may be provided an apparatus operable to displace and expand fluid which may be configured as heat pump to remove heat from a system (e.g. a refrigerator) or configured as a heat engine to extract work from a working fluid in order to provide a rotational output.

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The displacement section (e.g. pump) and expansion section (e.g. turbine) of the present device can sustain their optimal efficiency at near identical speeds and be subject to a single set of mechanical constraints by virtue of being housed within a common device. Hence arrangements of the present disclosure may be substantially thermodynamically ideal.

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The apparatus may comprise a core element having linked displacement and expansion chambers which are defined by walls of a single common rotor. The rotor is pivotable relative to a rotatable piston. Hence this arrangement provides a positive displacement system which is operable and effective at lower rotational speed than examples of the related art. The system is also operable up to and including speeds equivalent to examples of the related art.

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The core elements may be described as a 'roticulator' since the rotor of the present disclosure is operable to simultaneously 'rotate' and 'articulate', for example as described in PCT Application PCT/GB2016/052429 (Published as WO2017/089740) . Hence there is provided heat engine or heat pump which comprises a 'roticulating apparatus'.

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Roticulation and the roticulating concept hence describe a device in which a single body (e.g. a rotor) rotates whilst simultaneously articulating, describing a 3D spatial movement which can be used to perform volumetric 'work' in conjunction and translation with rotation.

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Hence the apparatus offers absolute management and control of multiple volumetric chambers within a single order of mechanical constraints/losses. Given this high ratio of volumetric chambers over mechanical losses the efficiency of the device is of a high order when compared to conventional devices.

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Thus this disclosure describes a device capable of both positive displacement and absolute evacuation of its working volumes, such is characteristic of an 'ideal' expander/compressor/pump, offering a high expansion/compression ratio many orders beyond conventional devices.

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The apparatus offers the highly desirable characteristic of a single device operable to simultaneously perform the action of expansion of a working fluid as well as compression and/or displacement of the same working fluid.

15 Thus a heat engine according to the present disclosure may operate with a lower heat differential, utilising lower quality heat than examples of the related art.

Since the first fluid flow section and second fluid flow sections (e.g. the expansion and displacement sections) are linked, a heat pump according to the present disclosure is
20 inherently more efficient than an example of the related art as expansion of the fluid is utilised to drive the displacement/pump/compressing section, thereby requiring less external input from a motor.

Hence apparatus according to the present disclosure may efficiently operate over a
25 wide range of conditions, thereby allowing the device to produce outputs with input conditions which would not provide sufficient energy for examples of the related art to operate.

Brief Description of the Drawings

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Examples of the present disclosure will now be described with reference to the accompanying drawings, in which:

Figure 1 shows a part exploded view of an example of an apparatus, including
35 a rotor assembly and housing, according to the present disclosure;

Figure 2 shows a perspective external view of an apparatus according to the present disclosure with a different housing and porting to that shown in Figure 1;

5 Figure 3 shows a perspective semi "*transparent*" assembled view of the apparatus of Figure 1;

Figure 4 shows the rotor assembly of Figure 1 in more detail;

10 Figure 5 shows the rotor of the rotor assembly of Figure 4;

Figure 6 shows an end on view of the rotor assembly of Figure 4;

Figure 7 shows an end on view of the rotor of Figure 5;

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Figure 8 shows a perspective view of an axle of the rotor assembly;

Figure 9 shows an perspective view of a shaft of the rotor assembly;

20 Figure 10 shows an assembly of the axle of Figure 8 and the shaft of Figure 9;

Figure 11 shows a plan view of the housing shown in Figure 1, with hidden detail shown in dotted lines;

25 Figure 12 shows an internal view of the housing shown in Figure 11;

Figure 13 shows an internal view of the rotor housing of Figure 2;

Figure 14 shows an alternative example of a rotor;

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Figure 15 shows a first example of a closed loop heat pump according to the present disclosure suitable for a refrigeration apparatus;

Figure 16 shows a second example of a closed loop heat pump according to
35 the present disclosure suitable for a refrigeration apparatus;

Figures 17, 18 show alternative means of providing differential rotor volumes which may form part of the heat pumps of Figures 15, 16 respectively, or part of the heat engines of further examples of the present disclosure;

5 Figure 19 shows a first example of a closed loop heat engine according to the present disclosure suitable for, but not limited to, an energy harvesting apparatus;

10 Figure 20 shows a second example of a closed loop heat engine according to the present disclosure suitable for, but not limited to, an energy harvesting apparatus;

15 Figure 21 shows a first example of an open loop heat engine according to the present disclosure suitable for, but not limited to, a power generation apparatus;

20 Figure 22 shows a second example of an open loop heat engine according to the present disclosure suitable for, but not limited to, a power generation apparatus;

 Figure 23 shows a third example of an open loop heat engine according to the present disclosure suitable for, but not limited to, a power generation apparatus;

25 Figure 24 shows a fourth example of an open loop heat engine according to the present disclosure suitable for, but not limited to, a power generation apparatus;

30 Figure 25 shows an example of an open loop heat pump according to the present disclosure suitable for a refrigeration apparatus;

 Figure 26 shows an exploded example of an alternative rotor assembly; and

35 Figure 27A and 27B shows a side view and cross-sectional view of the rotor assembly of Figure 26.

Detailed Description

An apparatus and method of operation of the present disclosure is described below.

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In particular the present disclosure is concerned with an apparatus comprising a roticulating thermodynamic apparatus operable as a heat pump and/or heat engine.

That is to say, the apparatus is suitable for use as part of a fluid working apparatus operable as a heat pump and/or a heat engine. Core elements of the apparatus are described as well as non-limiting examples of applications in which the apparatus may be employed.

The term "*fluid*" is intended to have its normal meaning, for example : a liquid, gas, vapour, or a combination of liquid, gas and/or vapour, or material behaving as a fluid.

Figure 1 shows a part exploded view of a core 10 part of an apparatus according to the present disclosure. Features of the core 10 are shown in Figures 1 to 14, 17, 18, and Figures 15, 16, & 19 to 24 illustrate how the core 10 is combined with other features in order to produce a heat pump and/or heat engine of the present disclosure. The core comprises a housing 12 and rotor assembly 14. Figure 2 shows an alternative example of a housing 12 when it is closed around the rotor assembly 14.

In the example shown in Figure 1 the housing 12 is divided into two parts 12a, 12b which close around the rotor assembly 14. However, in an alternative example the housing may be fabricated from more than two parts, and/or split differently to that shown in Figure 1.

The rotor assembly 14 comprises a rotor 16, a shaft 18, an axle 20 and a piston member 22. The housing 12 has a wall 24 which defines a cavity 26, the rotor 16 being rotatable and pivotable within the cavity 26.

The shaft 18 defines, and is rotatable about, a first rotational axis 30. The axle 20 extends around the shaft 18. The axle extends at an angle to the shaft 18. Additionally the axle defines a second rotational axis 32. Put another way, the axle 20 defines the

second rotational axis 32, and the shaft 18 extends through the axle 20 at an angle to the axle 20. The piston member 22 is provided on the shaft 18.

5 In the examples shown the apparatus is provided with two piston members 22, i.e. a first and second piston member 22. The rotor 16 also defines two chambers 34a,b, one diametrically opposite the other on either side of the rotor 16.

10 In examples in which the apparatus is part of a fluid compression device, each chamber 34 may be provided as a compression chamber. Likewise, in examples in which the apparatus is a fluid displacement device, each chamber 34 may be provided as a displacement chamber. In examples in which the apparatus is a fluid expansion device, each chamber 34 may be provided as an expansion or metering chamber.

15 Although the piston member 22 may in fact be one piece that extends all of the way through the rotor assembly 14, this arrangement effectively means each chamber 34 is provided with a piston member 22. That is to say, although the piston member 22 may comprise only one part, it may form two piston members sections 22, one on either side of the rotor assembly 14.

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Put another way, a first piston member 22 extends from one side of the axle 20 along the shaft 18 towards one side of the housing 12, and a second piston member 22 extends from the other side of the axle 20 along the shaft 18 towards the other side of the housing 12. The rotor 16 comprises a first chamber 34a having a first opening 36
25 on one side of the rotor assembly 14, and a second chamber 34b having a second opening 36 on the other side of the rotor assembly 14. The rotor 16 is carried on the axle 20, the rotor 16 being pivotable relative to the axle 20 about the second rotational axis 32. The piston member 22 extends from the axle 20 across the chambers 34a,b towards the openings 36. A small clearance is maintained between the edges of the
30 piston member 22 and the wall of the rotor 16 which defines the chamber 34. The clearance may be small enough to provide a seal between the edges of the piston member 22 and the wall of the rotor 16 which defines the chamber 34. Alternatively, or additionally, sealing members may be provided between the piston members 22 and the wall of the rotor 16 which defines the chamber 34.

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The chambers 34 are defined by side walls (i.e. end walls of the chambers 34) which travel to and from the piston members 22, the side walls being joined by boundary walls which travel past the sides of the piston member 22. That is to say, the chambers 34 are defined by side/end walls and boundary walls provided in the rotor
5 16.

Hence the rotor 16 is rotatable with the shaft 18 around the first rotational axis 30, and pivotable about the axle 20 about the second rotational axis 32. This configuration results in the first piston member 22 being operable to travel (i.e. traverse) from one
10 side of the first chamber 34a to an opposing side of the first chamber 34a as the rotor 16 rotates about the first rotational axis 30. Put another way, since the rotor 16 is rotatable with the shaft 18 around the first rotational axis 30, and the rotor 16 is pivotable about the axle 20 about the second rotational axis 32, during operation there is a relative pivoting (i.e. rocking) motion between the rotor 16 and the first piston
15 member 22 as the rotor 16 rotates about the first rotational axis 30. That is to say, the apparatus is configured to permit a controlled pivoting motion of the rotor 16 relative to the first piston member 22 as the rotor 16 rotates about the first rotational axis 30.

The configuration also results in the second piston member 22 being operable to
20 travel (i.e. traverse) from one side of the second chamber 34b to an opposing side of the second chamber 34b as the rotor 16 rotates about the first rotational axis 30. Put another way, since the rotor 16 is rotatable with the shaft 18 around the first rotational axis 30, and the rotor 16 is pivotable about the axle 20 about the second rotational axis 32, during operation there is a relative pivoting (i.e. rocking) motion between the
25 rotor 16 and both piston members 22 as the rotor 16 rotates about the first rotational axis 30. That is to say, the apparatus is configured to permit a controlled pivoting motion of the rotor 16 relative to both piston members 22 as the rotor 16 rotates about the first rotational axis 30.

30 The relative pivoting motion is induced by a pivot actuator, as described below.

The mounting of the rotor 16 such that it may pivot (i.e. rock) relative to the piston members 22 means that the piston members 22 provide a moveable division between two halves of the or each chambers 34a,b to form sub-chambers 34a1, 34a2, 34b1,
35 34b2 within the chambers 34a,34b. In operation the volume of each sub chamber

34a1, 34a2, 34b1 and 34b2 varies depending on the relative orientation of the rotor 16 and piston members 22.

When the housing 12 is closed about the rotor assembly 14, the rotor 16 is disposed
5 relative to the housing wall 24 such that a small clearance is maintained between the chamber opening 34 over the majority of the wall 24. The clearance may be small enough to provide a seal between the rotor 16 and the housing wall 24.

Alternatively or additionally, sealing members may be provided in the clearance
10 between the housing wall 24 and rotor 16.

Ports are provided for the communication of fluid to and from the chambers 34a,b. For each chamber 34, the housing 12 may comprise an inlet port 40 for delivering fluid into the chamber 34, and an exhaust/outlet port 42 for expelling fluid from the
15 chamber 34. The ports 40, 42 extend through the housing and open onto the wall 24 of the housing 12.

The inlet and outlet/exhaust ports 40, 42 are shown in different orientations in Figure 1 and Figure 2. In Figure 1 the flow direction defined by each port is at an angle to the
20 first rotational axis 30. In Figure 2 the flow direction defined by each port is parallel to the first rotational axis 30. The ports 40, 42 may have the same flow areas. In other examples the ports 40, 42 may have different flow areas.

Also provided is a bearing arrangement 44 for supporting the ends of the shaft 18.
25 This may be of any conventional kind suitable for the application.

The ports 40, 42 may be sized and positioned on the housing 12 such that, in operation, when respective chamber openings 36 move past the ports 40, 42, in a first relative position the openings 36 are aligned with the ports 40, 42 such that the
30 chamber openings are fully open, in a second relative position the openings 36 are out of alignment such that the openings 36 are fully closed by the wall 24 of the housing 12, and in an intermediate relative position, the openings 36 are partly aligned with the ports 40, 42 such that the openings 36 are partly restricted by the wall of the housing 24.

Alternatively, the ports 40,42 may be sized and positioned on the housing 12 such that, in operation, in a first range (or set) of relative positions of the ports 40,42 and the respective rotor openings 36, the ports 40,42 and rotor openings 36 are out of alignment such that the openings 36 are fully closed by the wall 24 of the housing 12 to prevent fluid flow between the sub-chambers 34a1, 34a2 and their respective port(s) 40,42, and to prevent fluid flow between the sub-chambers 34b1, 34b2 and their respective port(s) 40,42. In a second range (or set) of relative positions of the ports 40,42 and the respective rotor chamber openings 36, the openings 36 are at least partly aligned with the ports 40,42 such that the openings 36 are at least partly open to allow fluid to flow between the sub chambers of chamber(s) 34a,b and their respective port(s) 40,42. Hence the sub-chambers are operable to increase in volume at least when in fluid communication with an inlet port (to allow for fluid flow into the sub-chamber), and the sub-chambers are operable to decrease in volume at least when in fluid communication with an outlet port (to allow for fluid flow out of the sub-chamber).

The placement and sizing of the ports may vary according to the application (i.e. whether used as part of a fluid pump apparatus, fluid displacement apparatus, fluid expansion apparatus) to facilitate best possible operational efficiency. The port locations herein described and shown in the figures is merely indicative of the principle of media (e.g. fluid) entry and exit.

In some examples of the apparatus of the present disclosure (not shown) the inlet ports and outlet ports may be provided with mechanical or electro-mechanical valves operable to control the flow of fluid/media through the ports 40,42.

The apparatus may comprise a pivot actuator. A non-limiting example of the pivot actuator is illustrated in Figure 3, which corresponds to that shown in Figures 1, 2.

However, the pivot actuator may comprise any suitable form of guide means configured to control the pivoting motion of the rotor. For example, the pivot actuator may comprise an electromagnetic arrangement configured to control the pivoting motion of the rotor. That is to say the pivot actuator may comprise a first guide feature 52 provided on the rotor 119, 219, and a second guide feature 50 provided on the housing 112, the first guide feature 52 operable to co-operate with the second guide feature 50 to pivot the rotor about the axle. At least one of the first guide feature 52

and second guide feature 50 comprises an electro-magnet operable to magnetically couple to the other of the first guide feature 52 and second guide feature 50.

In whatever form provided, the pivot actuator is operable (i.e. configured) to pivot the rotor 16 about the axle 20. That is to say, the apparatus may further comprise a pivot actuator operable (i.e. configured) to pivot the rotor 16 about the second rotational axis 32 defined by the axle 20. The pivot actuator may be configured to pivot the rotor 16 by any angle appropriate for the required performance of the apparatus. For example the pivot actuator may be operable to pivot the rotor 16 through an angle of substantially about 60 degrees.

The pivot actuator may comprise, as shown in the examples, a first guide feature on the rotor 16, and may have a second guide feature on the housing 12. Hence the pivot actuator may be provided as a mechanical link between the rotor 16 and housing 12 configured to induce a controlled relative pivoting motion of the rotor 16 relative to the piston member 22 as the rotor 16 rotates about the first rotational axis 30. That is to say, it is the relative movement of the rotor 16 acting against the guide features of the pivot actuator which induces the pivoting motion of the rotor 16.

The first guide feature is complementary in shape to the second guide feature. One of the first or second guide features define a path which the other of the first or second guide members features is constrained to follow as the rotor rotates about the first rotational axis 30. The path, perhaps provided as a groove, has a route configured to induce the rotor 16 to pivot about the axle 20 and axis 32. This route also acts to set the mechanical advantage between the rotation and pivoting of the rotor 16.

As shown in the example of Figure 1, and more clearly in Figure 4, a stylus 52 is provided on the rotor 16 and, as shown in Figures 1, 3, a guide groove 50 is provided in the housing 12. That is to say, the guide path 50 may be provided on the housing, and the other guide feature, the stylus 52 may be provided on the rotor 16.

A rotor assembly 14 akin to the example shown in Figures 1, 3 is shown in Figures 4 to 7. As can be seen there is provided a stylus 52 on the rotor 16 for engagement with the guide groove 50 on the housing 12.

The rotor 16 may be substantially spherical. As shown, the rotor 16 may be, at least in part, substantially spherical. For convenience Figure 4 shows the entire rotor assembly 14 with shaft 18, axle 20 and piston member 22 fitted. By contrast, Figure 5 shows the rotor 16 by itself, and a cavity 60 which extends through the rotor 14 and is configured to receive the axle 20. Figure 6 shows a view looking along the first rotational axis 30 on Figure 6, and Figure 7 the same view as shown in Figure 6 looking down the opening 36 which defines the chamber 34 of the rotor 14.

Figure 8 shows a perspective view of the axle 20 having the passage 62 for receiving the axle 18 and piston member 22. The axle 20 is substantially cylindrical. Figure 9 shows an example configuration of the shaft 18 and piston member 22. The shaft 18 and piston member 22 may be integrally formed, as shown in Figure 10, or may be fabricated from a number of parts. The piston member 22 is substantially square or rectangular in cross section. As shown in the figures, the shaft 18 may comprise cylindrical bearing regions which extend from the piston member 22 in order to seat on the bearing arrangement 44 of the housing 12, and hence permit rotation of the shaft 18 around the first rotational axis 30.

Figure 10 shows the shaft 18 and piston member 22 assembled with the axle 20. They may be formed as an assembly, as described above, or they may be integrally formed as one, perhaps by casting or forging.

The axle 20 may be provided substantially at the centre of the shaft 18 and piston member 22. That is to say, the axle 20 may be provided substantially halfway between the two ends of the shaft 18. When assembled, the shaft 18, axle 20 and piston member 22 may be fixed relative to one another. The axle 20 may be substantially perpendicular to the shaft and piston member 22, and hence the second rotational axis 32 may be substantially perpendicular to the first rotational axis 30.

The piston members 22 are sized to terminate proximate to the wall 24 of the housing 12, a small clearance being maintained between the end of the piston members 22 and the housing wall 24. The clearance may be small enough to provide a seal between the piston members 22 and the housing wall 24. Alternatively or additionally, sealing members may be provided in the clearance between the housing wall 24 the piston members 22.

Further examples of a guide groove 50 are shown in cross section in Figures 11, 12 which correspond to the example of Figure 1. In this example the guide groove 50 is substantially circular (i.e. with no inflexions).

5 The rotor 14 may be provided in one or more parts which are assembled together around the shaft 18 and axle 20 assembly. Alternatively the rotor 16 may be provided as one piece, whether integrally formed as one piece or fabricated from several parts to form one element, in which case the axle 20 may be slid into the cavity 60, and then the shaft 18 and piston member 22 slid into a passage 62 formed in the axle 20,
10 and then fixed together. A small clearance may be maintained between the axle 20 and bore of the cavity 60 of rotor 16. The clearance may be small enough to provide a seal between the axle 20 and the rotor 16 bore of the cavity 60. Alternatively or additionally, sealing members may be provided in the clearance between the axle 20 and rotor 16 bore of the cavity 60.

15

As shown clearly in Figure 13, in an example where the guide feature is provided as a path on the housing 12, the guide path 50 describes a path around (i.e. on, close to, and/or to either side of) a first circumference of the housing. In this example the plane of the first circumference overlays, or is aligned with, the plane described by the
20 second rotational axis 32 as it rotates about the first rotational axis 30.

Figure 13 shows a half housing split along the horizontal plane upon which the first rotational axis 30 sits. The guide path 50 comprises at least a first inflexion point 70 (on one side of the housing 12) to direct the path away from a first side of the plane of
25 the second rotational axis 32, then toward a second side of the plane of the second rotational axis 32, and a second inflexion point 72 (on the opposite side of the housing) to direct the path 50 away from the second side of the plane of the second rotational axis 32 and then back toward the first side of the plane of the second rotational axis 32. Hence the path 50 is not aligned with the plane of the second
30 rotational axis 32, but rather oscillates from side to side of the plane of the second rotational axis 32. That is to say, the path 50 does not sit on the plane of the second rotational axis 32, but defines a sinusoidal route between either side of the plane of the second rotational axis 32. The path 50 may be offset from the second rotational axis 32. Hence as the rotor 16 is turned about the first rotational axis 30, the
35 interaction of the path 50 and stylus 52 tilts (i.e. rocks or pivots) the rotor 16 backwards and forwards around the axle 20 and hence the second rotational axis 32.

In such an example, the distance which the guide path extends from an inflexion 70,72 on one side of the plane of the second rotational axis 32 to an inflexion 70,72 on the other side of the plane of the second rotational axis 32 defines the relationship
5 between the pivot angle of the rotor 16 about the second rotational axis 32 and the angular rotation of the shaft 18 about the first rotational axis 30. The number of inflexions 70,72 defines a ratio of number of pivots (e.g. compression, expansion, displacement cycles etc) of the rotor 16 about the second rotational axis 32 per revolution of the rotor 16 about the first rotational axis 30.

10

That is to say, the trend of the guide path 50 defines a ramp, amplitude and frequency of the rotor 16 about the second rotational axis 32 in relation to the rotation of the first rotational axis 30, thereby defining a ratio of angular displacement of the chambers 34 in relation to the radial reward from the shaft (or vice versa) at any point.

15

Put another way the attitude of the path 50 directly describes the mechanical ratio/relationship between the rotational velocity of the rotor and the rate of change of volume of the rotor chambers 34a, 34b. That is to say, the trajectory of the path 50 directly describes the mechanical ratio/relationship between the rotational velocity of
20 the rotor 16 and the rate of pivot of the rotor 16. Hence the rate of change and extent of displacement in chamber volume in relation to the rotational velocity of the rotor assembly 14 is set by the severity of the trajectory change (i.e. the inflexion) of the guide path.

25 The profile of the groove can be tuned to produce a variety of displacement versus compression characteristics, as combustion engines for petrol, diesel (and other fuels), pump and expansion may require different characteristics and/or tuning during the operational life of the rotor assembly. Put another way, the trajectory of the path 50 can be varied.

30

Thus the guide path 50 provides a "programmable crank path" which may be pre-set for any given application of the apparatus. That is to say, the route may be optimised to meet the needs of the application. Put another way, the guide path may be programmed to suit differing applications.

35

Alternatively the features defining the guide path 50 may be moveable to allow adjustment of the path 50, which may provide dynamic adjustment of the crank path while the apparatus is in operation. This may allow for tuning of rate and extent of the pivoting action of the rotor about the second rotational axis to assist with controlling performance and/or efficiency of the apparatus. That is to say, an adjustable crank path would enable variation of the mechanical ratio/relationship between the rotational velocity of the rotor and the rate of change or extent of displacement of the volume of the rotor chambers 34a, 34b. Hence the path 50 may be provided as a channel element, or the like, which is fitted to the rotor 12 and rotor housing 16, and which can be moved and/or adjusted, in part or as a whole, relative to the rotor 12 and rotor housing 16.

Thus the path 50 and inflexions 70, 72 define the rate of change of displacement of the rotor 16 relative to the piston 22, enabling a profound effect on the mechanical reward between the rotation and pivoting of the rotor 16.

Figure 14 shows another non limiting example of a rotor 16, akin to that shown in Figures 4 to 7. Bearing lands 73 are shown for receiving a bearing assembly (e.g. a roller bearing arrangement), or providing a bearing surface, to carry the rotor 16 on the axle 20. Also shown is a "cut out" feature 74 provided as a cavity in a non-critical region of the rotor, which lightens the structure (i.e. provides a weight saving feature) and provides a land to grip/clamp/support the rotor 16 during manufacture. An additional land 75 adjacent the stylus 52 may also be provided to grip/clamp/support the rotor 16 during manufacture. In this example the stylus 52 is provided as a roller bearing, rotatable about an axis perpendicular to axis 32. The bearing engages with, and runs along, the guide path 50, rotating as it moves along the track, thereby minimising friction between the guide member and track features.

Figures 15, 16 and 19 to 24 illustrate how the rotor apparatus of Figures 1 to 14, 17, 18 may be adapted to operate as a heat pump or heat engine. Any of the features described with reference to Figures 1 to 14, 17, 18 may be included in the arrangements of Figures 15, 16 and 19 to 24. Common terminology is used to identify common features, although in order to distinguish between features of the examples, alternative reference numerals are used as appropriate.

EXAMPLE 1 - SINGLE UNIT, CLOSED LOOP, HEAT PUMP

Figure 15 illustrates an apparatus 100 according to the present disclosure arranged as a closed loop heat pump, for example a refrigeration unit.

5 As described with reference to Figures 1 to 14, the apparatus 100 comprises a first shaft portion 118 (akin to shaft 18) which defines, and is rotatable about, a first rotational axis 130 (akin to rotational axis 30). A first axle 120 (akin to axle 20) defines a second rotational axis 132 (akin to rotational axis 32), the first shaft portion 118 extending through the first axle 120. The second rotational axis 132 is substantially
10 perpendicular to the first rotational axis 130. A first piston member 122a (akin to first piston member 22) is provided on the first shaft portion 118, the first piston member 122a extending from the first axle 120 towards a distal end of the first shaft portion 118. A first rotor 119 (akin to rotor 16 in Figures 1 to 14, 17, 18) is carried on the first axle 120. A housing 112 (akin to housing 12) is provided around the rotor 119
15 assembly.

The first rotor 119 comprises a first chamber 134a (akin to first chamber 34a), the first piston member 122a extending across the first chamber 134a. A wall of the housing 112 is provided adjacent the first chamber 134a.

20

Provided in the wall of the housing 112, and adjacent the first chamber 134a, is a first port 114a and a second port 114b (i.e akin to ports 40, 42). The ports 114a, 114b are in flow communication with the first chamber 134a, and are operable as flow inlets/outlets.

25

The first chamber 134a is divided into sub-chambers 134a1, 134a2 (akin to sub-chambers 34a1, 34a2), each on opposite sides of the piston 122a. Hence at any one time, the ports 114a, 114b may be in flow communication with one of the sub-chambers 134a1, 134a2, but not both.

30

The first rotor 119 comprises a second chamber 134b (akin to second chamber 34b). A wall of the housing 112 is provided adjacent the second chamber 134b. The housing 112 comprises a third port 116a and fourth port 116b, which are in flow communication with the second chamber 134b. The ports 116a, 116b are in flow
35 communication with the first chamber 134b, and are operable as flow inlets/outlets.

The second chamber 134b is divided into sub-chambers 134b1, 134b2 (akin to sub-chambers 34b1, 34b2), each on opposite sides of the piston 122b. Hence at any one time, the ports 116a, 116b may be in flow communication with one of the sub-chambers 134b1, 134b2, but not both.

5

The first piston member 122a extends from one side of the first axle 120 along the first shaft portion 118, and a second piston member 122b (akin to second piston member 22) extends from the other side of the first axle 120 along the first shaft portion 118, across the second chamber 134b. Thus, as described in relation to the examples of
10 Figures 1 to 14, the arrangement is configured to permit relative pivoting motion between the first rotor 119 and the second piston member 122b as the first rotor 119 rotates about the first rotational axis 130.

The first shaft portion 118, first axle 120 and first piston member(s) 122a, 122b may
15 be fixed relative to one another.

Thus the first rotor 119 and first axle 120 are rotatable with the first shaft portion 118 around the first rotational axis 130, and the first rotor 119 is pivotable about the axle 120 about the second rotational axis 132 to permit relative pivoting motion
20 between the first rotor 119 and the first piston member 122a as the first rotor 119 rotates about the first rotational axis 130.

The second port 114b is in fluid communication with the third port 116a via a first duct/conduit 300a which comprises a first heat exchanger 302a. The first heat
25 exchanger 302a is operable to **remove** heat energy from working fluid passing through it. That is to say, the first heat exchanger 302a is a **heat sink** for the working fluid (i.e. a heat sink for the medium or media flowing through the system). A first section 300a1 of duct 300a connects the second port 114b to the first heat exchanger 302a, and a second section 300a2 of duct 300a connects the first heat
30 exchanger 302a to third port 116a. That is to say, a fluid in a duct/conduit 300a may pass through the first heat exchanger 302.

Hence the first chamber 134a, heat exchanger 302a and second chamber 134b are arranged in flow series.

35

The fourth port 116b is in fluid communication with the first port 114a via a second duct (or conduit) 304a which comprises a second heat exchanger 306a. The second heat exchanger 306a is operable to **add** heat energy from working fluid passing through it. That is to say, the second heat exchanger 306a is a **heat source** for the working fluid (i.e. a heat source for the medium or media flowing through the system).

The first heat exchanger 302a may be provided as any suitable **heat sink** (for example in thermal communication with a volume to be heated, a river, ambient air etc). The second heat exchanger 306a may comprise or be in thermal communication with any suitable **heat source** (for example, a volume to be cooled, the internal air of a food store etc).

A first section 304a1 of duct 304a connects the fourth port 116b to the second heat exchanger 306a, and a second section 304a2 of duct 304a connects the second heat exchanger 306a to the first port 114a.

A motor 308 is coupled to the first shaft portion 118 to drive the rotor 119 around the first rotational axis 130.

In the present example, the first chamber 134a and piston 122a hence provide a **first fluid flow section 111**, which in this example are operable as a compressor or displacement pump. Hence the **first fluid flow section 111** is configured for the passage of fluid between the first port 114a and second port 114b via the first chamber 134a.

Also the second chamber 134b and piston 122b hence provide a **second fluid flow section 115**, which in this example are operable as a metering section or expansion section. Hence the **second fluid flow section 115** is configured for the passage of fluid between the third port 116a and fourth port 116b via the second chamber 134.

The volumetric capacity of the first rotor second chamber 134b may be substantially the **same, less, or greater than** the volumetric capacity of the first rotor first chamber 134a.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the first fluid flow section 111.

- 5 For example the volumetric capacity of the first rotor second chamber 134b may be at most half the volumetric capacity of the first rotor first chamber 134a.

Alternatively the volumetric capacity of the first rotor second chamber 134b may be at least twice the volumetric capacity of the first rotor first chamber 134a.

10

Hence in the present example, this provides an expansion ratio within the confines of a single device (for example as shown in Figure 17).

- 15 This may be achieved by providing the first rotor first chamber 134a as a different width than the first rotor second chamber 134b, with the first piston 122a consequentially having a different width than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chambers 134a, 134b and swept volume of the pistons 122a, 122b will differ.

20

- As shown in Figure 17, which shows just the rotor assembly 116, the different volumes may be achieved by providing the first rotor first chamber 134a as **wider** than the first rotor second chamber 134b, with the first piston 122a consequentially being **wider** than the second piston 122b. Hence although the pistons will pivot, and hence
25 travel, to the same extent around the second rotational axis 132, the volume of the chamber 134a will be **greater than** the volume of chamber 134b, and hence the swept volume of the piston 122a will be **greater than** piston 122b.

- 30 In operation (as described later) a working fluid is introduced into and cycles around the system.

The fluid may be a refrigerant fluid or other media, for example, but not limited to, Ethanol, R22 or Super saturated CO₂.

- 35 Given the system is essentially closed, the working fluid may not be consumed or rendered inoperable after each cycle. That is to say, for the majority of its operation

the same fixed volume of working fluid will remain and continually cycle around the system. In alternative examples, the working fluid may be partly or wholly replaced during operation of the device (for example during each cycle, or after a predetermined number of cycles).

5

Since the **first fluid flow section 111** (in this example a displacement/compressor/pump section) and **second fluid flow section 115** (in this example an metering/expansion section) are two sides of the same rotor, the rotation of the rotor 119 is driven both by the motor and the metering/expansion of the fluid in the second chamber 134b (i.e. in sub-chambers 134b1, 134b2). Thus the configuration of the device of the present disclosure recovers some of the energy from the expansion phase to partly drive the rotor 119.

10

Operation of the device 100 will now be described.

15

Stage 1

In the example as shown in Figure 15 the working fluid enters the sub-chamber 134a1 via port 114a.

20

The working fluid is then pumped (e.g. compressed) by the action of the piston 122a, driven by the motor 308, in the sub-chamber 134a and exits via the second port 114b.

At the same time as working fluid is being drawn into the sub-chamber 134a1, working fluid is being exhausted from sub-chamber 134a2 through the second port 114b.

25

At the same time as working fluid is being exhausted from the sub-chamber 134a1, working fluid is being drawn into sub-chamber 134a2 through the first port 114b.

30

Stage 2

In the example as shown in Figure 15, after being exhausted from the first chamber 134a of rotor 119, working fluid travels along duct 300a1 and enters the first heat exchanger 302a, which is configured as a **heat sink**. Hence heat is extracted from the working fluid as it passed through the first heat exchanger 302a.

35

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the first heat exchanger 302a.

Stage 3

5

In the example as shown in Figure 15 the working fluid travels along duct 300a2 and enters the sub-chamber 134b1 of the rotor via the third port 116a where its pressure is restrained and the working fluid is metered into duct 304a via the fourth port 116b.

10

At the same time as working fluid is entering sub-chamber 134b1, working fluid is being exhausted from sub-chamber 134b2 via the fourth port 116b.

15

As the rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134b1 via the fourth port 116b, and more working fluid enters the sub-chamber 134b2 via the third port 116a where it expands.

20

In all examples, sequential expansion of the working fluid in the rotor sub-chambers 134b1, 134b2 induces a force to thereby (at least in part) cause pivoting of the rotor about its second rotational axis, and to cause rotation of the rotor about its first rotational axis. This force is in addition to that provided by the motor 308.

Stage 4

25

In the example as shown in Figure 15 working fluid then travels from the second chamber 134b along duct 304a1 and enters the second heat exchanger 306a, which in this example is configured as a **heat source**.

30

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the second heat exchanger 306a.

35

Hence the working fluid absorbs heat from the heat source and then leaves the second heat exchanger 306a and travels along duct 304a2 before entering the first chamber 134a to re-start the cycle.

EXAMPLE 2 - DOUBLE UNIT, CLOSED LOOP, HEAT PUMP

Figure 16 illustrates another example of a closed loop heat pump, for example a refrigeration unit. This example includes many features in common with, or equivalent to, the example of Figure 15, and are hence referred to with the same reference numerals.

Hence the apparatus 200 comprises a **first fluid flow section 111** which, akin to the example of Figure 15 may be operable as a compressor or displacement pump. The **first fluid flow section 111** has a first port 114a and a second port 114b, which are operable as flow inlets/outlets.

It also comprises a **second fluid flow section 115** which, akin to the example of Figure 15, may be operable as a metering section or expansion section. The **second fluid flow section 115** has a third port 116a and a fourth port 116b, which are operable as flow inlets/outlets.

The apparatus 200 comprises a first shaft portion 118 which defines and is rotatable about a first rotational axis 130. A first axle 120 defines a second rotational axis 132, the first shaft portion 118 extending through the first axle 120. The second rotational axis 132 is substantially perpendicular to the first rotational axis 130. A first piston member 122a is provided on the first shaft portion 118, the first piston member 122a extending from the first axle 120 towards a distal end of the first shaft portion 118. A first rotor 119 is carried on the first axle 120. The first rotor 119 comprises a first chamber 134a, the first piston member 122a extending across the first chamber 134a. The first displacement outlet 113a and first displacement inlet 114a are in flow communication with the first chamber 134a.

The first shaft portion 118, first axle 120 and first piston member(s) 122a, 122b may be fixed relative to one another.

Also the first rotor 119 comprises a second chamber 134b. The first piston member 122a extends from one side of the first axle 120 along the first shaft portion 118 through the first chamber 134a to define sub-chambers 134a1, 134a2, and a second piston member 122b extends from the other side of the first axle 120 along the first shaft portion 118, across the second chamber 134b to define sub-chambers 134b1, 134b2. Hence the arrangement is configured to permit relative pivoting motion

between the first rotor 119 and the second piston member 122b as the first rotor 119 rotates about the first rotational axis 130.

Thus, as described in relation to the examples of Figures 1 to 14, the first rotor 119 and first axle 120 are rotatable with the first shaft portion 118 around the first rotational axis 130, and the first rotor 119 is pivotable about the axle 120 about the second rotational axis 132 to permit relative pivoting motion between the first rotor 119 and the first piston member 122a and second piston member 122b as the first rotor 119 rotates about the first rotational axis 130.

The apparatus 200 further comprises a second shaft portion 218 rotatable about the first rotational axis 130 and coupled to the first shaft portion 118 such that the first shaft portion 118 and second shaft portion 218 are rotatable together around the first rotational axis 130.

A second axle 220 defines a third rotational axis 232, the second shaft portion 218 extending through the second axle 220. The third rotational axis 232 is substantially perpendicular to the first rotational axis 130 and parallel to the second rotational axis 132 of the first rotor, and would hence extend out of/into the page as shown in Figure 16.

A second rotor 219 is carried on the second axle 220. The first shaft portion 118 is directly coupled to the second shaft portion 218 such that the first rotor 119 and second rotor are operable to only rotate at the same speed as each other. A second housing 212 (akin to housing 12) is provided around the second rotor 219.

Similar to first rotor 119, the second rotor 219 comprises a first chamber 234a and a second chamber 234b. A second piston member 222b is provided on the second shaft portion 218, the second piston member 222b extending from the second axle 220 across the second chamber 234b towards a distal end of the second shaft portion 218 to define sub-chambers 234b1, 234b2.

The second piston member 222b extends from one side of the second axle 220 along the second shaft portion 218. A second rotor first piston member 222a extends from the other side of the second axle 220 along the second shaft portion 218, across the first chamber 234a to define sub-chambers 234a1, 234a2. Thus, as described in

relation to the examples of Figures 1 to 14, the arrangement is configured to permit relative pivoting motion between the second rotor 219 and the first and second piston members 222a, 222b as the second rotor 219 rotates about the first rotational axis 130.

5

The second shaft portion 218, second axle 220 and second piston member(s) 222a, 222b may be fixed relative to one another.

10 In this example the third port 116a and fourth port 116b are in flow communication with the second chamber 234b, the third port 116a and fourth port 116b being provided in a wall of housing 212 of the second rotor.

Hence the second rotor 219 and second axle 220 are rotatable with the second shaft portion 218 around the first rotational axis 130, and the second rotor 219 is pivotable
15 about the second axle 220 about the third rotational axis 232 to permit relative pivoting motion between the second rotor 219 and the first and second piston members 222a, 222b as the second rotor 219 rotates about the first rotational axis 130.

20 The second port 114b of the first rotor 119 is in fluid communication with the third port 116a of the second rotor 219 via a first duct/conduit 300a which comprises a first heat exchanger 302a. In common with the example of Figure 15, the first heat exchanger 302a is operable to **remove** heat energy from working fluid passing through it (i.e. is a **heat sink**). A first section 300a1 of duct 300a connects the second
25 port 114b to the first heat exchanger 302a, and a second section 300a2 of duct 300a connects the first heat exchanger 302a to the third port 116a.

The first rotor second chamber 134b is in flow communication with a fifth port 114c and a sixth port 114d provided in a wall of the first housing 112, such that the
30 arrangement is configured for the passage of fluid between the fifth port 114c and sixth port 114d via the first rotor second chamber 134b.

The second rotor first chamber 234a is in flow communication with a seventh port 116c and an eighth port 116d provided in a wall of the second housing 212, such
35 that the arrangement is configured for the passage of fluid between the seventh port 116c and eighth port 116d via the second rotor first chamber 234a.

The sixth port 114d of the first rotor 119 is in fluid communication with the seventh port 116c of the second rotor 219 via a second duct/conduit 300b which comprises (i.e. extends through) the first heat exchanger 302a. A first section 300b1 of duct 300b connects the sixth port 114d to the first heat exchanger 302a, and a second section 300b2 of duct 300b connects the first heat exchanger 302a to the seventh port 116c.

The fourth port 116b of the second rotor 219 is in fluid communication with the first port 114a of the first rotor 119 via a second duct/conduit 304a which comprises a second heat exchanger 306a. In common with the example of Figure 15, the second heat exchanger 306a is operable to **add** heat energy to the working fluid passing through it (i.e. is a **heat source**). A first section 304a1 of duct 304a connects the fourth port 116b to the second heat exchanger 306a, and a second section 304a2 of duct 300a connects the second heat exchanger 306a to the first port 114a.

The eighth port 116d of the second rotor 219 is in fluid communication with the fifth port 114c of the first rotor via a second duct/conduit 304b which comprises (i.e. extends through) the second heat exchanger 306a. A first section 304b1 of duct 304b connects the eighth port 116d to the second heat exchanger 306a, and a second section 304b2 of duct 304b connects the second heat exchanger 306a to the fifth port 114c.

Hence there are two fluid flow circuits in this example (e.g. between the first rotor first chamber 134a and second rotor second chamber 234b, and between the first rotor second chamber 134b and second rotor first chamber 234a) which may be fluidly isolated from one another. The working fluid may be the same as described in relation to the Figure 15 example.

In the present example, the first rotor 119 assembly (i.e. the first rotor chambers 134a, 134b and first rotor pistons 122a, 122b) and first housing 112 hence provide the **first fluid flow section 111**, which in this example are operable as a compressor or displacement pump. Hence the **first fluid flow section 111** is configured for the passage of fluid between the first port 114a and second port 114b via the first rotor first chamber 134a, and for the passage of fluid between the fifth port 114c and sixth port 114d via the first rotor second chamber 134b.

Also the rotor 219 assembly (i.e. second rotor chambers 234a, 234b and first rotor pistons 222a, 222b) and second housing 212 hence provide the **second fluid flow section 115**, which in this example are operable as a metering section or expansion section. Hence the **second fluid flow section 115** is configured for the passage of fluid between the third port 116a and fourth port 116b via the second rotor second chamber 234b, and for the passage of fluid between the seventh port 116c and eighth port 116d via the second rotor first chamber 234a,

As shown in Figure 16, the first chamber 134a and second chamber 134b of the first rotor 119 (i.e. **first fluid flow section 111**) have substantially the same volumetric capacity as each other. The first chamber 234a and second chamber 234b of the second rotor 219 (i.e. the **second fluid flow section 115**) have substantially the same volumetric capacity as each other. However, the volumetric capacity of the first rotor chambers 134a, 134b (first fluid flow section 111) may be substantially the **same, less, or greater than** the volumetric capacity of the second rotor chambers 234a, 234b (second fluid flow section 115).

That is to say, in the present example, the volumetric capacity of the rotor chambers 234a, 234b of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the rotor chambers 134a, 134b first fluid flow section 111.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at most half** the volumetric capacity of the first fluid flow section 111.

Alternatively, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at least twice** the volumetric capacity of the first fluid flow section 111.

As shown in Figure 18, which shows just the rotors 119, 219, pistons 122, 222 and shafts 118, 218, the difference in volumetric capacity may be achieved by providing the first rotor chambers 134a, 134b as **wider** than the second rotor chambers 234a, 234b, with the first rotor pistons 122a, 122b consequentially being **wider** than the second rotor pistons 222a, 222b. Hence although the pistons 122, 222 may pivot by

the same angle, the volume of the first chambers 134a, 134b will be **greater** than the second chambers 234a, 234b, and the swept volume of the first rotor pistons 122a, 122b will be **greater** than the swept volume of the second rotor pistons 222a, 222b.

- 5 Since the shaft 118 of the **first fluid flow section 111** (first rotor 119) and shaft 218 of the **first fluid flow section 115** (second rotor 219) are coupled so they rotate together, the rotation of the first rotor 119 is driven both by the motor 308 and the expansion of the fluid in the sub-chambers 234a1, 234a2, 234b1, 234b2 of the second rotor 219.

10

In other examples the first rotor shaft 118 and second rotor shaft 218 are integrally formed as one, and extend through both rotors 119, 219.

Operation of the device 200 will now be described.

15

Stage 1

In the example as shown in Figure 16 the working fluid enters the sub-chambers 134a1, 134b1 via the first port 114a and fifth port 114c respectively.

20

The working fluid is then pumped (e.g. compressed) by the action of the respective pistons 122a, 122b driven by the motor 308, in the sub-chambers 134a, 134b and exits via the second port 114b and sixth port 114d respectively.

- 25 At the same time as working fluid is being drawn into the sub-chambers 134a1, 134b1, working fluid is being exhausted from sub-chambers 134a2, 134b2 through the second port 114b and sixth port 114d respectively.

- 30 At the same time as working fluid is being exhausted from the sub-chambers 134a1, 134b1, working fluid is being drawn into sub-chambers 134a2, 134b2 through the first port 114a and fifth port 114c respectively.

Stage 2

- 35 In the example as shown in Figure 16, after being exhausted from the first rotor chambers 134a, 134b, working fluid travels along ducts 300a1, 300b1 respectively

and enters the first heat exchanger 302a, which is configured as a **heat sink**. Hence heat is extracted from the working fluid as it passed through the first heat exchanger 302a.

- 5 Depending on the nature of the working fluid, there may be a phase change of the working fluid in the first heat exchanger 302a.

Stage 3

- 10 In the example as shown in Figure 16 the working fluid travels along ducts 300a2, 300b2 and enters the sub-chambers 234b1, 234a1 of the second rotor via the third port 116a and seventh port 116c respectively where its pressure is restrained and the working fluid is metered into ducts 304a1, 304b1 respectively via the fourth port 116b and eighth port 116d respectively.

15

At the same time as working fluid is entering sub-chambers 234b1, 234a1, working fluid is being exhausted from sub-chambers 234b2, 234a2 via the fourth port 116b and eighth port 116d respectively.

- 20 As the second rotor 219 continues to rotate, the working fluid is exhausted from the sub-chambers 234b1, 234a1 via the fourth port 116b and eighth port 116d, and more working fluid enters the sub-chambers 234b2, 234a2 via the third port 116a and seventh port 116c.

- 25 In all examples, sequential delivery and behaviour of the working fluid in the rotor sub-chambers 234a1, 234a2, 234b1, 234b2 induces a force to thereby (at least in part) cause pivoting of the second rotor 219 about its second rotational axis 232, and to cause rotation of the rotor about its first rotational axis. This force is in addition to that provided by the motor 308.

30

Stage 4

- In the example as shown in Figure 16 working fluid then travels from the second rotor chambers 234a, 234b along ducts 304a1, 304b1 and enters the second heat
35 exchanger 306a, which in this example is configured as a **heat source**.

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the second heat exchanger 306a.

Hence the working fluid absorbs heat from the heat source and then leaves the second heat exchanger 306a and travels along ducts 304a2, 304b2 before entering the first rotor chambers 134a, 134b to re-start the cycle.

EXAMPLE 3 – SINGLE UNIT, CLOSED LOOP, HEAT ENGINE

Figure 19 illustrates an example of a closed loop heat engine (e.g. energy harvesting generator) apparatus 400 according to the present disclosure, which includes many features in common with, and potentially physically identical or equivalent to the example of Figure 15, and which are hence referred to with the same reference numerals.

15

The example of Figure 19 differs from the example of Figure 15 in that, instead of a motor 308, a power off take 408 is coupled to, and driveable by the first shaft 118. The power off take 408 may be provided as a coupling of a gear box for driving another device, for example an electrical generator.

20

Also the first heat exchanger 302a is configured as a **heat source** (rather than the **heat sink** of Example 1) and second heat exchanger 306a is configured as a **heat sink** (rather than the **heat source** of Example 1). Otherwise, the Examples of Figures 15, 19 are structurally the same.

25

That is to say, in practice, should the **heat sink** and **heat source** of the equipment configured as a **heat pump** in Figure 15 be swapped for one another, and the motor 308 of the Figure 15 example swapped for a generator 408, the result would be the **heat engine** of Figure 19.

30

That is to say, in practice, that if a thermodynamically reversible heat source and heat sink are provisioned and a motor 308 is provisioned which can also perform as a generator 408, that the same scheme may be thermodynamically reversible and perform both as a heat pump 100, or reverse and perform as a heat engine 400, in applications where such was seen as an advantage.

35

A consequence of this is that, in operation, the direction of fluid flow through the system of Figure 19, and hence the thermodynamic process, is reversed compared to the system of Figure 15.

- 5 Hence the sub-chambers 134a1, 134a2 (i.e. a **first fluid flow section 111**) which are operable as displacement/compression chambers in the Figure 15 example, are operable as expansion chambers in the Figure 19 example. That is to say, in this example the first chamber 134a and piston 122a (i.e. **first fluid flow section 111**) is operable as a fluid expansion section.

10

- Also the sub-chambers 134b1, 134b2 (i.e. **second fluid flow section 115**), which are operable as metering/expansion chambers in the Figure 15 example, are operable as displacement/compression/pumping chambers in the Figure 19 example. That is to say, in the present example, the second chamber 134b and piston 122b (i.e. **second**
15 **fluid flow section 115**) may be operable as a fluid displacement pump or, compressor.

- Hence since the expansion section (i.e. first fluid flow section 111) and displacement section (i.e. second fluid flow section 115) are two sides of the same rotor, the rotation
20 of the rotor 119 is driven by the expansion of the working fluid in the first chamber 134a (i.e. in sub-chambers 134a1, 134a2).

Operation of the device 400 will now be described.

25

Stage 1

- 30 In the example as shown in Figure 19 the working fluid travels along duct 300a1 and enters the sub-chamber 134a2 of the rotor via the second port 114b where it expands.

- At the same time as working fluid is entering and expanding in the sub-chamber 134a2, working fluid is being exhausted from sub-chamber 134a1 via the first
35 port 114a.

As the rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134a2 via the first port 114a, and more working fluid enters the sub-chamber 134a1 via the second port 114b where it expands.

- 5 In all examples, sequential expansion of the working fluid in the rotor sub-chambers 134a1, 134a2 induces a force to thereby cause pivoting of the rotor about its second rotational axis 132, and to cause rotation of the rotor about its first rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

10 **Stage 2**

In the example as shown in Figure 19, after being exhausted from the first chamber 134a of rotor 119, working fluid travels along duct 304a2 and enters the second heat exchanger 306a, which is configured as a **heat sink**. Hence heat is
15 extracted from the working fluid as it passed through the second heat exchanger 306a.

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the second heat exchanger 306a.

20

Stage 3

In the example as shown in Figure 19 the working fluid enters the sub-chamber 134b2 via the fourth port 116b.

25

The working fluid is then displaced/pumped by the action of the piston 122b, driven by the expansion of the working fluid in the first chamber 134a, and exits via the third port 116a.

- 30 At the same time as working fluid is being drawn into the sub-chamber 134b2, working fluid is being exhausted from sub-chamber 134b1 through the third port 116a.

At the same time as working fluid is being exhausted from the sub-chamber 134b2, working fluid is being drawn into sub-chamber 134b1 through the fourth port 116b.

35

Stage 4

In the example as shown in Figure 19 working fluid then travels from the second chamber 134b along duct 300a2 and enters the first heat exchanger 302a, which is configured as a **heat source**.

5

Hence the working fluid absorbs heat from the heat source and then leaves the first heat exchanger 302a and travels along duct 300a1 before entering the first chamber 134a to re-start the cycle.

- 10 Depending on the nature of the working fluid, there may be a phase change of the working fluid in the first heat exchanger 302a.

EXAMPLE 4 - DOUBLE UNIT, CLOSED LOOP, HEAT ENGINE

- 15 Figure 20 illustrates a second example of a closed loop heat engine (e.g. motor unit) apparatus 500 according to the present disclosure, which includes many features in common with, or equivalent to, the example of Figure 16, and are hence referred to with the same reference numerals.

- 20 The example of Figure 20 differs from the example of Figure 16 in that, instead of a motor 308, a power off take 408 is coupled to, and driveable by the first shaft 118. The power off take 408 may be provided as a coupling of a gear box for driving another device, for example an electrical generator.

- 25 Also the first heat exchanger 302a is configured as a **heat source** (rather than the **heat sink** of Example 2) and second heat exchanger 306a is configured as a **heat sink** (rather than the **heat source** of Example 2). Otherwise, the Examples of Figures 16, 20 are structurally the same.

- 30 That is to say, in practice, should the **heat sink** and **heat source** of the equipment configured as a **heat pump** in Figure 16 be swapped for one another, and the motor 308 of the Figure 16 example swapped for a generator 408, the result would be the **heat engine** of Figure 20.

A consequence of this is that, in operation, the direction of fluid flow through the system of Figure 20, and hence the thermodynamic process, is reversed compared to the system of Figure 16.

5 Hence the first rotor sub-chambers 134a1, 134a2, 134b1, 134b2 (i.e. a **first fluid flow section 111**) which are operable as displacement/compression chambers in the Figure 16 example, are operable as expansion chambers in the Figure 20 example. That is to say, in this example the first rotor first chamber 134a and piston 122a, and first rotor second chamber 134b and second piston 122b (i.e. **first fluid flow section**
10 **111**) are operable as a fluid expansion section.

Also the sub-chambers 234a1, 234a2, 234b1, 234b2 (i.e. **second fluid flow section 115**), which are operable as expansion/metering chambers in the Figure 16 example, are operable as displacement/compression/pumping chambers in the Figure 20
15 example. That is to say, in the present example, second rotor first chamber 234a and piston 222a, and second rotor second chamber 234b and second piston 222b (i.e. **second fluid flow section 115**) may be operable as a fluid displacement pump or compressor.

20 Since the shaft 118 first fluid flow section 111 (first rotor 119) and shaft 218 of the second fluid flow section 115 (second rotor 219) are coupled, they rotate together.

Hence since the shaft 118 of the expansion section (i.e. first fluid flow section 111) and shaft 218 of the displacement section (i.e. second fluid flow section 115) are
25 coupled so they rotate together, rotation of the second rotor 219 is driven by the expansion of the working fluid in the first rotor chamber 134a,b (i.e. in sub-chambers 134a1, 134a2, 134b1, 134b2).

Akin to Example 2 shown in Figure 16, the first chamber 134a and second chamber
30 134b of the first rotor 119 (i.e. **first fluid flow section 111**) have substantially the same volumetric capacity as each other. The first chamber 234a and second chamber 234b of the second rotor 219 (i.e. the **second fluid flow section 115**) have substantially the same volumetric capacity as each other. However, the volumetric capacity of the first rotor chambers 134a, 134b (first fluid flow section 111) may be
35 substantially the **same, less, or greater than** the volumetric capacity of the second rotor chambers 234a, 234b (second fluid flow section 115).

That is to say, in the present example, the volumetric capacity of the rotor chambers 234a, 234b of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the rotor chambers 134a, 134b first fluid flow section 111.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at most half** the volumetric capacity of the first fluid flow section 111.

Alternatively, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at least twice** the volumetric capacity of the first fluid flow section 111.

As shown in Figure 18, which shows just the rotors 119, 219, pistons 122, 222 and shafts 118, 218, the difference in volumetric capacity may be achieved by providing the first rotor chambers 134a, 134b as **wider** than the second rotor chambers 234a, 234b, with the first rotor pistons 122a, 122b consequentially being **wider** than the second rotor pistons 222a, 222b. Hence although the pistons 122, 222 may pivot by the same angle, the volume of the first chambers 134a, 134b will be **greater** than the second chambers 234a, 234b, and the swept volume of the first rotor pistons 122a, 122b will be **greater** than the swept volume of the second rotor pistons 222a, 222b.

Operation of the device 500 will now be described.

25

Stage 1

In the example as shown in Figure 20 the working fluid travels along ducts 300a1, 300b1 and enters the sub-chambers 134a2, 134b2 respectively of the first rotor 119 via the second port 114b and sixth port 114d respectively where it expands.

At the same time as working fluid is entering and expanding in the sub-chambers 134a2, 134b2, working fluid is being exhausted from the first rotor sub-chambers 134a1, 134a2 via the first port 114a and fifth port 114c respectively.

35

As the first rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134a2, 134b2 via the first port 114a and fifth port 114c respectively, and more working fluid enters the sub-chambers 134a1, 134a2 via the second port 114b and sixth port 114d where it expands.

5

In all examples, sequential expansion of the working fluid in the rotor sub-chambers 134a1, 134a2, 134b1, 134b2 induces a force to thereby cause pivoting of the first rotor about its second rotational axis 132, and to cause rotation of the first rotor 119 about its first rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

10

Stage 2

In the example as shown in Figure 20, after being exhausted from the first chambers 134a, 134b of the first rotor 119, working fluid travels along ducts 304a2, 304b2 respectively and enters the second heat exchanger 306a, which is configured as a **heat sink**. Hence heat is extracted from the working fluid as it passed through the second heat exchanger 306a.

15

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the second heat exchanger 306a.

20

Stage 3

In the example as shown in Figure 20 the working fluid enters the second rotor sub-chambers 234b2, 234a2 via the fourth port 116b eighth port 116d respectively.

25

The working fluid is then displaced/pumped by the action of the second rotor pistons 222a, 222b, driven by the expansion of the working fluid in the first rotor chambers 134a, 134b and exits via the third port 116a and seventh port 116 respectively.

30

At the same time as working fluid is being drawn into the second rotor sub-chamber 234b2, 234a2, working fluid is being exhausted from second rotor sub-chambers 234b1, 234a1 through the third port 116a and seventh port 116c respectively.

35

At the same time as working fluid is being exhausted from the second rotor sub-chambers 234b2, 234a2, working fluid is being drawn into the second rotor sub-chambers 234b1, 234a1 through the fourth port 116b and eighth port 116d respectively.

5

Stage 4

In the example as shown in Figure 20 working fluid then travels from the second rotor second chambers 234b, 234a along ducts 300a2, 300b2 and enters the first heat exchanger 302a, which is configured as a **heat source**.

10

Hence the working fluid absorbs heat from the heat source and then leaves the first heat exchanger 302a and travels along ducts 300a1, 300b1 before entering the first rotor first chambers 134a, 134b to re-start the cycle.

15

Depending on the nature of the working fluid, there may be a phase change of the working fluid in the first heat exchanger 302a.

20 EXAMPLE 5 – SINGLE UNIT, OPEN LOOP, HEAT ENGINE

Figure 21 illustrates a first example of an open loop motor unit (heat engine) apparatus 600 according to the present disclosure, which includes many features in common, or equivalent to, the example of Figure 19, and are hence referred to with the same reference numerals.

25

The example of Figure 21 differs from the example of Figure 19 in the following ways.

The system is an open loop, with no connection between the first port 114a and the fourth port 116b. That is to say, the second duct 304a and second heat exchanger 306a not present, and hence the first port 114a and the fourth port 116b are isolated from one another.

30

The fourth port 116b may be in fluid communication with a source of air, for example open to atmosphere. Hence in this example, the working fluid may comprise air.

35

The first heat exchanger 302a may comprise or be in thermal communication with any suitable heat source (for example solar heat, combustion exhaust or flue gases from another process, or steam). Alternatively the first heat exchanger 302a may comprise a combustion chamber 602 operable for continuous combustion. For example, the combustion chamber may include a burner supplied with a fuel to generate heat. The combustion process may be a continuous combustion process. Hence, akin Example 3 in Figure 19, the first heat exchanger 302a is a **heat source** configured to **add** heat energy to fluid passing through it.

- 10 The volumetric capacity of the first rotor second chamber 134b may be substantially the **same, less, or greater than** the volumetric capacity of the first rotor first chamber 134a.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the first fluid flow section 111.

For example the volumetric capacity of the first rotor second chamber 134b may be **at most half** the volumetric capacity of the first rotor first chamber 134a.

20 Alternatively the volumetric capacity of the first rotor second chamber 134b may be **at least twice** the volumetric capacity of the first rotor first chamber 134a.

Hence in the present example, this provides an expansion ratio within the confines of a single device (for example as shown in Figure 17).

This may be achieved by providing the first rotor first chamber 134a as a different width than the first rotor second chamber 134b, with the first piston 122a consequentially having a different width than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chambers 134a, 134b and swept volume of the pistons 122a, 122b will differ.

As shown in Figure 17, which shows just the rotor assembly 116, the different volumes may be achieved by providing the first rotor first chamber 134a as **wider** than the first rotor second chamber 134b, with the first piston 122a consequentially being

wider than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chamber 134a will be **greater than** the volume of chamber 134b, and hence the swept volume of the piston 122a will be **greater than** piston 122b.

5

Operation of the device 600 will now be described.

Stage 1

- 10 In the example as shown in Figure 21 the working fluid (for example air) enters the sub-chamber 134b2 via the fourth port 116b.

The working fluid is then displaced/compressed/metered by the action of the piston 122b, driven by expansion of working fluid in the first chamber 134a (described
15 below in stage 3), and exits via the third port 116a.

At the same time as working fluid is being drawn into the sub-chamber 134b2, working fluid is being exhausted from sub-chamber 134b1 through the third port 116a.

- 20 At the same time as working fluid is being exhausted from the sub-chamber 134b2, working fluid is being drawn into sub-chamber 134b1 through the fourth port 116b.

Stage 2

In the example as shown in Figure 21 working fluid then travels from the second chamber 134b along duct 300a2 and enters the first heat exchanger 302a, which is
5 configured as a **heat source**.

The working fluid may be mixed with fuel in the combustor 603 to be in part burned and in part heated, increasing pressure, before being passed to the second port 114b of the expansion section, which in this example is the first fluid flow section 111.
10

Hence the working fluid absorbs heat from the heat source and then leaves the first heat exchanger 302a and travels along duct 300a1 before entering the first chamber 134a.

15 Stage 3

In the example as shown in Figure 21 the working fluid travels along duct 300a1 and enters the sub-chamber 134a2 of the rotor via the second port 114b where it expands.

20 At the same time as working fluid is entering and expanding in the sub-chamber 134a2, working fluid is being exhausted from sub-chamber 134a1 via the first port 114a.

As the rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134a2 via the first port 114a, and more working fluid enters the sub-chamber 134a1 via the second port 114b where it expands.
25

Hence the exhaust gas expands sequentially in the sub-chambers 134a1, 134a2 of the first chamber 134a (hence the gas decreases in pressure and increases in
30 volume), so that work is done by the gas on the first piston 122a to urge the first piston 122a across the chamber 134a (operating as an expansion chamber), which drives the second piston 122b across the second chamber 134b to draw in and compress a further portion of air to start the process again.

35 Hence the sequential expansion of the working fluid in the rotor sub-chambers 134a1, 134a2 induces a force to thereby cause pivoting of the rotor about

its second rotational axis 132, and to cause rotation of the rotor about its first rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

EXAMPLE 6 - DOUBLE UNIT, OPEN LOOP, HEAT ENGINE

5

Figure 22 illustrates a second example of an open loop motor unit (heat engine) apparatus 700 according to the present disclosure, which includes many features in common with, or equivalent to, the example of Figure 20, and are hence referred to with the same reference numerals.

10

The example of Figure 22 differs from the example of Figure 20 in the following ways.

The system is an open loop, with no connection between the second rotor flow inlets (which in this example are the fourth port 116b and eighth port 116d) the first rotor flow outlets (which in this example are the first port 114c and fifth port 114c) respectively. That is to say, the second duct 304a and second heat exchanger 306a of Example 4 (Figure 20) are not present in the example of Figure 22, and hence the fourth port 116b and first port 114a are isolated from one another, and the eighth port 116d and fifth port 114c are isolated from one another.

20

The fourth port 116b and eighth port 116d may be in fluid communication with a source of air, for example open to atmosphere. Hence in this example, the working fluid may comprise air.

25 As in the example of Figure 20, the first heat exchanger 302a may comprise or be in thermal communication with any suitable heat source (for example solar heat, combustion exhaust or flue gases from another process, or steam). Alternatively, and akin to Example 5 of Figure 21, the first heat exchanger 302a may comprise a combustion chamber 602 operable for continuous combustion. For example, the combustion chamber may include a burner supplied with a fuel to generate heat. The combustion process may be a continuous combustion process. Hence, similar to the example of Figure 20, the first heat exchanger 302a is operable to add heat energy to fluid passing through it.

35 There may be provided a combustion chamber 602a, 602b for each fluid circuit. The chambers 602a, 602b may be fluidly isolated from one another. Hence a first

combustion chamber 602a may be provided in fluid communication with duct 300a, and a second combustion chamber 602b may be provided in fluid communication with duct 300b. The combustion chambers 602a, 602b may be provided within a single combustion chamber unit 602.

5

Operation of the device 700 will now be described.

Stage 1

10 In the example as shown in Figure 22 the working fluid (for example air) enters the second rotor sub-chambers 234b2, 234a2 via the fourth port 116b and eighth port 116d respectively.

The working fluid is then displaced/compressed/metered by the action of the second
15 rotor pistons 222a, 222b, driven by expansion of working fluid in the first rotor first chambers 134a, 134b (described below in stage 3), and exits via the third port 116a and seventh port 116c respectively.

At the same time as working fluid is being drawn into the sub-chambers 234b2, 234a2
20 working fluid is being exhausted from sub-chambers 234b1, 234a1 through the third port 116a and seventh port 116c respectively.

At the same time as working fluid is being exhausted from the sub-chamber 234b2, 234b1, working fluid is being drawn into sub-chambers 234b1, 234a1 through the
25 fourth port 116b and eighth port 116d respectively.

Stage 2

In the example as shown in Figure 22 working fluid then travels from the second rotor
30 second chambers 234b, 234a along ducts 300a2, 300b2 and enters the first heat exchanger 302a, which is configured as a **heat source**.

The working fluid may be mixed with fuel in the combustor 603 to be in part burned and in part heated, increasing pressure, before being passed to the second port 114b
35 and sixth port 114d of the first rotor 119 (i.e. the first fluid flow section 111, or “expansion” section).

Hence the working fluid absorbs heat from the heat source and then leaves the first heat exchanger 302a and travels along ducts 300a1, 300b1 before entering the first rotor chambers 134a, 134b.

5

Stage 3

In the example as shown in Figure 22 the working fluid travels along ducts 300a1, 300b1 and enters the sub-chambers 134a2, 134a2 of the first rotor 119 via the second port 114b and sixth port 114d where it expands.

10

At the same time as working fluid is entering and expanding in the sub-chambers 134a2, 134b2, working fluid is being exhausted from sub-chambers 134a1, 134b1 via the first port 114a and fifth port 114c respectively.

15

As the first rotor 119 continues to rotate, the working fluid is exhausted from the sub-chambers 134a2, 134b2 via the first port 114a and fifth port 114c, and more working fluid enters the sub-chambers 134a1, 134b1 via the second port 114b and sixth port 114d where it expands.

20

Hence the exhaust gas expands sequentially in the sub-chambers 134a1, 134a2, 134b1, 134b2 of the first rotor chambers 134a, 134b (hence the gas decreases in pressure and increases in volume), so that work is done by the gas on the first rotor pistons 122a, 122b to urge the first piston 122a across the chamber 134a (operating as an expansion chamber) and to urge the second piston 122b across the chamber 134b (operating as an expansion chamber), which drives the first and second pistons 122a, 122b across their respective chambers 134a, 134b to draw in a further portion of air to start the process again.

25

Hence the sequential expansion of the working fluid in the first rotor sub-chambers 134a1, 134a2, 134b1, 134b2 induces a force to thereby cause pivoting of the first rotor 119 about its second rotational axis 132, and to cause rotation of the first rotor about its first rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

35

Hence since the shaft 118 of the expansion section (i.e. first fluid flow section 111) and shaft 218 of the displacement section (i.e. second fluid flow section 115) are coupled so they rotate together, rotation of the second rotor 219 is driven by the expansion of the working fluid in the first rotor chamber 134a,b (i.e. in sub-chambers 134a1, 134a2, 134b1, 134b2).

EXAMPLE 7 - SINGLE UNIT, OPEN LOOP, HEAT ENGINE

Figure 23 illustrates a third example of an open loop heat engine (motor unit) apparatus 800 according to the present disclosure, which includes many features in common with, or equivalent to, the example of Figure 21, and are hence referred to with the same reference numerals.

The example of Figure 23 differs from the example of Figure 21 in the following ways.

The fourth port 116b is configured to be in fluid communication with a source of hot gas, for example flue or exhaust gas. Hence in this example, the working fluid may comprise a source of hot gas, for example flue or exhaust gas.

The first heat exchanger 302a comprises a chamber 810 operable to permit fluid flow between the displacement section (in this example the second fluid flow section 115) and the expansion section (in this example the first fluid flow section 111), and an injector 812 is configured to inject a cryogenic medium into the chamber 810 such that heat energy is transferred from the fluid to the cryogenic media to cause it to increase in pressure. Hence the first heat exchanger 302a is operable to remove heat energy from working fluid passing through it in return for an increase in pressure of the cryogenic medium, and is thus configured as a **heat sink**.

The cryogenic fluid may be a gas in normal atmospheric conditions stored in a compressed liquid or state, which requires heat input during its phase change back to a gas, for example liquid nitrogen or liquid air. In the present disclosure the term 'cryogenic fluid' is intended to mean any medium stored in a low temperature liquid or gas state which will expand, perhaps aggressively, with introduction of heat.

The volumetric capacity of the first rotor second chamber 134b may be substantially the **same, less, or greater than** the volumetric capacity of the first rotor first chamber 134a.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the first fluid flow section 111.

5

For example the volumetric capacity of the first rotor second chamber 134b may be **at most half** the volumetric capacity of the first rotor first chamber 134a.

Alternatively the volumetric capacity of the first rotor second chamber 134b may be **at**
10 **least twice** the volumetric capacity of the first rotor first chamber 134a.

Hence in the present example, this provides an expansion ratio within the confines of a single device (for example as shown in Figure 17).

15 This may be achieved by providing the first rotor first chamber 134a as a different width than the first rotor second chamber 134b, with the first piston 122a consequentially having a different width than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chambers 134a, 134b and swept volume of the
20 pistons 122a, 122b will differ.

As shown in Figure 17, which shows just the rotor assembly 116, the different volumes may be achieved by providing the first rotor first chamber 134a as **wider** than the first rotor second chamber 134b, with the first piston 122a consequentially being
25 **wider** than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chamber 134a will be **greater than** the volume of chamber 134b, and hence the swept volume of the piston 122a will be **greater than** piston 122b.

30 Operation of the device 800 will now be described.

Stage 1

In the example as shown in Figure 23 the working fluid enters the sub-chamber 134b2
35 via the fourth port 116b.

The working fluid is then displaced/metered by the action of the piston 122b, driven by expansion of working fluid in the first chamber 134a (described below), and exits via the third port 116a.

- 5 At the same time as working fluid is being drawn into the sub-chamber 134b2, working fluid is being exhausted from sub-chamber 134b1 through the third port 116a.

At the same time as working fluid is being exhausted from the sub-chamber 134b2, working fluid is being drawn into sub-chamber 134b1 through the fourth port 116b.

10

Stage 2

- In the example as shown in Figure 23 working fluid then travels from the second chamber 134b along duct 300a2 and enters the first heat exchanger 302a, which is
15 configured as a **heat sink**.

- The hot gas may be mixed with the cryogenic medium in the chamber 810 such that heat is transferred to the cryogenic medium causing it to increase in pressure before being passed to the second port 114b of the expansion section (in this example, the
20 first fluid flow section 111).

- Hence the cryogenic medium is mixed with, and absorbs heat from, the working fluid and then leaves the first heat exchanger 302a and travels along duct 300a1 before entering the first chamber 134a.

25

Stage 3

- In the example as shown in Figure 23 the working fluid travels along duct 300a1 and enters the sub-chamber 134a2 of the rotor via the second port 114b where it expands.

30

At the same time as working fluid is entering and expanding in the sub-chamber 134a2, working fluid is being exhausted from sub-chamber 134a1 via the first port 114a.

As the rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134a2 via the first port 114a, and more working fluid enters the sub-chamber 134a1 via the second port 114b where it expands.

- 5 Hence the mix of exhaust and cryogen expands sequentially in the sub-chambers 134a1, 134a2 of the first chamber 134a (hence the gas decreases in pressure and increases in volume), so that work is done by the gas on the first piston 122a to urge the first piston 122a across the chamber 134a (operating as an expansion chamber), which drives the second piston 122b across the second chamber 134a to draw in and
10 compress/displace a further portion of working fluid to start the process again.

Hence the sequential expansion of the working fluid in the rotor sub-chambers 134a1, 134a2 induces a force to thereby cause pivoting of the rotor about its second rotational axis 132, and to cause rotation of the rotor about its first
15 rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

EXAMPLE 8 - DOUBLE UNIT, OPEN LOOP, HEAT ENGINE

Figure 24 illustrates a fourth example of an open loop heat engine motor unit
20 apparatus 900 according to the present disclosure, which includes many features in common with, or equivalent to, the example of Figure 22, and are hence referred to with the same reference numerals.

The example of Figure 24 differs from the example of Figure 22 in that the second
25 rotor flow inlets (which in this example are the fourth port 116b and eighth port 116d are configured to be in fluid communication with a source of hot gas, for example flue or exhaust gas.

Hence in this example, the working fluid may comprise a source of hot gas, for
30 example flue or exhaust gas.

Akin to Examples 2, 4, 6, the first chamber 134a and second chamber 134b of the first rotor 119 (i.e. **first fluid flow section 111**) have substantially the same volumetric capacity (i.e. the same volume) as each other. The first chamber 234a and second
35 chamber 234b of the second rotor 219 (i.e. the second **fluid flow section 115**) have substantially the same volumetric capacity (i.e. the same volume) as each other.

However, the volumetric capacity (i.e. volume) of the first rotor chambers 134a, 134b (first fluid flow section 111) may be substantially the **same, less, or greater than** the volumetric capacity (i.e. volume) of the second rotor chambers 234a, 234b (second fluid flow section 115).

5

That is to say, in the present example, the volumetric capacity (i.e. volume) of the rotor chambers 234a, 234b of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity (i.e. volume) of the rotor chambers 134a, 134b first fluid flow section 111.

10

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at most half** the volumetric capacity of the first fluid flow section 111.

15

Alternatively, in the present example, the volumetric capacity of the second fluid flow section 115 may be **at least twice** the volumetric capacity of the first fluid flow section 111.

20

Also, and akin to the example of Figure 23, the first heat exchanger 302a comprises a chamber 810 operable to permit fluid flow between the displacement section (in this example the second rotor 219, i.e. the second fluid flow section 115) and the expansion section (in this example the first rotor 119, i.e. the first fluid flow section 111), and an injector 812 is configured to inject a cryogenic medium into the chamber 810 such that heat energy is transferred from the fluid to the cryogenic media to cause it to increase in pressure. Hence the first heat exchanger 302a is operable to remove heat energy from working fluid passing through it in return for an increase in pressure of the cryogenic medium, and is thus configured as a **heat sink**.

25

30

There may be provided a mixing chamber 810a, 810b and injector 812 for each fluid circuit. The chambers 810a, 810b may be fluidly isolated from one another. Hence a first cryogenic chamber 810a may be provided in fluid communication with duct 300a, and a second cryogenic chamber 810b may be provided in fluid communication with duct 300b. The mixing chambers 810a, 810b may be provided within a single mixing chamber unit 810.

35

Operation of the device 900 will now be described.

Stage 1

In the example as shown in Figure 23 the working fluid enters the second rotor sub-
5 chambers 234b2, 234a2 via the fourth port 116b and eight port 116d respectively.

The working fluid is then displaced/compressed/metered by the action of the second
rotor pistons 222a, 222b, driven by expansion of working fluid in the first rotor first
chambers 134a, 134b (described below in stage 3), and exits via the third port 116a
10 and seventh port 116c respectively.

At the same time as working fluid is being drawn into the sub-chambers 234b2, 234a2
working fluid is being exhausted from sub-chambers 234b1, 234a1 through the third
port 116a and seventh port 116c respectively.

15

At the same time as working fluid is being exhausted from the sub-chamber 234b2,
234b1, working fluid is being drawn into sub-chambers 234b1, 234a1 through the
fourth port 116b and eight port 116d respectively.

20 Stage 2

In the example as shown in Figure 24 working fluid then travels from the second rotor
second chambers 234b, 234a along ducts 300a2, 300b2 and enters the first heat
exchanger 302a, which is configured as a **heat sink**.

25

The hot gas may be mixed with the cryogenic medium in the mixing chamber 810
such that heat is transferred to the cryogenic medium causing it to increase in
pressure before being passed to the second port 114b and sixth port 114d of the first
rotor 119 (i.e. the first fluid flow section 111, or “expansion” section).

30

Hence the cryogenic medium is mixed with, and absorbs heat from, the working fluid
and then leaves the first heat exchanger 302a and travels along ducts 300a1, 300b1
before entering the first rotor chambers 134a, 134b.

35

Stage 3

In the example as shown in Figure 24 the working fluid travels along ducts 300a1, 300b1 and enters the sub-chambers 134a2, 134a2 of the first rotor 119 via the second port 114b and sixth port 114d where it expands.

At the same time as working fluid is entering and expanding in the sub-chambers 134a2, 134b2, working fluid is being exhausted from sub-chambers 134a1, 134b1 via the first port 114a and fifth port 114c respectively.

10

As the first rotor 119 continues to rotate, the working fluid is exhausted from the sub-chambers 134a2, 134b2 via the first port 114a and fifth port 114c, and more working fluid enters the sub-chambers 134a1, 134b1 via the second port 114b and sixth port 114d where it expands.

15

Hence the exhaust gas expands sequentially in the sub-chambers 134a1, 134a2, 134b1, 134b2 of the first rotor chambers 134a, 134b (hence the gas decreases in pressure and increases in volume), so that work is done by the gas on the first rotor pistons 122a, 122b to urge the first piston 122a across the chamber 134a (operating as an expansion chamber) and to urge the second piston 122b across the chamber 134b (operating as an expansion chamber), which drives the first and second pistons 122a, 122b across their respective chambers 134a, 134b to draw in a further portion of air to start the process again.

20

Hence the sequential expansion of the working fluid in the first rotor sub-chambers 134a1, 134a2, 134b1, 134b2 induces a force to thereby cause pivoting of the first rotor 119 about its second rotational axis 132, and to cause rotation of the first rotor about its first rotational axis 130. This rotational force drives the generator 408 via the shaft 118.

30

Hence since the shaft 118 of the expansion section (i.e. first fluid flow section 111) and shaft 218 of the displacement section (i.e. second fluid flow section 115) are coupled so they rotate together, rotation of the second rotor 219 is driven by the expansion of the working fluid in the first rotor chamber 134a,b (i.e. in sub-chambers 134a1, 134a2, 134b1, 134b2).

35

EXAMPLE VARIANTS OF DOUBLE UNITS

5 In an alternative double unit examples (for example variants of Examples 2 (Figure 16), Example 4 (Figure 20), Example 6 (Figure 22) and Example 8 (Figure 24), the first rotor first chamber 134a may have a volumetric capacity substantially **less than** or substantially **greater than** the volumetric capacity of the first rotor second chamber 134b. Additionally or alternatively, the second rotor second
10 chamber 234b may have a volumetric capacity substantially **less than** or substantially **greater than** the volumetric capacity of the second rotor first chamber 234a.

For example, the first rotor first chamber 134a may have a volumetric capacity of **at most half** or **at least twice** the volumetric capacity of the first rotor second
15 chamber 134b. Additionally or alternatively, the second rotor second chamber 234b may have a volumetric capacity of **at most half** or **at least twice** the volumetric capacity of the second rotor first chamber 234a.

Such an example provides a multi stage device, or two working fluid circuits with
20 different expansion ratios through a common system.

Ducts 300a, 300b and ducts 304a, 304b have been illustrated as discrete circuits. However duct 300a and duct 300b may, at least in part, be combined to define a common flow path which passes through heat exchanger 302. Likewise duct 304a
25 and duct 304b may, at least in part, be combined to define a common flow path which passes through heat exchanger 306. Alternatively the ducts 300a, 300b may pass through entirely separate heat exchanger units 302 having different, or the same, heat capacities as each other. Likewise alternatively the ducts 304a, 304b may pass through entirely separate heat exchanger units 306 having different, or the same, heat
30 capacities as each other.

In the preceding examples, drive shafts 118, 218 are described as being rigidly/directly linked and so they operate at the same rotational speed as each other to provide lossless operation between them. However, in an alternative example the
35 first shaft 118 and second shaft 218 may be coupled by mechanical (for example by a

gear box) or virtual means (for example by an electronic control system) so they may rotate at different speeds relative to one another.

5 The core of the apparatus of the present disclosure is a true positive displacement unit which offers up to a 100% internal volume reduction per revolution. It is operable to simultaneously 'push' and 'pull' the piston 122 across its chamber, so for example, in the same chamber can create a full vacuum on one side of a piston whilst simultaneously producing compression and/or displacement on the other.

10 Coupling of the displacement section and expansion sections (i.e. direct drive between the **first fluid flow section 111** and **second fluid flow section 115**, whether part of the same rotor as shown in Figures 15, 19, 21, 23 or linked rotors as shown in Figures 16, 20, 22, 24) means that mechanical losses are minimised relative to examples of the related art, as well as enabling recovery from the processes in
15 each section to help drive the other side.

Hence significantly higher expansion or compression ratios are achievable than with examples of the related art. For example, a single stage expansion or compression in excess of 10:1 is achievable, which is significantly greater than with examples of the
20 related art.

Positive displacement using both continuous (and simultaneous) expansion and displacement/compression on opposing faces of a single piston provides for a device which is inherently more efficient than devices of the related art.

25

This also means the device can perform efficient operation under varied loads and varied speeds, which is not possible with a conventional arrangement (for example those including an axial flow turbine). This allows for harvesting of energy at input levels not previously achievable.

30

The apparatus of the present invention can be scaled to any size to suit different capacities or power requirements, its dual output drive shaft also makes it easy to mount multiple drives on a common line shaft, thereby increasing capacity, smoothness, power output, offering redundancy, or more power on demand. Hence a
35 heat engine device of the present disclosure could be carried on a vehicle to provide

additional drive or electrical generation to supplement the output of a larger engine with little weight penalty.

5 The device inherently has an extremely low inertia which offers low load and quick and easy start-up.

With respect to the heat pumps (examples 1, 3) of Figures 15, 19 and heat engines (examples 2, 4) of Figures 16, 20, these arrangements are especially advantageous as they are inherently thermodynamically reversible. Hence the devices may operate
10 with working fluids at different phases (for examples in different phases) in either direction. Thus apparatus according to the present invention are more applicable to a wider range of uses than devices of the related art.

Thus there is provided a mechanically simple and scalable apparatus for refrigeration
15 or generation purposes. Additionally, such heat pumps or heat engines according to the present disclosure may be highly efficient in either mode of operation.

With respect to the heat engines (Examples 2, 4 to 8) of Figures 16, 21 to 24, the apparatus of the present disclosure provides a technical solution with a high
20 thermodynamic efficiency, which can operate at low speed. Operation at low speed is advantageous as it enables electricity generation at speeds closer to or at the required frequency, thereby reducing reliance, and losses due to, gearing and signal inversion.

25 The rotor 14 and housing 12 may be configured with a small clearance between them thus enabling oil-less and vacuum operation, and/or obviate the need for contact sealing means between rotor 16 and housing 12, thereby minimising frictional losses.

Where applications which would benefit from such, the shaft 18, 118, 218 may extend
30 out of both sides of the rotor housing to be coupled to a powertrain for driving device and/or an electrical generator.

EXAMPLE 9 – SINGLE UNIT, OPEN LOOP, AIR CYCLE

35 Figure 25 illustrates an example of an open loop air cycle apparatus 1000 according to the present disclosure, which includes many features in common, or equivalent to,

the example of Figure 21, and are hence referred to with the same reference numerals.

The system is an open loop, with no connection between the first port 114a and the fourth port 116b. That is to say, the second duct 304a and second heat exchanger 306a not present, and hence the first port 114a and the fourth port 116b are isolated from one another.

A motor 308 is coupled to the first shaft portion 118 to drive the rotor 119 around the first rotational axis 130.

In the present example, the first chamber 134a and piston 122a hence provide a **first fluid flow section 111**, which in this example are operable as a compressor or displacement pump. Hence the **first fluid flow section 111** is configured for the passage of fluid between the first port 114a and second port 114b via the first chamber 134a.

Also the second chamber 134b and piston 122b hence provide a **second fluid flow section 115**, which in this example are operable as a metering section or expansion section. Hence the **second fluid flow section 115** is configured for the passage of fluid between the third port 116a and fourth port 116b via the second chamber 134.

The first port 114a may be in fluid communication with a source of ambient air, for example open to atmosphere. Hence in this example, the working fluid may comprise air. However, in other examples, the fluid may be any suitable fluid.

The first heat exchanger 302a may be in thermal communication with any suitable heat source or a substance to be cooled. In one example, a substance, for example a second fluid to be cooled, is passed through a duct 303 in the first heat exchanger 302a, such that the substance may transfer heat to the working fluid and the substance is cooled as it passes through the first heat exchanger 302. The substance may be any medium that may flow and be cooled, such as a fluid such as air, gas or liquid. In some examples, the substance is medium for cooling personal climatic conditions, for example to provide temperature control in buildings. In other examples, the substance may be used to cool or heat electronics systems.

Hence, the first heat exchanger 302a is a **heat source** configured to **add** heat energy to working fluid passing through it.

The volumetric capacity of the first chamber 134a may be substantially the **same**,
5 **less, or greater than** the volumetric capacity of the second chamber 134b.

That is to say, in the present example, the volumetric capacity of the second fluid flow section 115 may be the **same, less, or greater than** the volumetric capacity of the first fluid flow section 111. In this example, the volumetric capacity of the second fluid
10 flow section 115 is preferably greater than the volumetric capacity of the first fluid flow section 111.

For example the volumetric capacity of the second chamber 134b may be **at most half** the volumetric capacity of the first rotor first chamber 134a.

15

In other examples, the volumetric capacity of the second chamber 134b may be at most 20% of the volumetric capacity of the first rotor first chamber 134a

Alternatively the volumetric capacity of the first rotor second chamber 134b may be **at**
20 **least twice** the volumetric capacity of the first rotor first chamber 134a.

Alternatively the volumetric capacity of the first rotor second chamber 134b may be **at least three times** the volumetric capacity of the first rotor first chamber 134a.

25 Hence in the present example, this provides an expansion ratio within the confines of a single device (for example as shown in Figure 17).

This may be achieved by providing the first chamber 134a as a different width than the second chamber 134b, with the first piston 122a consequentially having a different
30 width than the second piston 122b. Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the chambers 134a, 134b and swept volume of the pistons 122a, 122b will differ.

The different volumes may be achieved by providing the second chamber 134b as
35 **wider** than the first chamber 134a, with the second piston 122b consequentially being **wider** than the first piston 122a.

Hence although the pistons will pivot, and hence travel, to the same extent around the second rotational axis 132, the volume of the second chamber 134b will be **greater than** the volume of the first chamber 134a, and hence the swept volume of the piston 5 122b will be **greater than** piston 122a.

Since the first fluid flow section 111 (in this example a displacement/compressor/pump section) and second fluid flow section 115 (in this example a metering/expansion section) are two sides of the same rotor, the rotation of 10 the rotor 119 is driven both by the motor and the metering/expansion of the fluid in the second chamber 134b (i.e. in sub-chambers 134b1, 134b2).

Operation of the device 1000 will now be described.

15 **Stage 1**

In the example shown in Figure 25, the working fluid (for example air) enters the sub-chamber 134a1 via the first port 114a.

20 The working fluid is then displaced/compressed/metered by the action of the piston 122a, driven by the motor 308 and the expansion of working fluid in the second chamber 134b (described below in stage 3), and exits via the second port 114b.

At the same time as working fluid is being drawn into the sub-chamber 134a1, working 25 fluid is being exhausted from sub-chamber 134a2 through the second port 114b.

At the same time as working fluid is being exhausted from the sub-chamber 134a2, working fluid is being drawn into sub-chamber 134a1 through the first port 114a.

30 **Stage 2**

In the example as shown in Figure 25, the working fluid then travels from the first chamber 134a along duct 300a1 and enters the first heat exchanger 302a, which is configured as a **heat source**. Hence heat is added to the working fluid as it passes 35 through the first heat exchanger 302a.

A substance, such as air, gas or liquid may also be passed through the heat exchanger 302a, via a separate inlet and acts to transfer heat to the working fluid. Put another way, a substance enters the heat exchanger 302a at a first temperature and leaves the heat exchanger at a second temperature, wherein the second temperature is lower than the first temperature. The heat from the substance is transferred to the working fluid. Hence the working fluid absorbs heat from the heat source (for example, the substance) and then leaves the first heat exchanger 302a and travels along duct 300a2 before entering the second chamber 134b.

10 Stage 3

In the example as shown in Figure 25 the working fluid exits the first heat exchanger 302a via the duct 300a2. The pressure of the working fluid is held at a relatively low pressure in the duct 300a2, for example below atmospheric pressure.

15

The working fluid travels along duct 300a2 and enters the sub-chamber 134b1 of the rotor via the third port 116a and the working fluid is expanded.

At the same time as working fluid is entering and expanding in the sub-chamber 134b1, working fluid is being exhausted from sub-chamber 134b2 via the fourth port 116b.

As the rotor 119 continues to rotate, the working fluid is exhausted from the sub-chamber 134b2 via the fourth port 116b, and more working fluid enters the sub-chamber 134b1 via the third port 116a where it expands.

Hence the exhaust gas expands sequentially in the sub-chambers 134b1, 134b2 of the second chamber 134b (hence the fluid decreases in pressure and increases in volume). In one example, this expansion results in a negative pressure being maintained in the duct 300a, which in turn contributes to driving the first piston 122a across chamber 134a introducing a further portion of air to start the process again. The expansion of the exhaust gas in sub-chambers 134b1, 134b2 may result in work being done by the fluid on the second piston 122b to urge the first piston 122b across the chamber 134b (operating as an expansion chamber), which drives the first piston 122a across the first chamber 134a to draw in and compress a further portion of air to start the process again.

Hence the sequential expansion of the working fluid in the rotor sub-chambers 134b1, 134b2 induces a force to thereby cause pivoting of the rotor about its second rotational axis 132, and to cause rotation of the rotor about its first rotational axis 130. This rotational force is in addition to the force provided by the motor 308.

Hence, the system shown in Figure 25 is operable to work as an air source cold pump.

10

In use, the system of Figure 25 is reversible such that if the direction of the motor 308 is reversed, a positive pressure difference is created between the second fluid flow section 115 and the first fluid flow section 111. In this example, the heat exchanger 302 extracts heat from the fluid passing therethrough to heat a substance in duct 303. In this example, the system is an air source heat pump. Put another way, the motor 308 may be reversible. When the motor 308 is configured to drive the rotor 119 around the first rotational axis 130 in a first direction, the first heat exchanger 302a is operable to act as a heat source to transfer heat from the substance to the fluid.

20 As the system is reversible, when the motor is configured to drive the rotor 119 around the first rotational axis 130 in a second direction, opposite to the first direction, the first heat exchanger 302a is operable to act as a heat source to transfer heat from the fluid to the substance. In this example, the system is operable to work as an air source heat pump.

25

Figure 26 shows a part exploded view of an alternative example of a core 510 forming part of an apparatus according to the present disclosure. The core 510 comprises a housing 512 and rotor assembly 514. Figures 27A and 27B shows a side view and cross-sectional example of the housing 512 when it is closed around the rotor assembly 514.

30

In the example shown in Figure 26 the housing 512 is divided into three parts 512a, 512b and 512c which close around the rotor assembly 14. However, in an alternative example the housing may be fabricated from more than two parts, and/or split differently to that shown in Figure 26. In this example, the housing 512 comprises a first housing end 512a and a second housing end 512b, which may be coupled to a

35

spacer ring 512c in use. In some examples, the first housing end 512a and the second housing end 512b may be clamped to the spacer ring 512c. In this example, the outer race of a bearing 529 is coupled to the spacer ring 512c. In one example, the outer race of a bearing is formed on the inner surface of the spacer ring 512c or
5 housing 512.

The piston member 522 and the axle 520 are substantially identical to the piston member 22 and the axle 20 shown in Figures 8 to 10. In this example, one or more bearings 521 may be provided on the rotor 516 to enable the axle 520 to rotate
10 relative to the rotor 516. A bearing pin 523 may be placed in the one or more bearings 521 to axially fix the axle 520 relative to the rotor 516, whilst enabling rotational movement about the axis 532. In some examples, a cap 525 may be placed over the bearing pin 523 and bearing 521.

15 In this example, there may be an orbital slewing ring 527A, 527B located around the outside of the rotor 516. In the example shown, the orbital slewing ring comprises a first ring 527A and a second ring 527B configured to couple with the inner race of a bearing 529. In some examples, the first ring 527A and a second ring 527B are configured to be clamped together to clamp at least part of the bearing 529
20 therebetween. In one example, the first guide feature (552) may comprise a stylus configured to be received in or coupled with the slewing ring (527).

In this example, the second guide feature 550 comprises the orbital slewing ring 527A, 527B, and the bearing 529, which may be made up of inner race, outer race
25 and rolling element.

In use, a first guide feature 552 may be mechanically coupled with the second guide feature 550. In some examples, the first guide feature 552 comprises a stylus configured to be received in the orbital slewing ring 527 so as to couple the rotor 516
30 to the orbital slewing ring 527A, 527B. . The bearing 529 forms a guide path to pivot the rotor 516 relative to the shaft 522 around axis 530.

As shown in Figures 27A and 27B, the guide path resulting from the coupling of the first guide feature 552 and the second guide feature 550 may describe a path around
35 (i.e. on, close to, and/or to either side of) a first circumference of the housing 512.

The provision of the bearing track formed from the first guide feature 552 and the second guide feature 550 reduces the friction and noise, vibration and harshness in the apparatus.

- 5 Bearing 529 may be in any form, ie with rolling, ball or other frictionless element or of a plain bearing type. The example shown is an angular contact back to back ball bearing pair.

10 In some examples, a back to back pair of angular contact bearings offers a higher speed tolerance, higher load tolerance, larger rolling element, track load is spread over a larger area rather than a single point. In addition, there reduced the dead space inside apparatus because there is little or no play as both sides of the bearing remain in permanent contact. Further, the bearing can be used to hold the rotor 516 on centre within the housing 512 so thermal growth is equal in each direction away
15 from the centre point.

The trend of the guide path defines a ramp, amplitude and frequency of the rotor 516 about the second rotational axis 532 in relation to the rotation of the first rotational axis 530, thereby defining a ratio of angular displacement of the chambers 534 in
20 relation to the radial reward from the shaft (or vice versa) at any point.

Put another way the attitude of the path directly describes the mechanical ratio/relationship between the rotational velocity of the rotor and the rate of change of volume of the rotor chambers 534a, 534b. That is to say, the trajectory of the path 550
25 directly describes the mechanical ratio/relationship between the rotational velocity of the rotor 516 and the rate of pivot of the rotor 516.

In this example the guide path , resulting from the coupling of the first guide feature 552 and the second guide feature 550 is at a 30 degree angle to vertical, in other
30 examples this angle may differ.

Attention is directed to all papers and documents which are filed concurrently with or previous to this specification in connection with this application and which are open to public inspection with this specification, and the contents of all such papers and
35 documents are incorporated herein by reference.

All of the features disclosed in this specification (including any accompanying claims, abstract and drawings), and/or all of the steps of any method or process so disclosed, may be combined in any combination, except combinations where at least some of such features and/or steps are mutually exclusive.

5

Each feature disclosed in this specification (including any accompanying claims, abstract and drawings) may be replaced by alternative features serving the same, equivalent or similar purpose, unless expressly stated otherwise. Thus, unless expressly stated otherwise, each feature disclosed is one example only of a generic

10

series of equivalent or similar features.

The invention is not restricted to the details of the foregoing embodiment(s). The invention extends to any novel one, or any novel combination, of the features disclosed in this specification (including any accompanying claims, abstract and drawings), or to any novel one, or any novel combination, of the steps of any method

15

or process so disclosed.

CLAIMS

- 1 A roticulating thermodynamic apparatus having a **first fluid flow section** comprising :

a first shaft portion which defines, and is rotatable about, a first rotational axis;

a first axle defining a second rotational axis, the first shaft portion extending through the first axle;

a first piston member provided on the first shaft portion, the first piston member extending from the first axle towards a distal end of the first shaft portion;

a first rotor carried on the first axle;

the first rotor comprising :

a first chamber,

the first piston member extending across the first chamber;

a first casing wall adjacent the first chamber,

a first port and second port provided in the housing wall and each in flow communication with the first chamber;

whereby :

the first rotor and first axle are rotatable with the first shaft portion around the first rotational axis; and

the first rotor is pivotable about the axle about the second rotational axis to permit the first rotor to pivot relative to the first piston member as the first rotor rotates about the first rotational axis;

such that the **first fluid flow section** is configured for the passage of fluid between the first port and second port via the first chamber;

the apparatus further comprising a **second fluid flow section**, which comprises :

a second chamber,

a second housing wall adjacent the second chamber,

a third port and a fourth port provided in the second housing wall and each in flow communication with the second chamber,

such that the **second fluid flow section** is configured for the passage of fluid between the third port and fourth port via the second chamber;

the second port being in fluid communication with the third port via a first heat exchanger.

2 An apparatus as claimed in claim 1 wherein :

the second rotational axis is substantially perpendicular to the first rotational axis.

3 An apparatus as claimed in claim 1 or claim 2 wherein

the first rotor comprises the second chamber;

the first piston member extends from one side of the first axle along the first shaft portion; and

a second piston member extends from the other side of the first axle along the first shaft portion,

across the second chamber

to permit the first rotor to pivot relative to the second piston member as the first rotor rotates about the first rotational axis.

- 4 An apparatus as claimed in claim 3 wherein

the fourth port is in fluid communication with the first port
via

a second heat exchanger.

- 5 An apparatus as claimed in any one of claims 2 to 4 wherein

the volumetric capacity of the first rotor first chamber is substantially the **same, less, or greater than** the volumetric capacity of first rotor second chamber.

- 6 An apparatus as claimed in any one of the preceding claims wherein

the first shaft portion, first axle and first piston member(s) are fixed relative to one another.

- 7 An apparatus as claimed in claim 1 or claim 2 which further comprises :

a second rotor comprising the second chamber,

a second shaft portion rotatable about the first rotational axis; and

the second shaft portion is coupled to the first shaft portion such that the first shaft portion and second shaft portion are rotatable together around the first rotational axis;

a second axle defining a third rotational axis, the second shaft portion extending through the second axle;

a second piston member provided on the second shaft portion, the second piston member extending from the second axle towards a distal end of the second shaft portion;

the second rotor carried on the second axle;

the second piston member extending across the second chamber;

whereby :

the second rotor and second axle are rotatable with the second shaft portion around the first rotational axis; and

the second rotor is pivotable about the second axle about the third rotational axis

to permit the second rotor to pivot relative to the second piston member as the second rotor rotates about the second rotational axis.

8 An apparatus as claimed in claim 7 wherein

the third rotational axis is substantially perpendicular to the first rotational axis.

9 An apparatus as claimed in claim 7 or claim 8 wherein

the first rotor comprises :

a first rotor second chamber,

the first piston member extending from one side of the first axle along the first shaft portion; and

a second piston member extends from the other side of the first axle along the first shaft portion,

across the first rotor second chamber

to permit the first rotor to pivot relative to the second piston member
as the first rotor rotates about the first rotational axis; and

the second rotor comprises :

a second rotor first chamber

the second piston member extends from one side of the second axle
along the second shaft portion; and

a second rotor first piston member extends from the other side of the
second axle along the second shaft portion,

across the second rotor first chamber

to permit the second rotor to pivot relative to the second rotor first
piston member as the second rotor rotates about the first rotational
axis;

wherein :

the first rotor second chamber is in flow communication with :

a fifth port and
a sixth port;

to thereby form part of the **first fluid flow section**, and configured for the
passage of fluid between the fifth port and sixth port via the first rotor second
chamber;

the second rotor first chamber is in flow communication with

a seventh port and

an eighth port;

to thereby form part of the **second fluid flow section**, and configured for the passage of fluid between the seventh port and eighth port via the second rotor second chamber;

wherein the sixth port is in fluid communication with the seventh port via the first heat exchanger.

10 An apparatus as claimed in any one of claims 7 to 9 wherein

the eighth port is in fluid communication with the fifth port via

a second heat exchanger.

11 An apparatus as claimed in claim 10 wherein

the fourth port is in fluid communication with the first port via the second heat exchanger.

12 An apparatus as claimed in any one of claims 9 to 11 wherein

the first chamber and second chamber of the first rotor have substantially the same volumetric capacity;

the first chamber and second chamber of the second rotor have substantially the same volumetric capacity;

the volumetric capacity of the first rotor chambers are substantially the **same, less, or greater than** the volumetric capacity of the second rotor chambers.

13 An apparatus as claimed in any one of claims 7 to 12 wherein

the first shaft portion is directly coupled to the second shaft portion such that

the first rotor and second rotor are operable to only rotate at the same speed as each other.

- 14 An apparatus as claimed in any one of claim 7 to 13 wherein

the second shaft portion, second axle and second piston member(s) are fixed relative to one another.

- 15 An apparatus as claimed in any one of claims 1 to 14 wherein

the first heat exchanger is operable as a **heat sink** to remove heat energy from fluid passing through it.

- 16 An apparatus as claimed claim 15 when dependent on claim 4 or claim 10 wherein

the second heat exchanger is operable as a **heat source** to add heat energy to fluid passing through it.

- 17 An apparatus as claimed in claim 15 wherein

the first heat exchanger comprises :

a chamber operable to permit fluid flow between the **first fluid flow section** and the **second fluid flow section**; and

an injector configured to inject a cryogenic medium into the chamber such that heat energy is transferred from the fluid to the cryogenic media.

- 18 An apparatus as claimed in any one of claims 1 to 14 wherein

the first heat exchanger is operable as a **heat source** to add heat energy to fluid passing through it.

- 19 An apparatus as claimed claim 15 when dependent on claim 4 or claim 10 wherein

the second heat exchanger is operable as a **heat sink** to remove heat energy from fluid passing through it.
- 20 An apparatus as claimed in claim 18 wherein

the first heat exchanger comprises :

a combustion chamber operable for continuous combustion.
- 21 An apparatus as claimed in any one of the preceding claims wherein

the or each chamber has an opening; and

the or each respective piston member extends from its respective axle across its corresponding chamber towards the corresponding opening.
- 22 An apparatus as claimed in any one of claims 1 to 21 wherein the apparatus further comprises :

a pivot actuator operable to pivot the rotor about the axle;

wherein the pivot actuator comprises :

a first guide feature provided on the rotor; and

a second guide feature provided on the housing;

the first guide feature operable to co-operate with the second guide feature to pivot the rotor about the axle.
- 23 An apparatus as claimed in any one of claims 1 to 21 wherein the apparatus further comprises :

a pivot actuator operable to pivot the rotor about the axle;

wherein the pivot actuator comprises :

a first guide feature on the rotor; and

a second guide feature on the housing;

the first guide feature being complementary in shape to the second guide feature; and

one of the first or second guide features defining a path which the other of the first or second guide feature, is constrained to follow;

the other of the first or second guide feature comprising a rotatable member which is operable to engage the path and rotate as it moves along the path.

- 24 An apparatus according to any of claims 22 or 23, wherein the second guide feature comprises a slewing ring configured to hold at least part of a bearing that is coupled with the housing.
- 25 An apparatus according to claim 24, wherein the first guide feature comprises a stylus configured to be coupled with the slewing ring.
- 26 An apparatus as claimed in claim 18, wherein the heat source comprises a substance passing through a duct in the first heat exchanger, wherein the apparatus provides cooling to the substance.
- 27 An apparatus as claimed in claim 26, wherein the fluid comprises air.
- 28 An apparatus as claimed in claims 26 or 27, wherein the apparatus comprises a motor coupled to the first shaft portion configured to drive the rotor around the first rotational axis.
- 29 An apparatus as claimed in claim 28, wherein the motor is reversible, such that when the motor is configured to drive the rotor around the first rotational axis in

a first direction, the first heat exchanger is operable to act as a heat source to transfer heat from the substance to the fluid, and wherein when the motor is configured to drive the rotor around the first rotational axis in a second direction, opposite to the first direction, the first heat exchanger is operable to act as a heat sink to transfer heat from the fluid to the substance.

- 30 An apparatus as claimed in any preceding claim, wherein the first fluid flow section and the second fluid flow section are two sides of the first rotor and wherein one of the first fluid flow section and the second fluid flow section is operable as a compressor and the other one of the first fluid flow section and the second fluid flow section is operable as an expander.