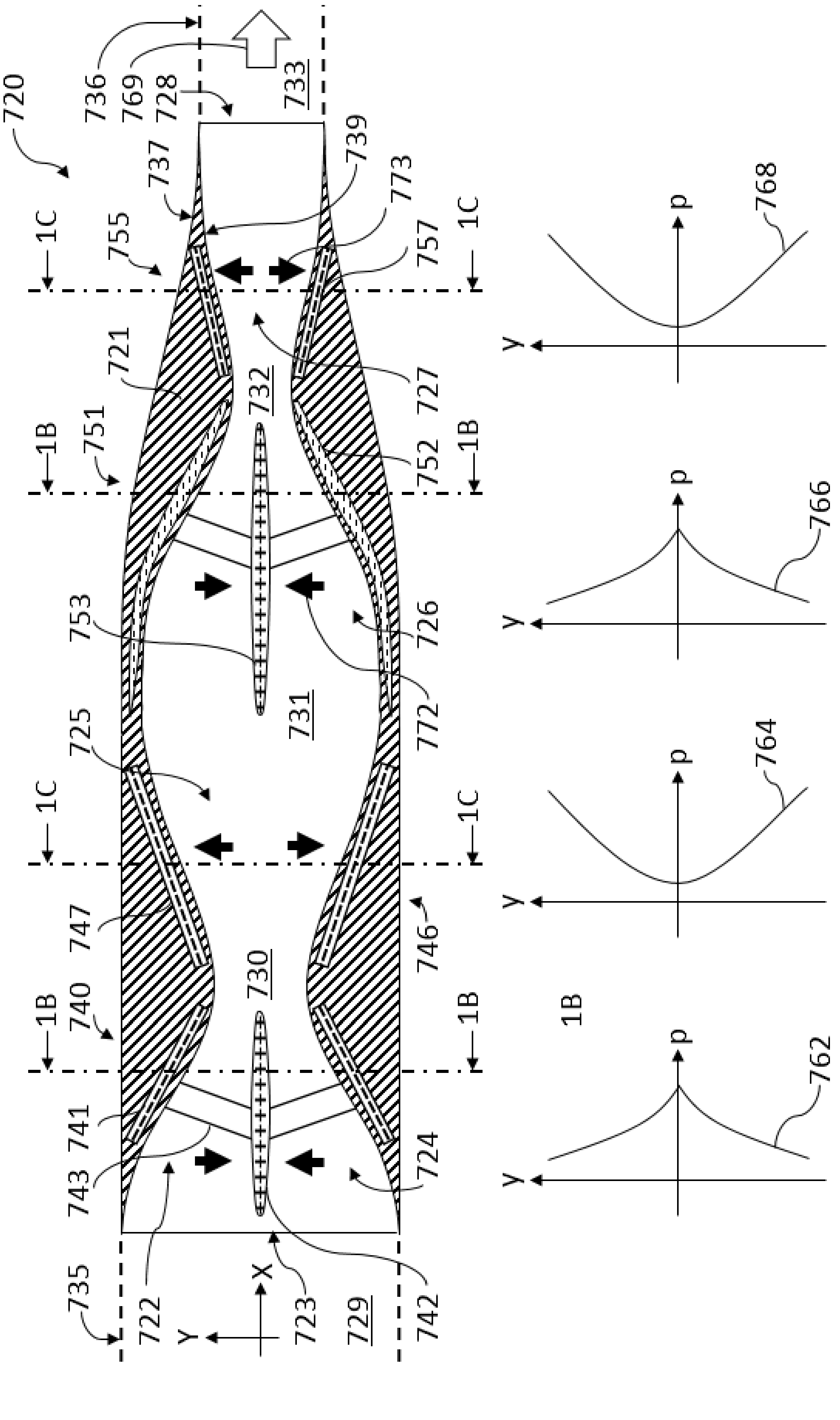
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733
737
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757
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1C
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732
727
751
752
1B
1B
753
726
731
772
725
1C
1C
747
746
730
740
1B
1B
741
743
724
722
735
X
Y
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729
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y
768
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y
766
p
y
764
1B
p
y
762

FIG. 1A

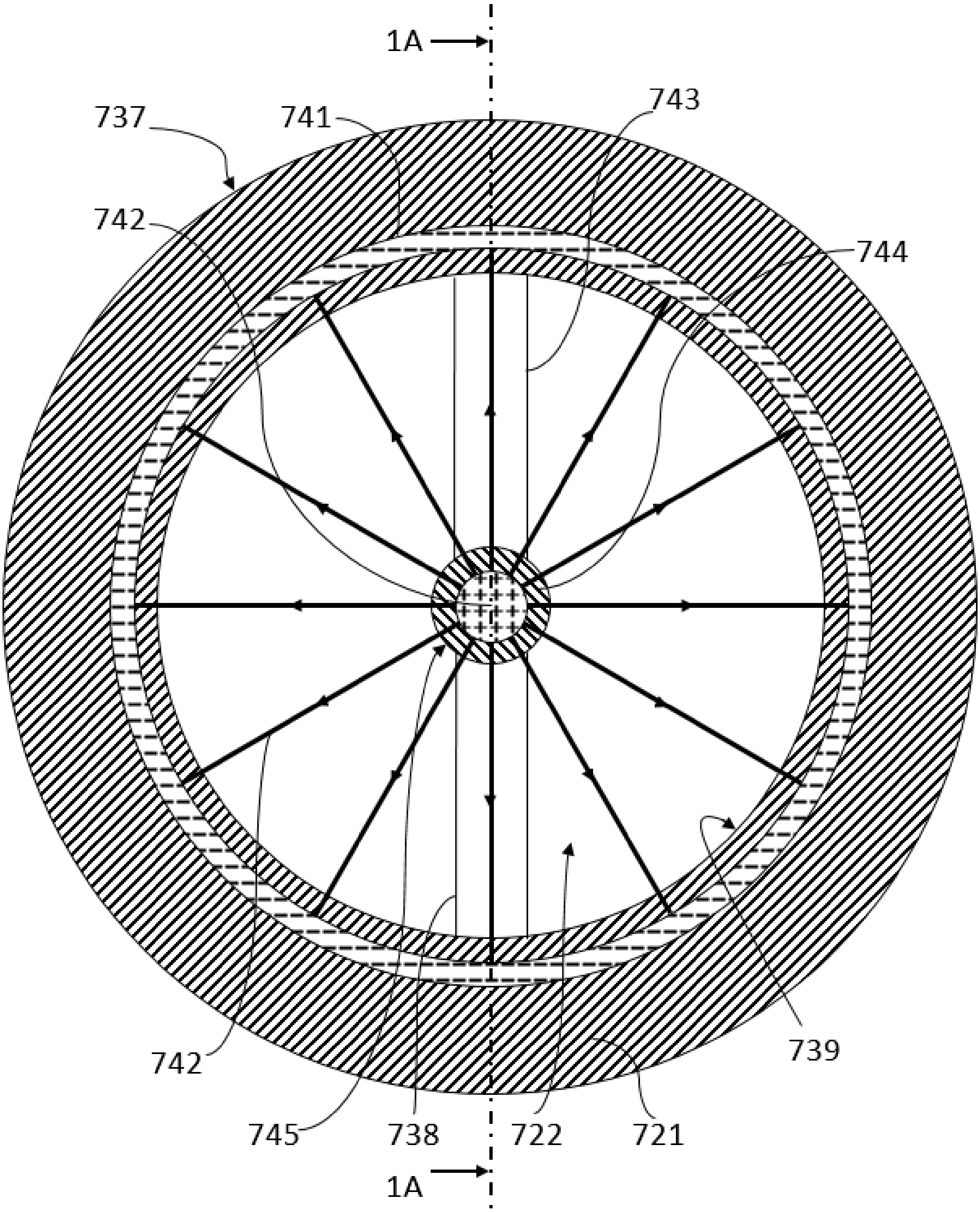


FIG. 1B

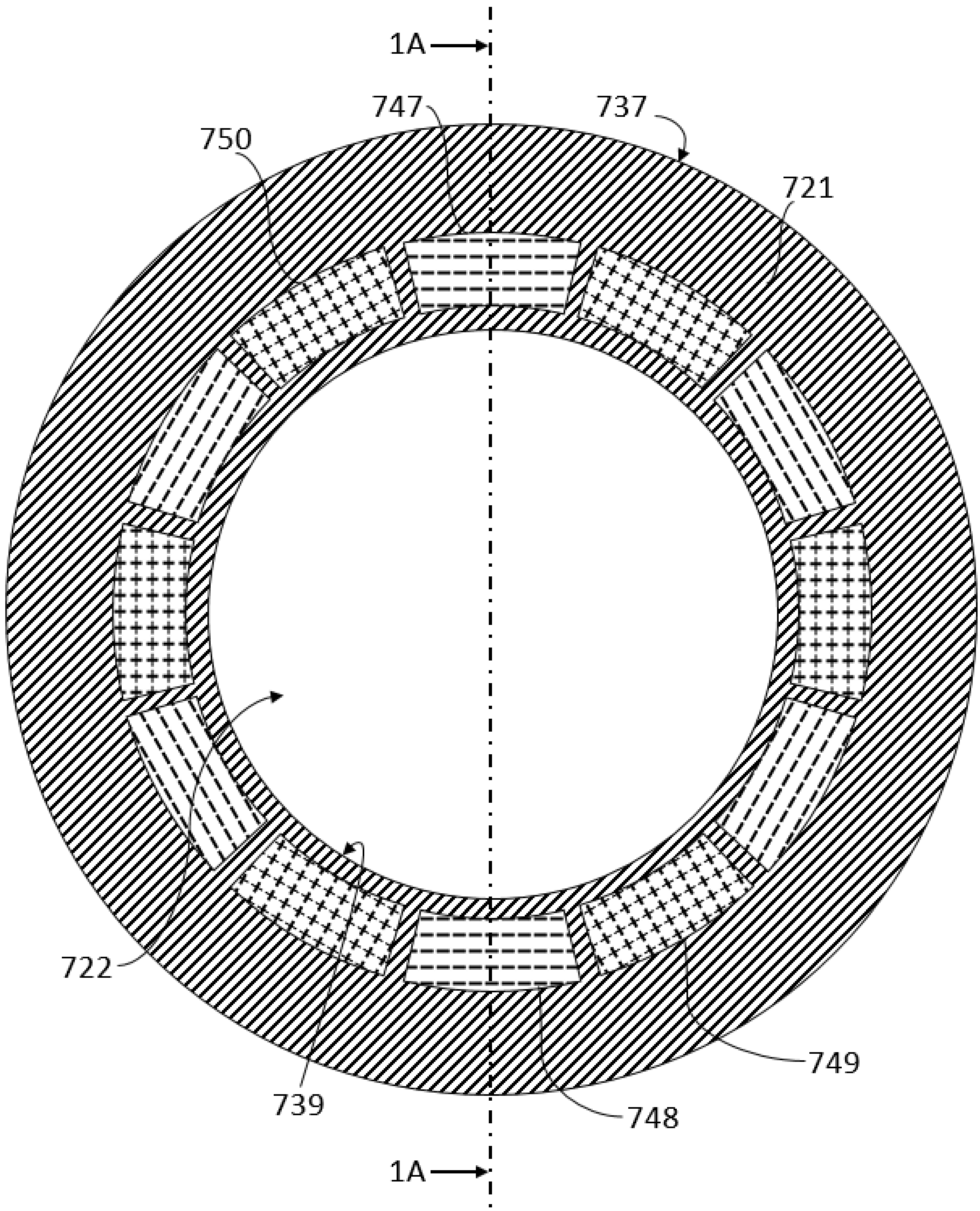
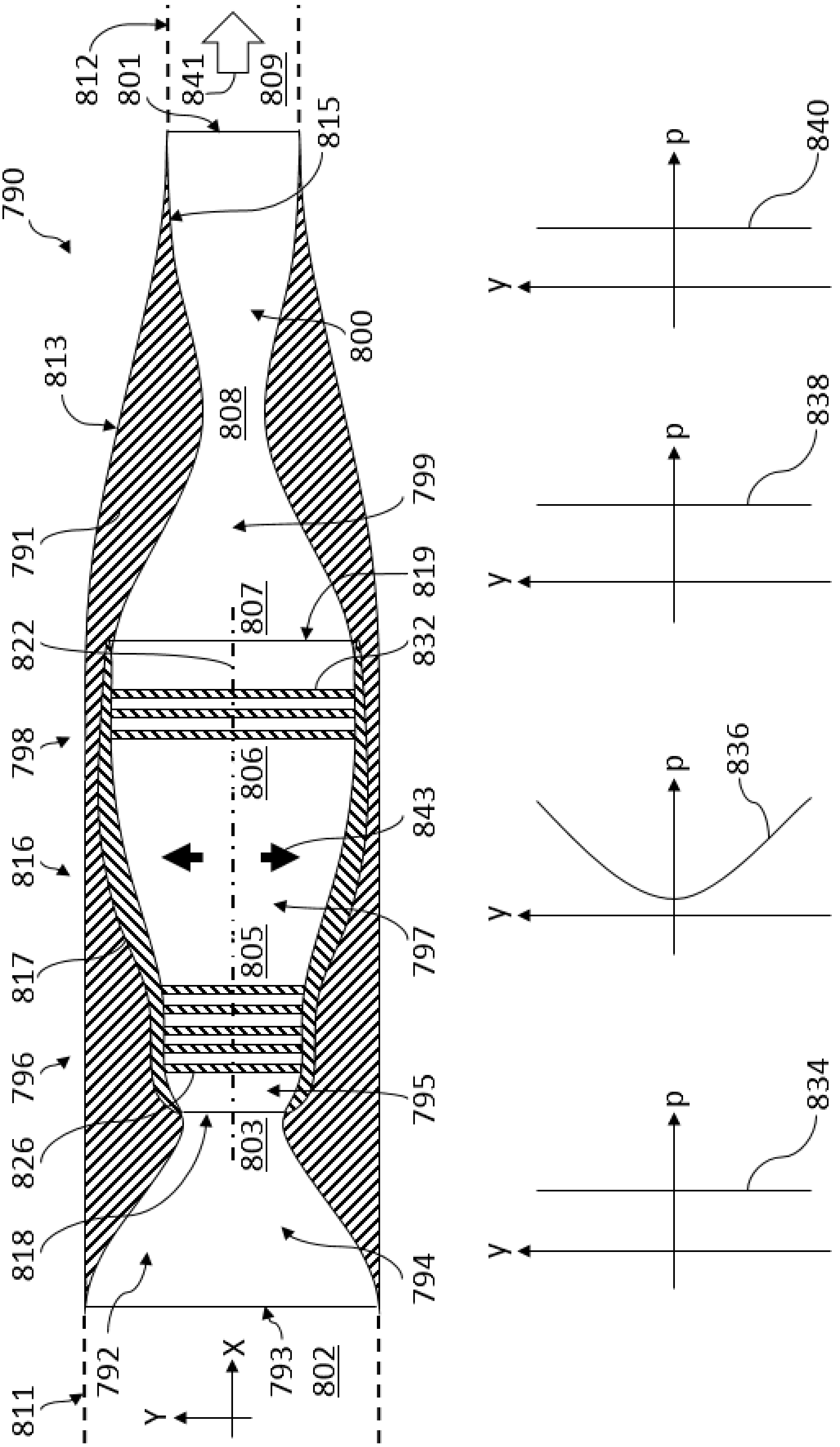


FIG. 1C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838
840

FIG. 2

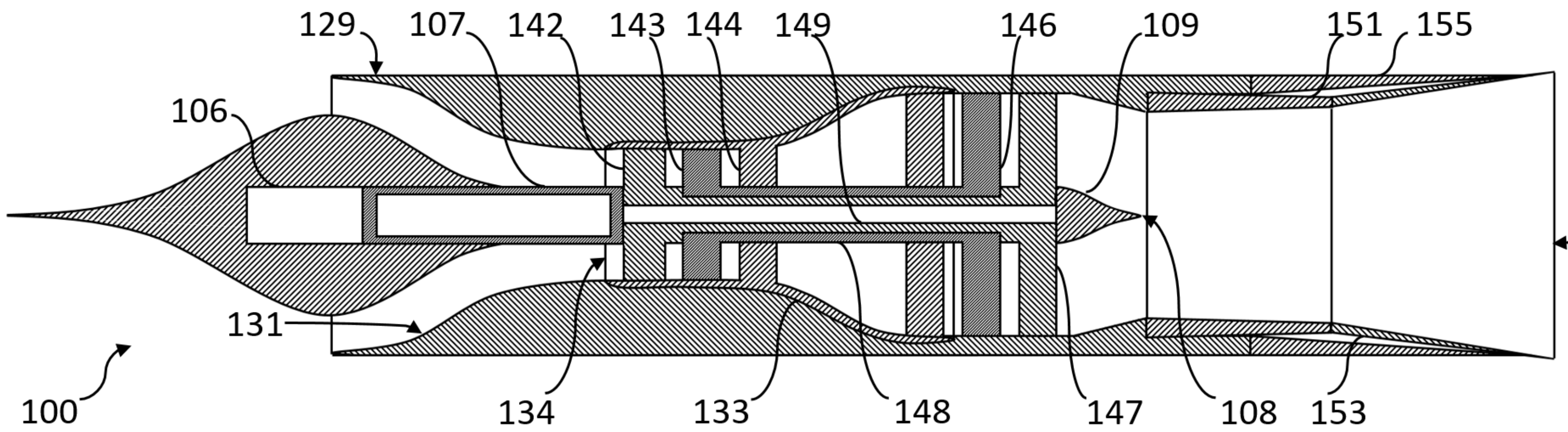
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FIG. 3A

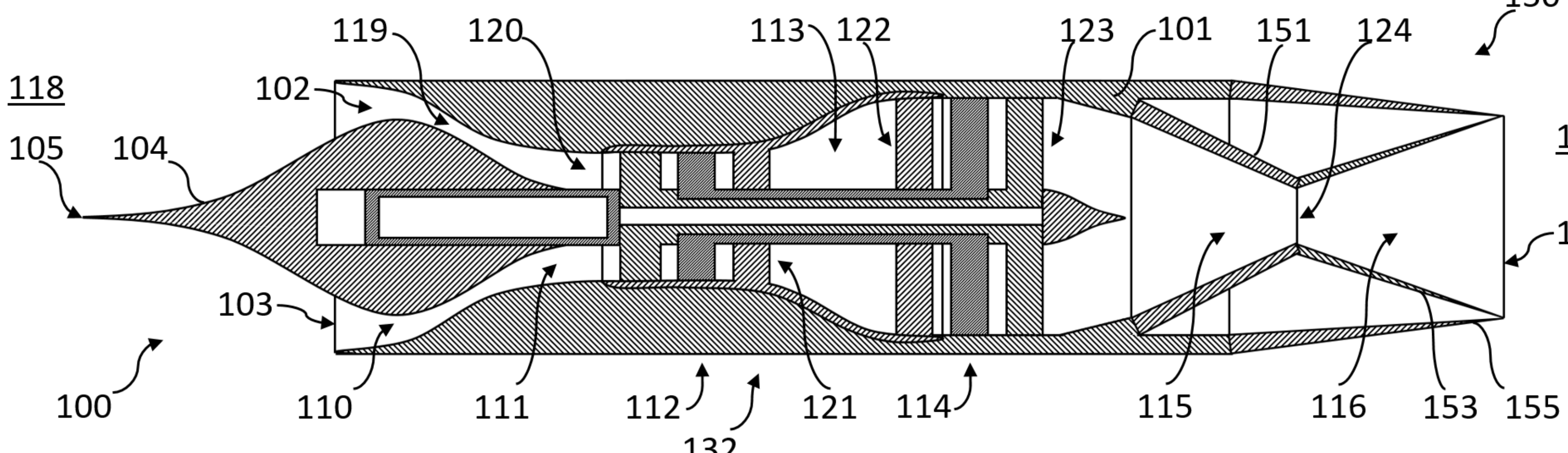
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FIG. 3B

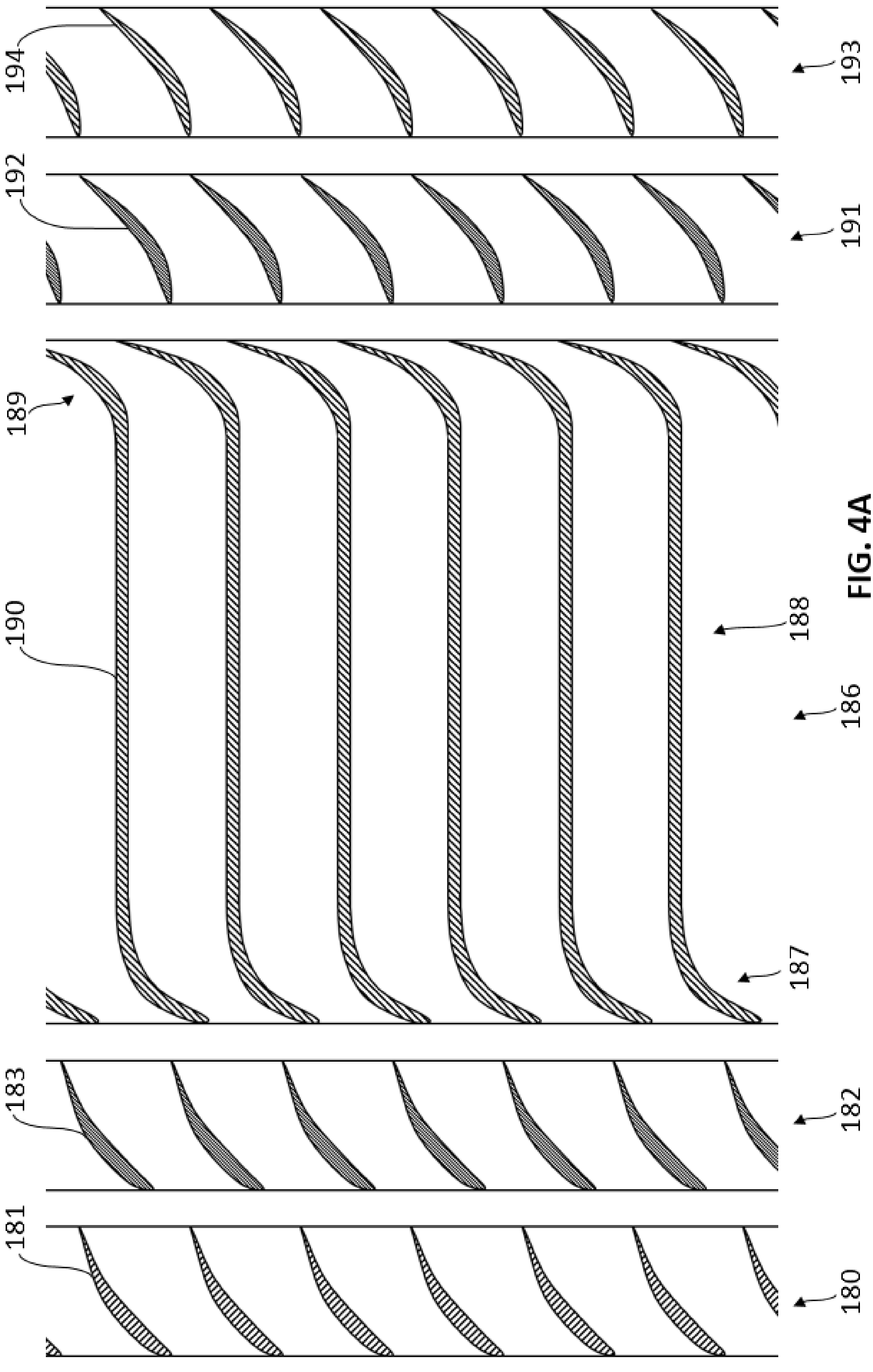

FIG. 4A

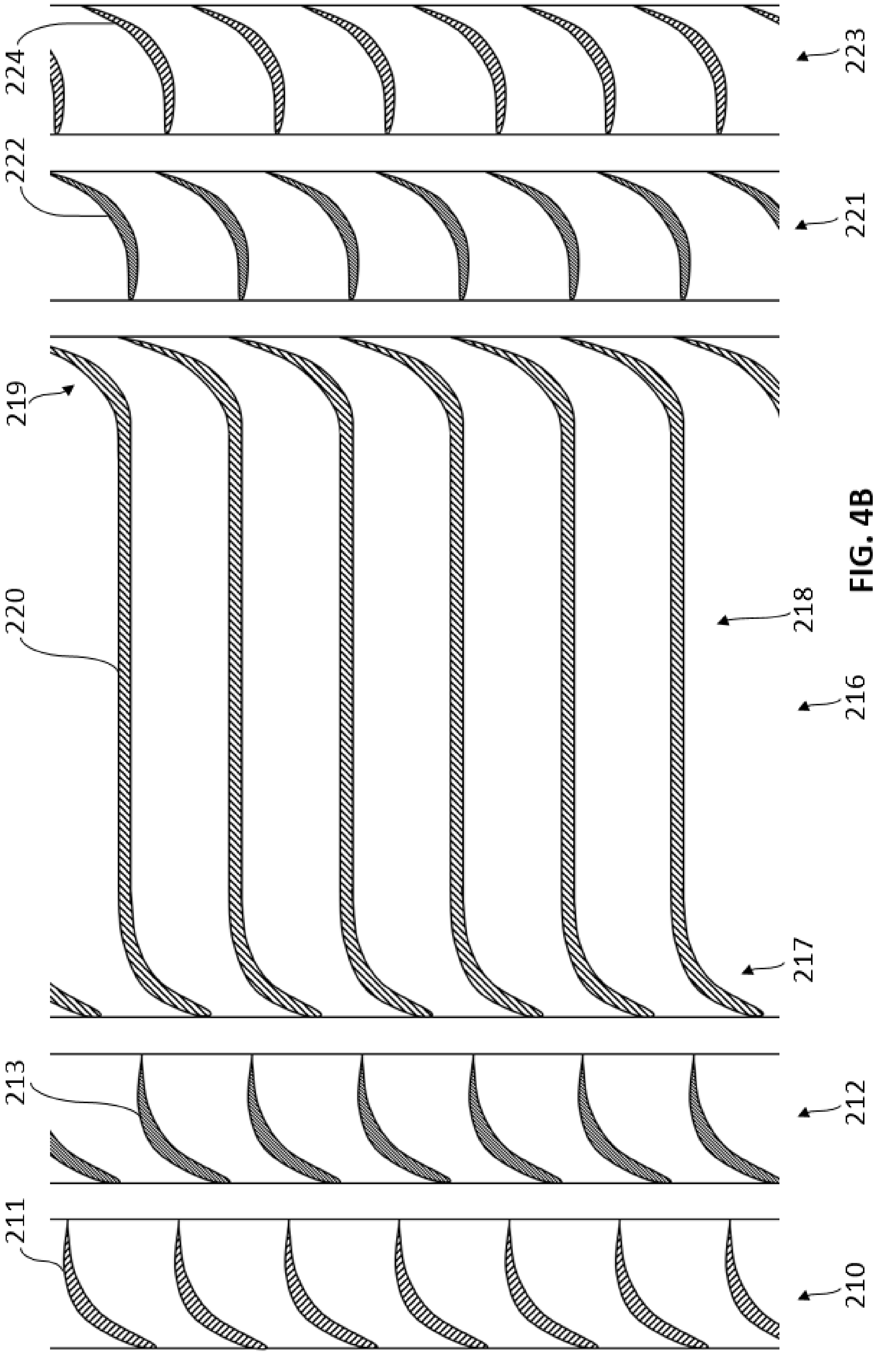

FIG. 4B

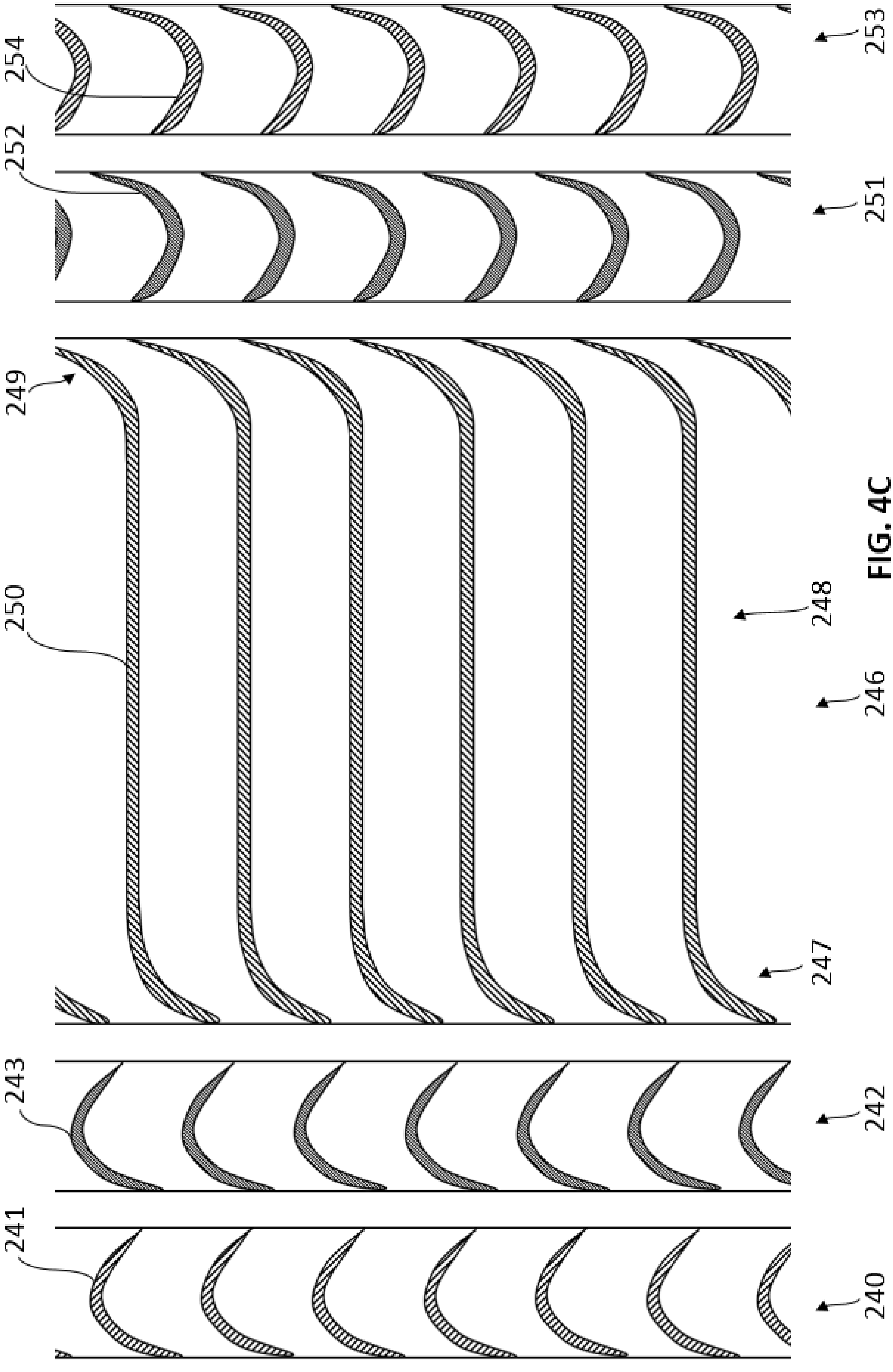

FIG. 4C

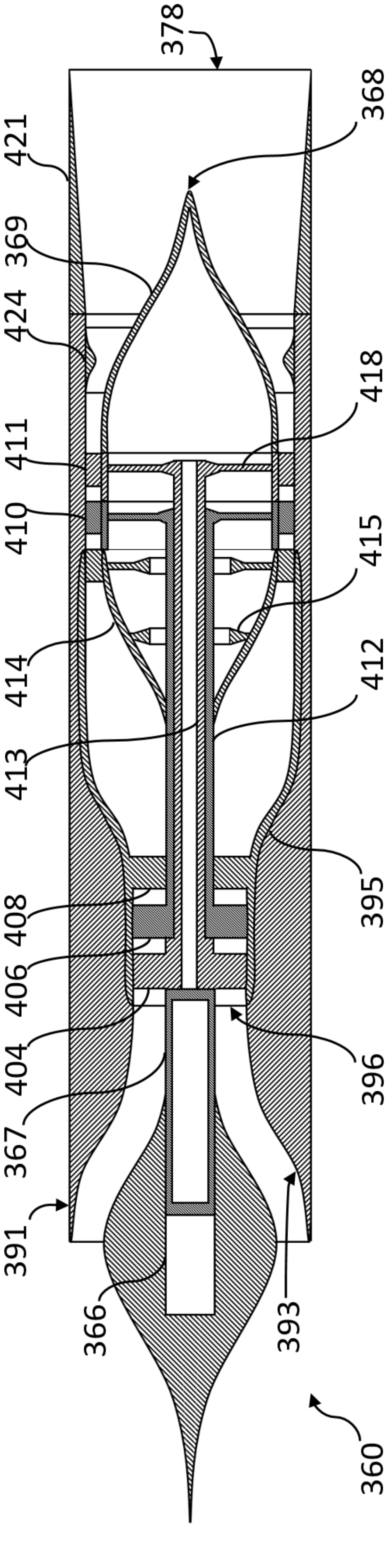
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FIG. 5A

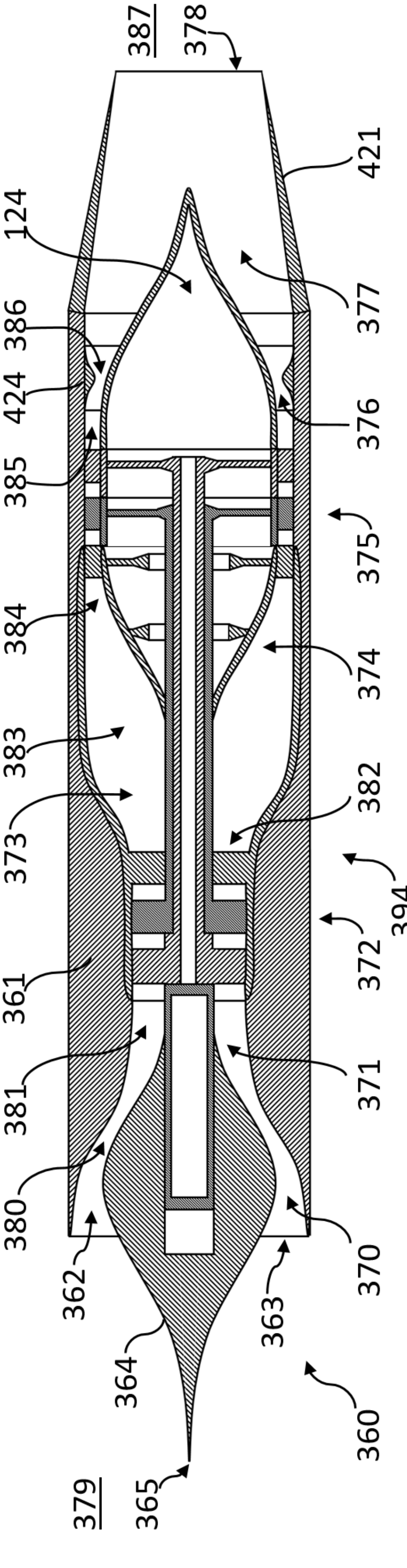
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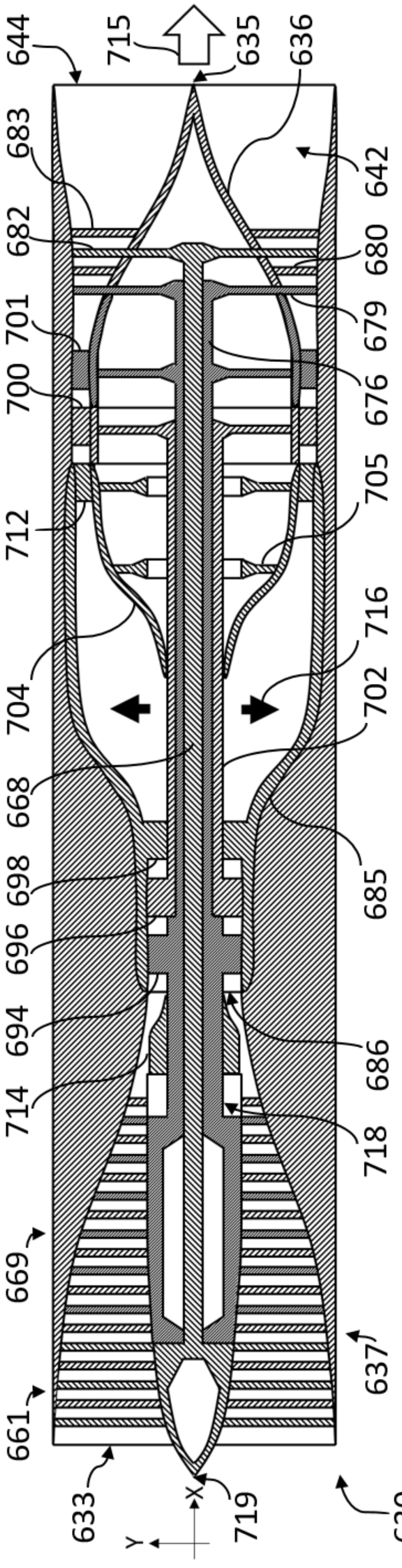
FIG. 5B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696
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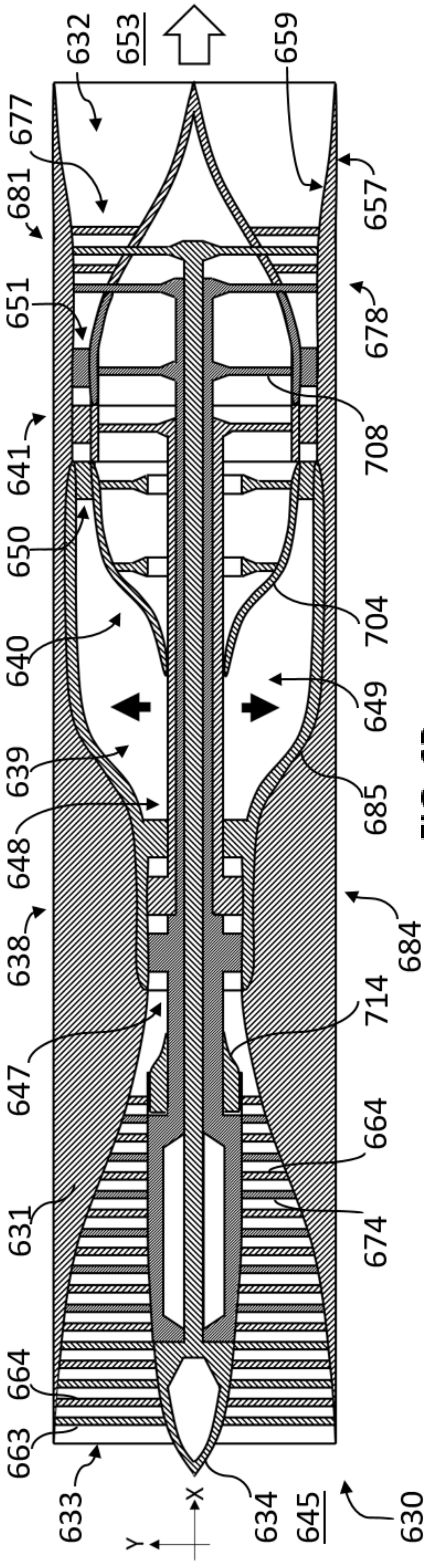
714
718
669
637
661
633
719
630
X
Y

FIG. 6A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630
X
Y

FIG. 6B

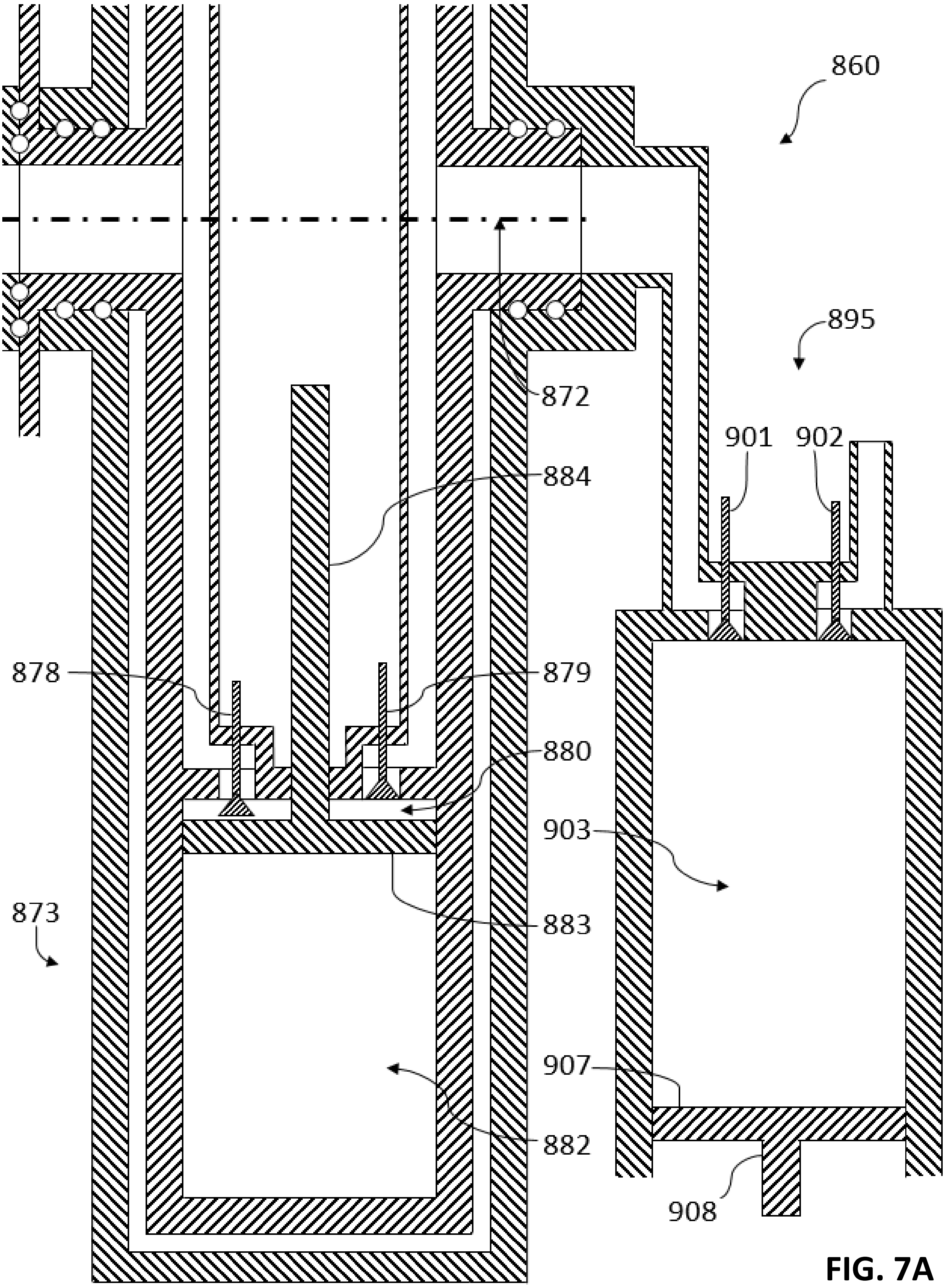


FIG. 7A

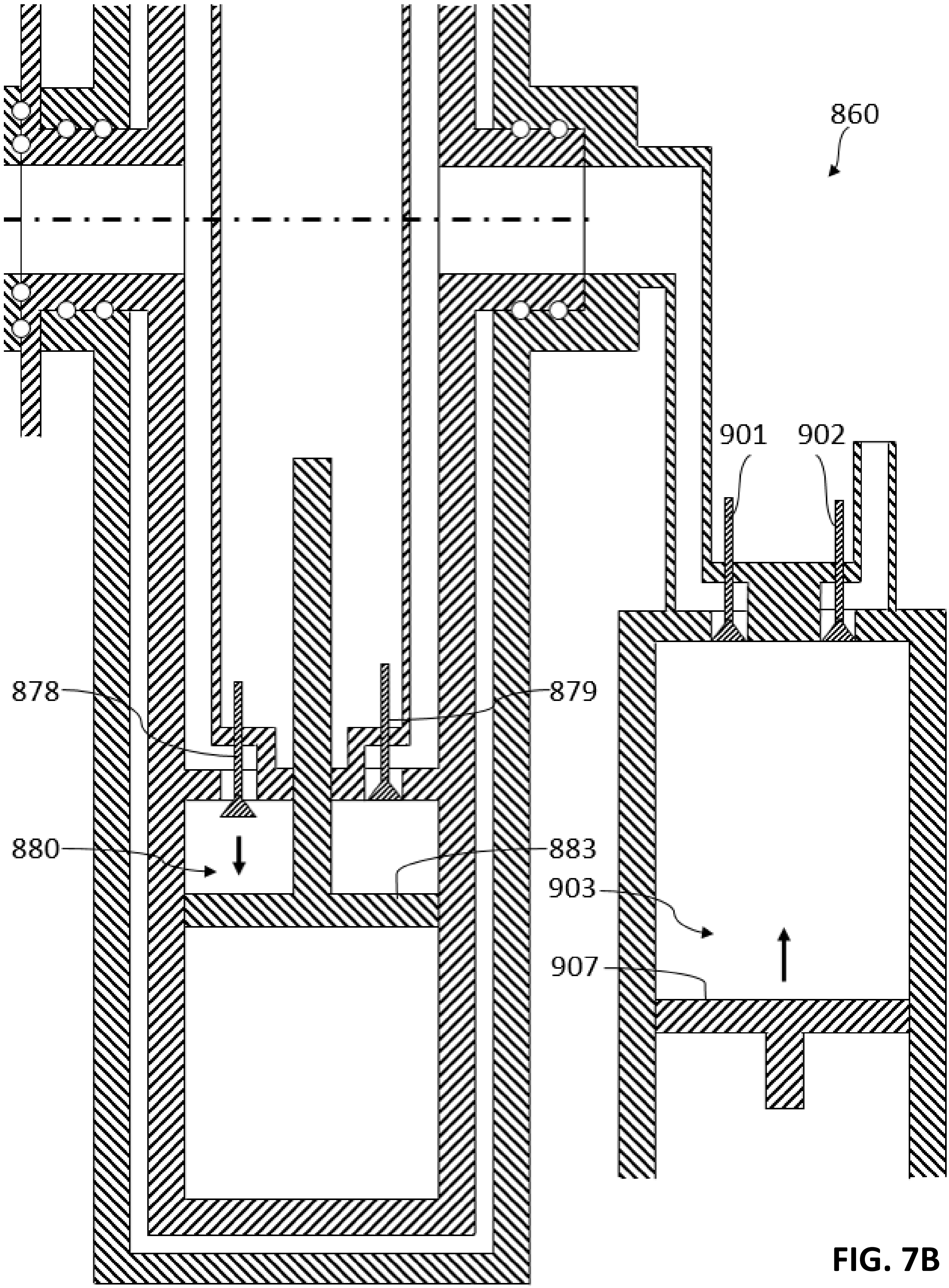


FIG. 7B

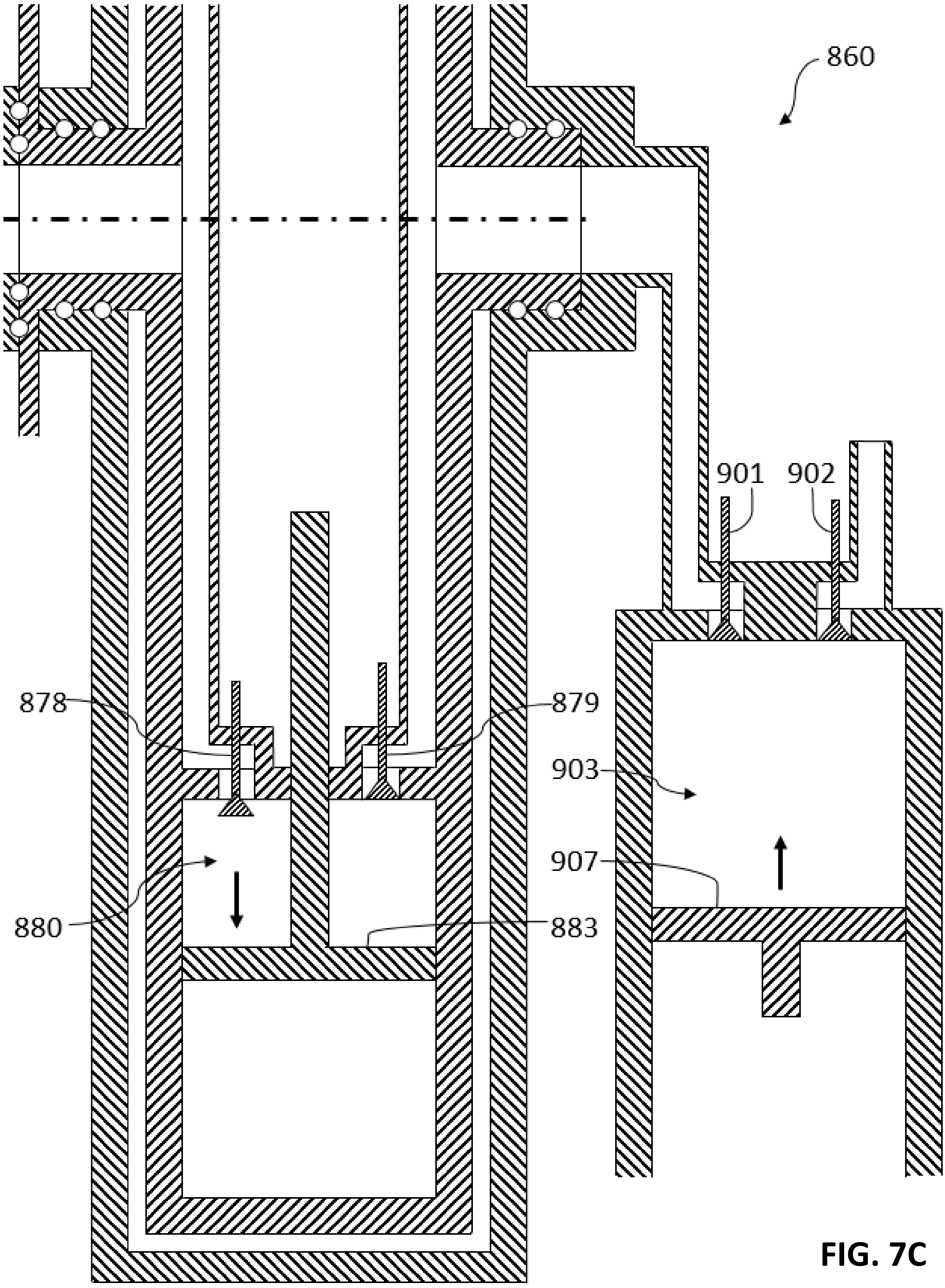


FIG. 7C

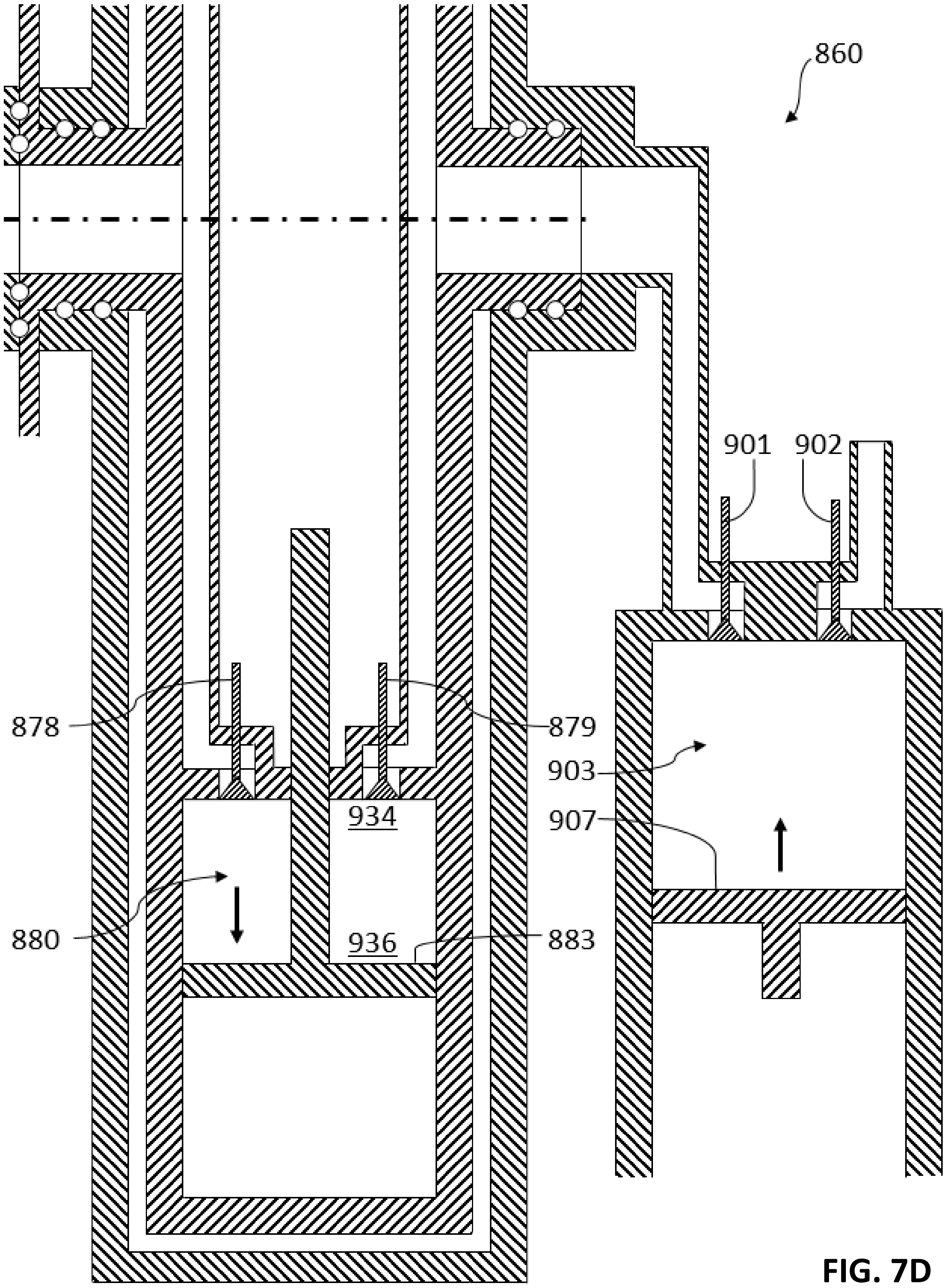


FIG. 7D

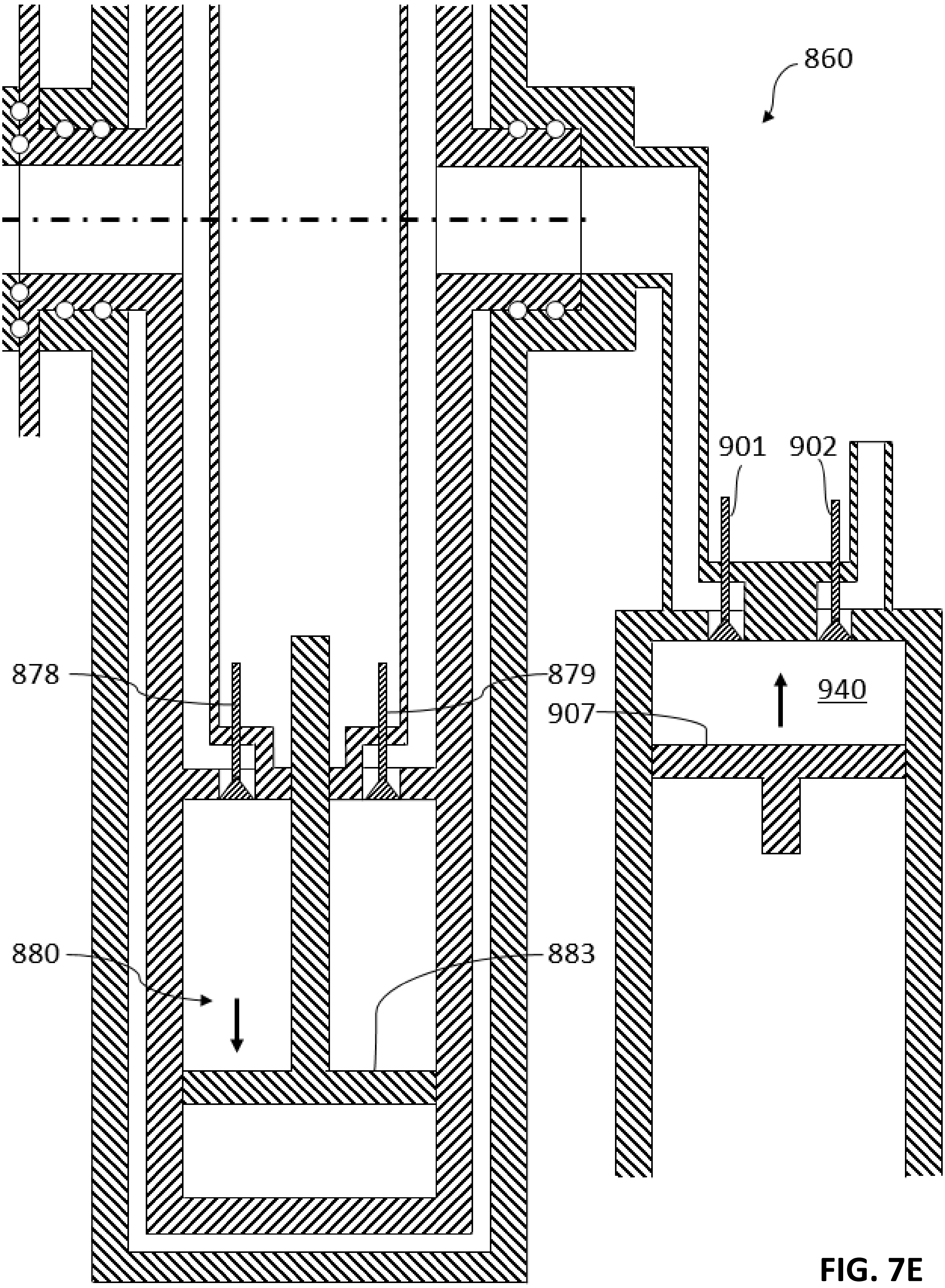


FIG. 7E

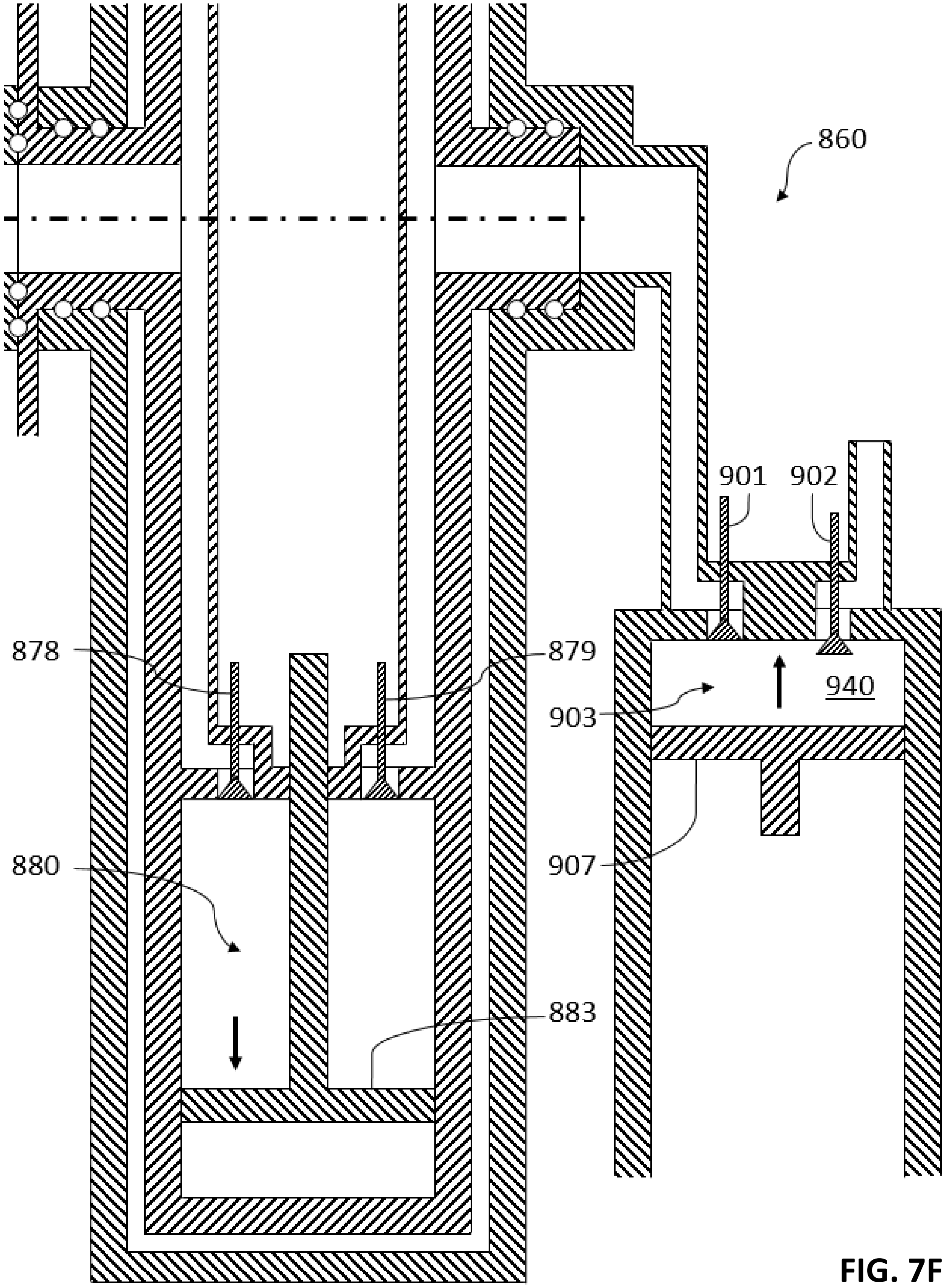
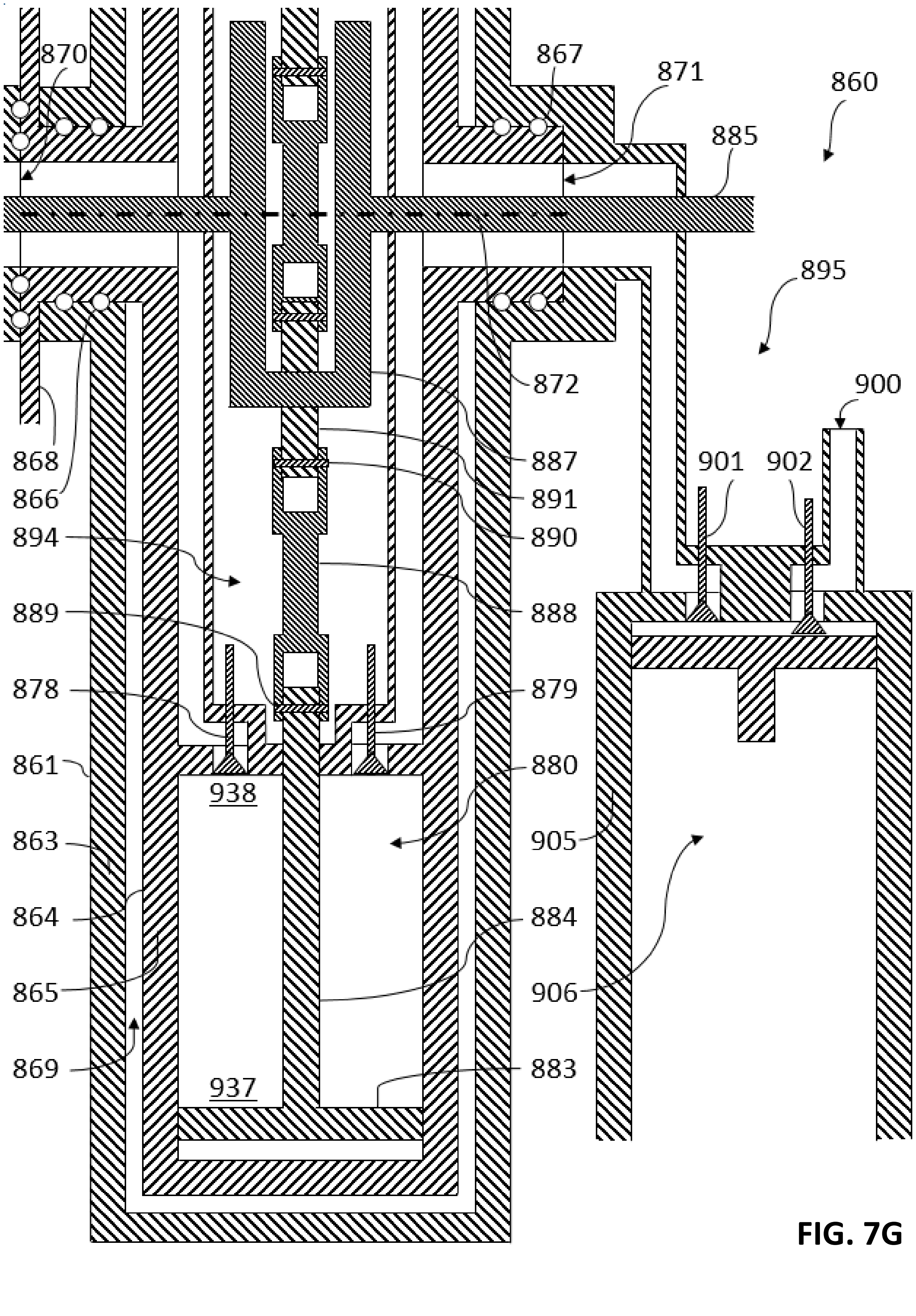


FIG. 7F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937

FIG. 7G

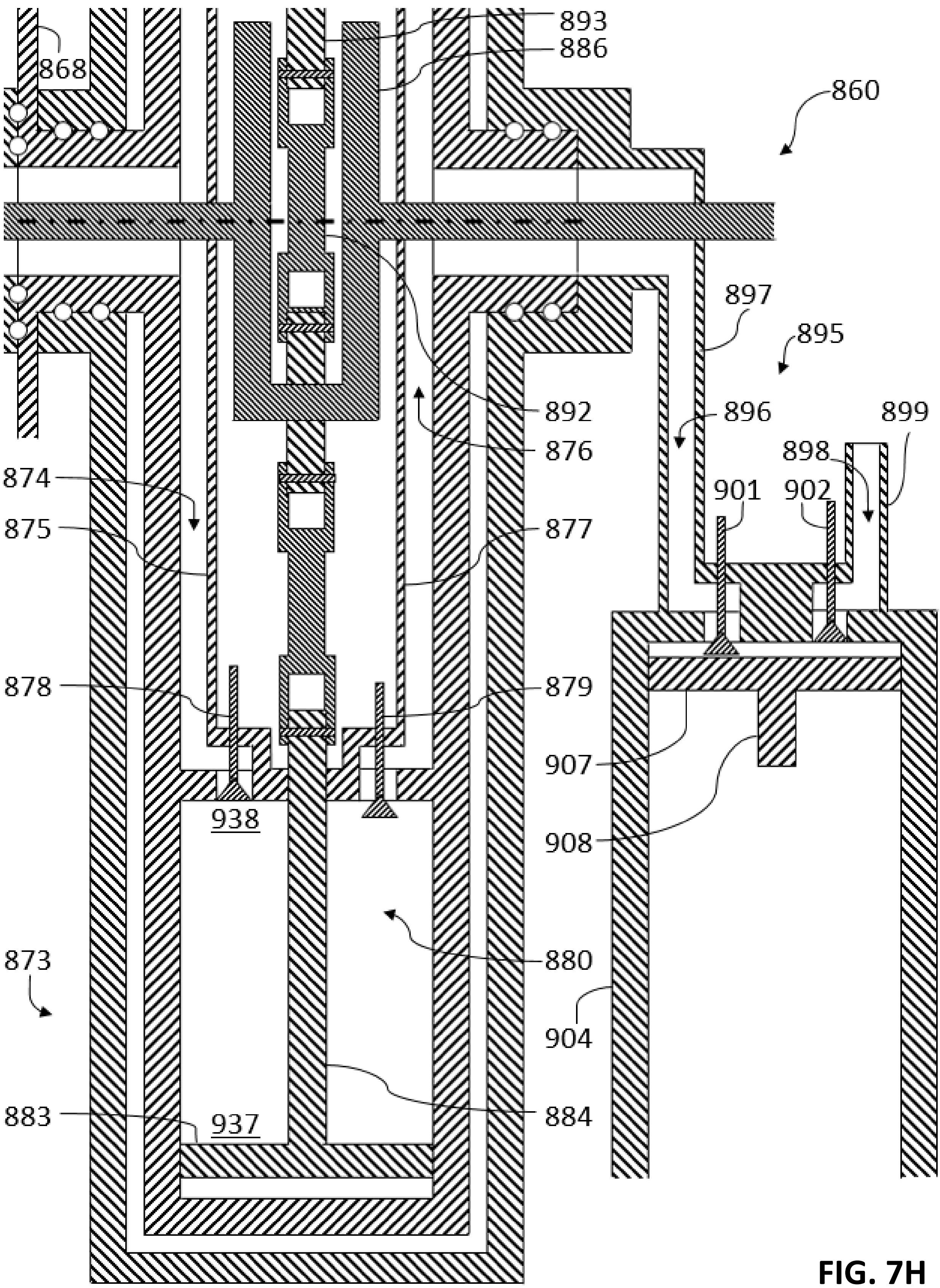
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FIG. 7H

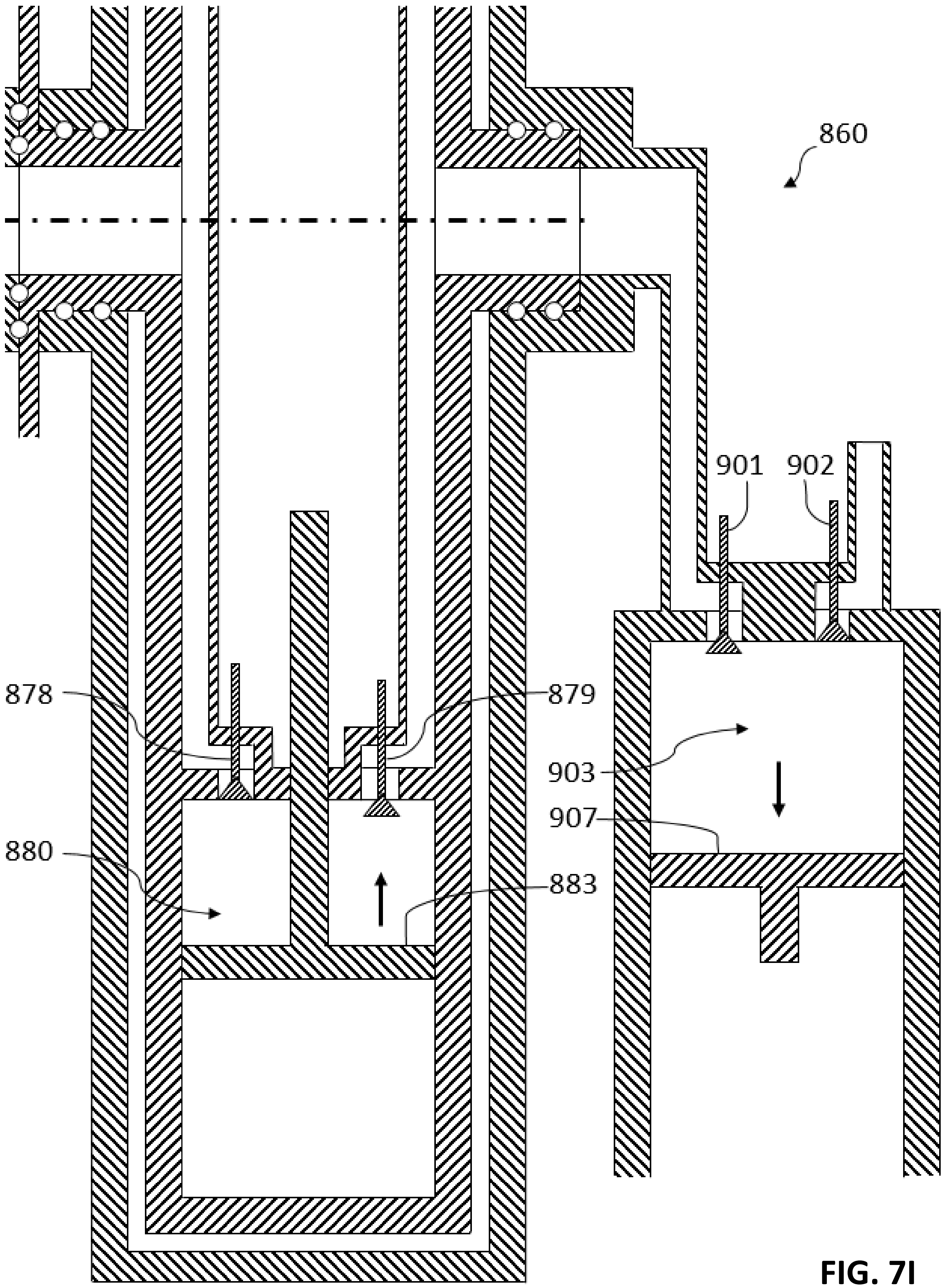


FIG. 7I

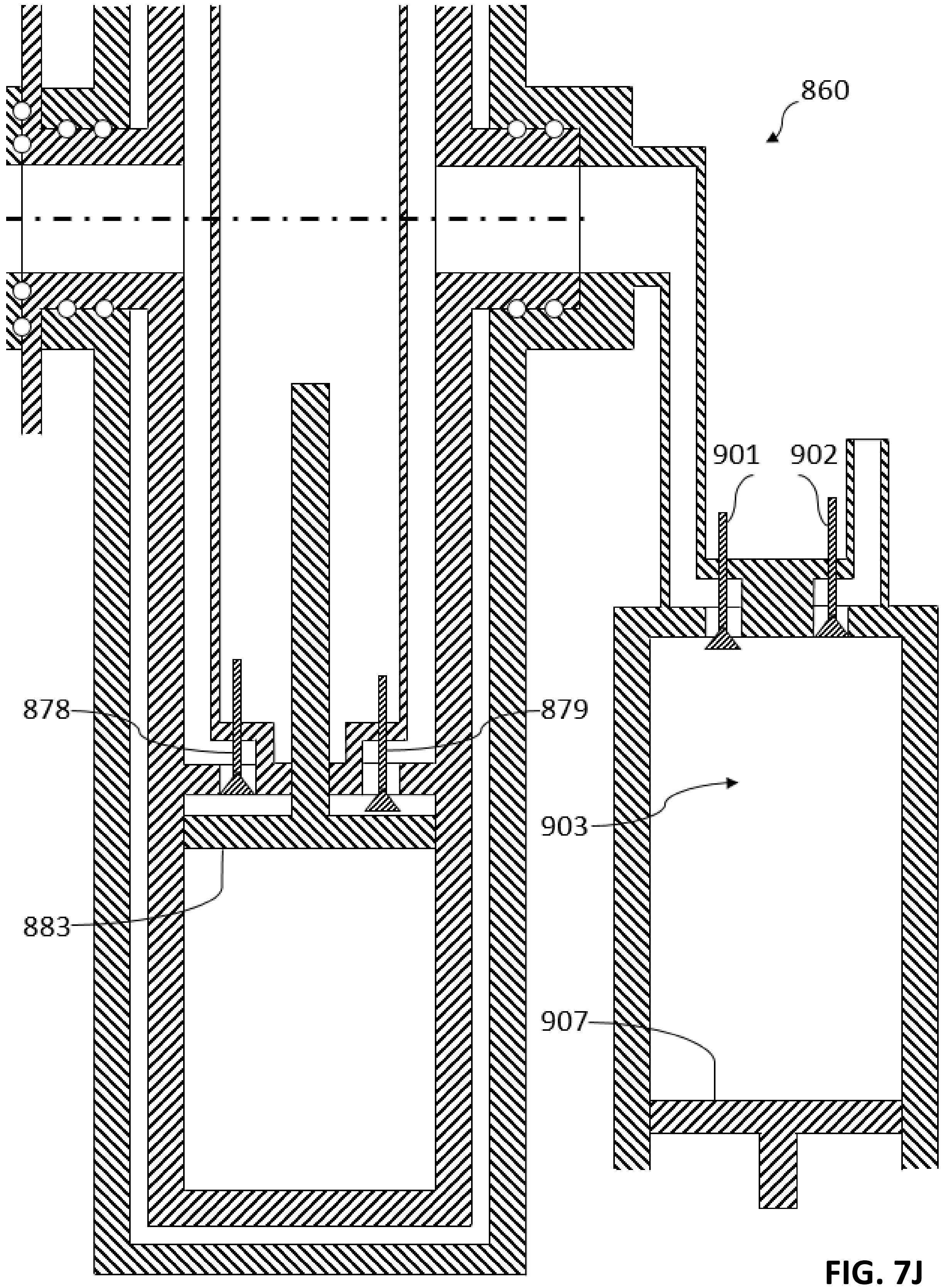
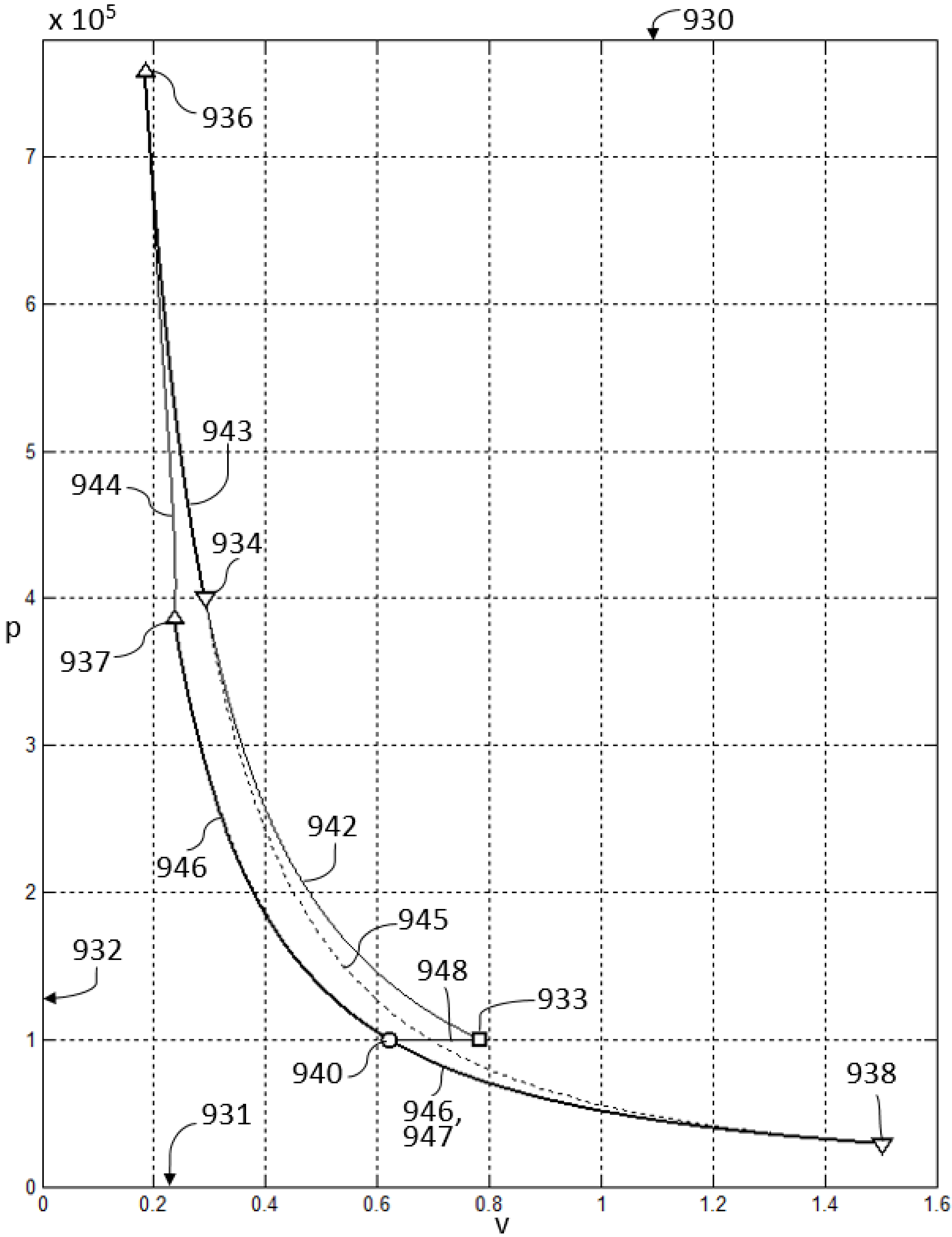


FIG. 7J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0.8
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1.2
1.4
1.6
v

FIG. 8

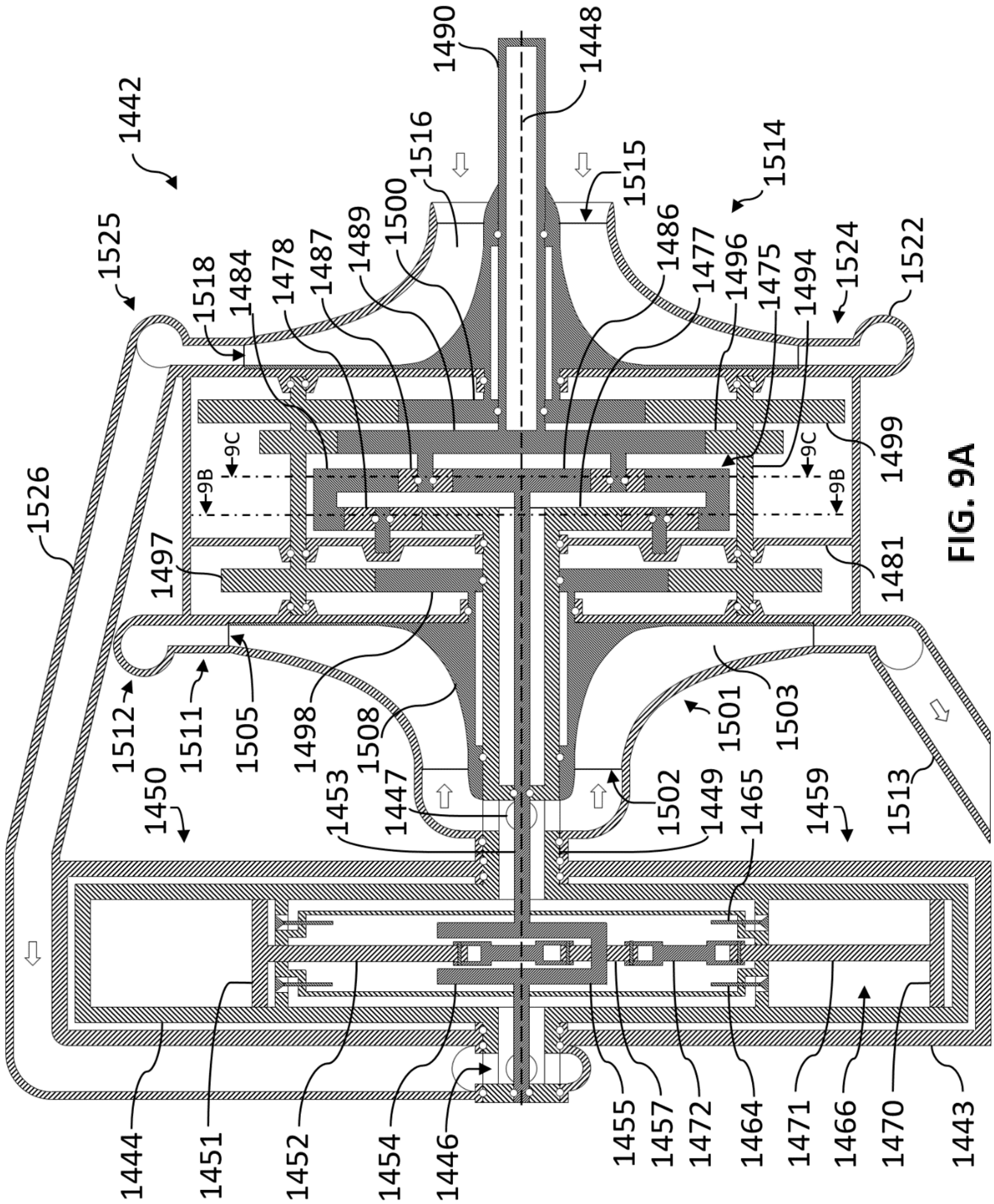
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FIG. 9A

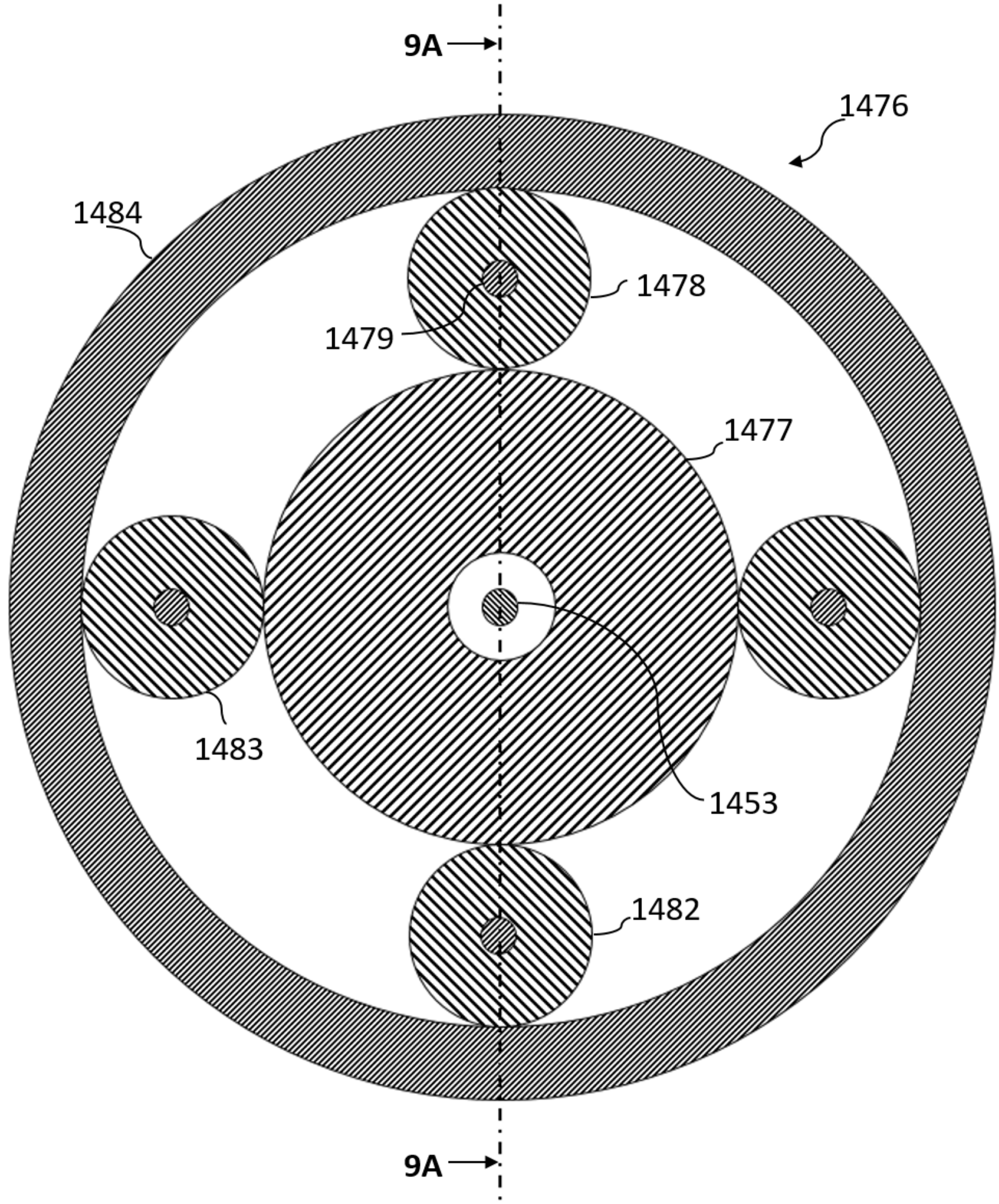

FIG. 9B

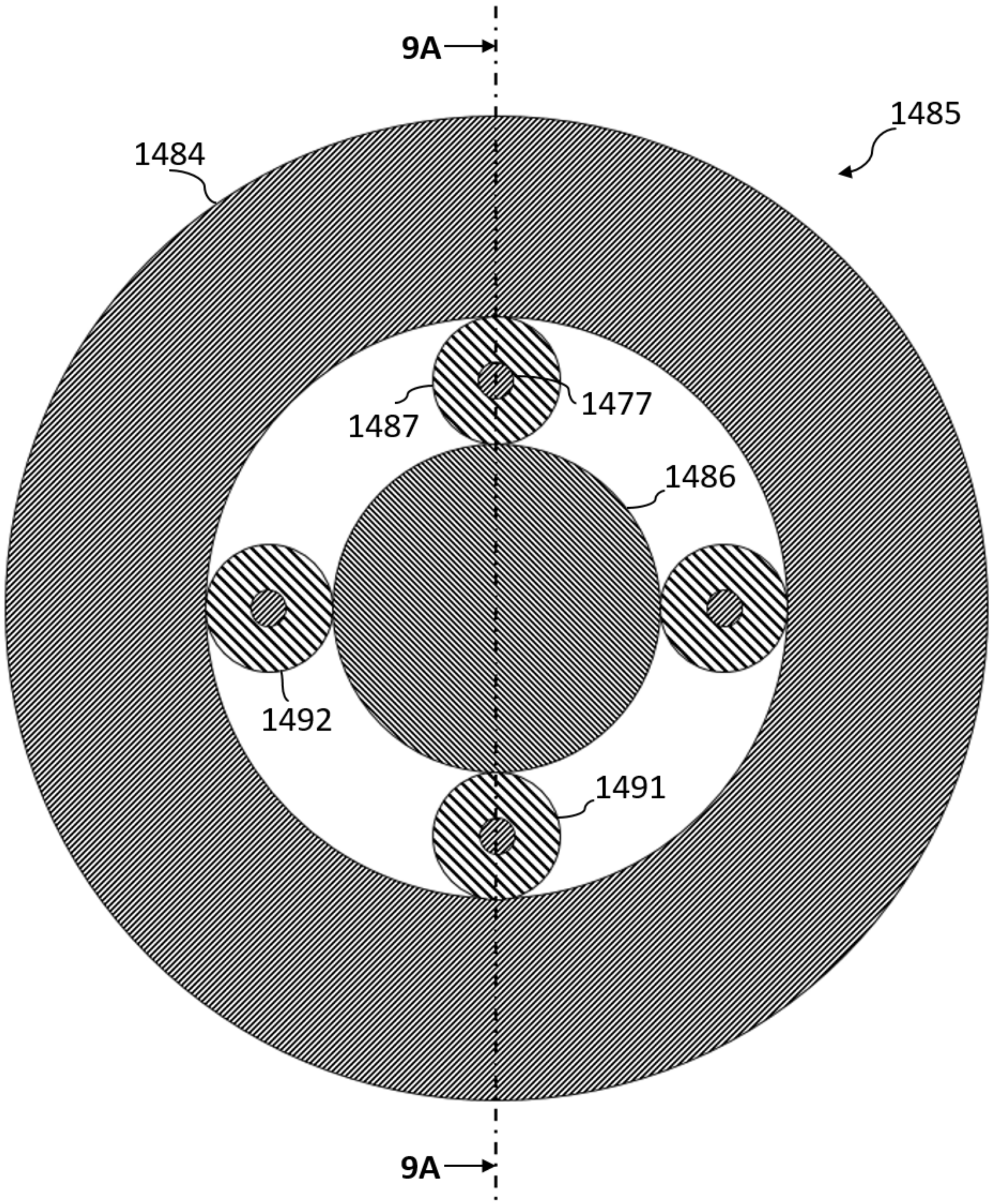

FIG. 9C

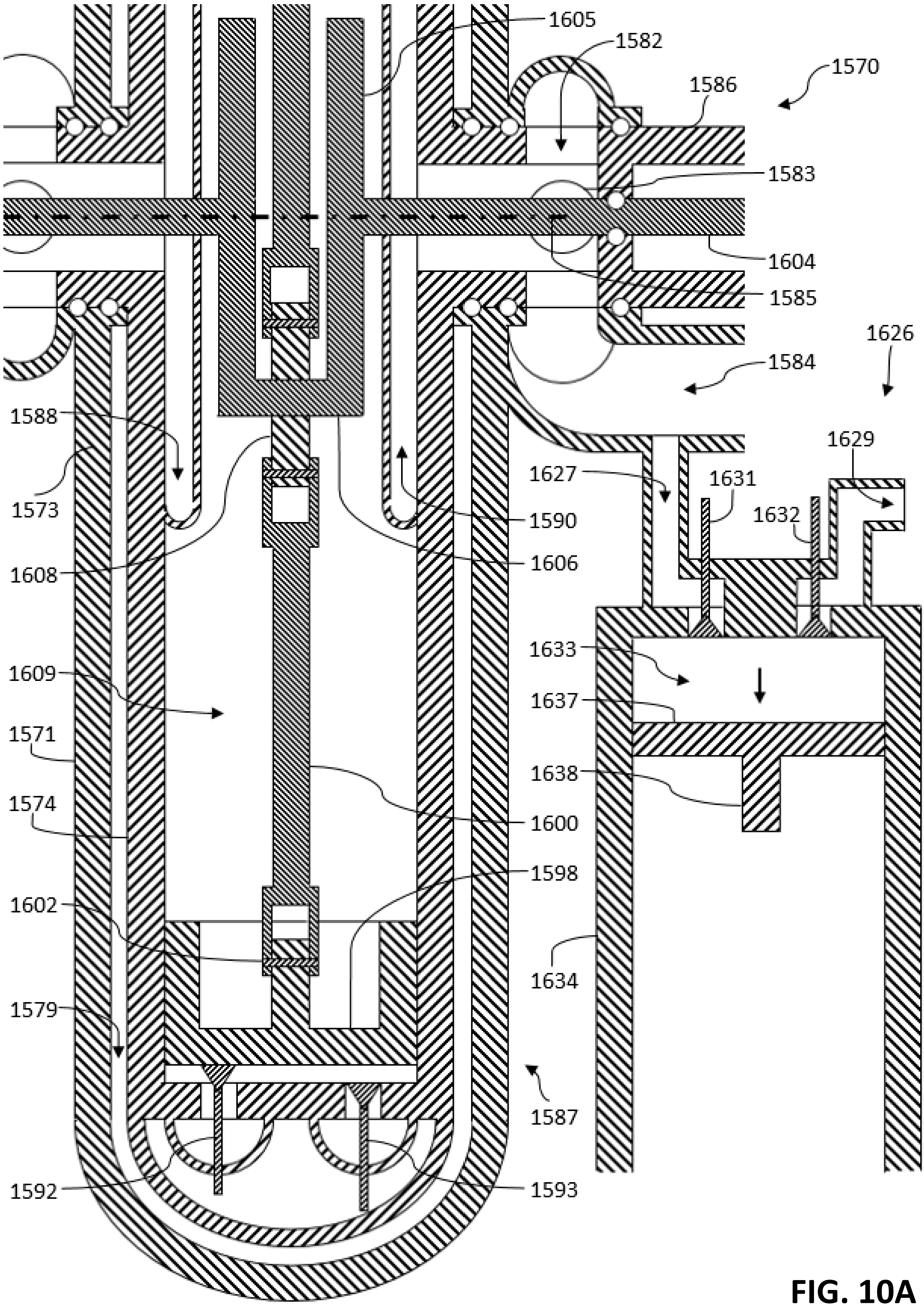
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FIG. 10A

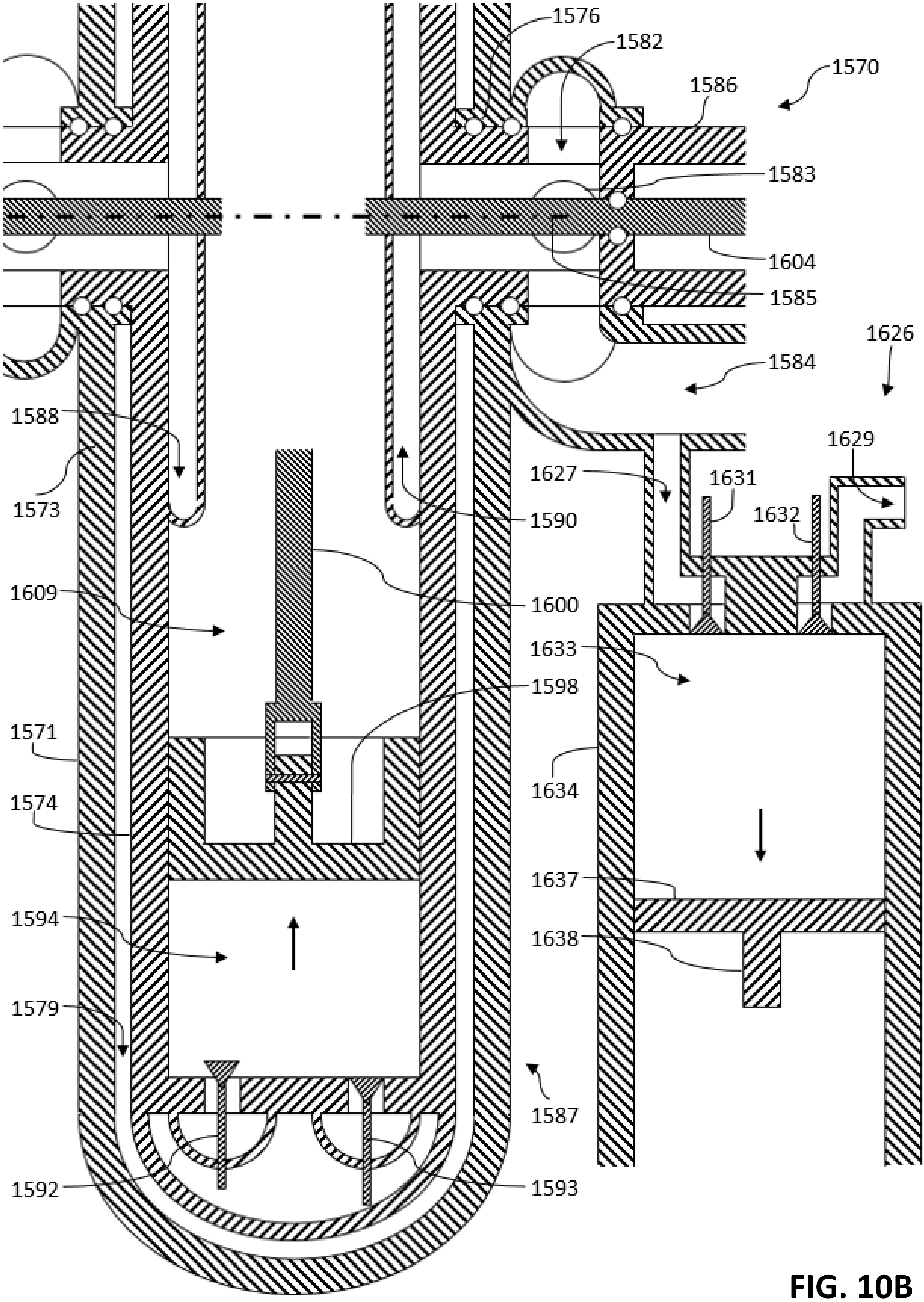
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FIG. 10B

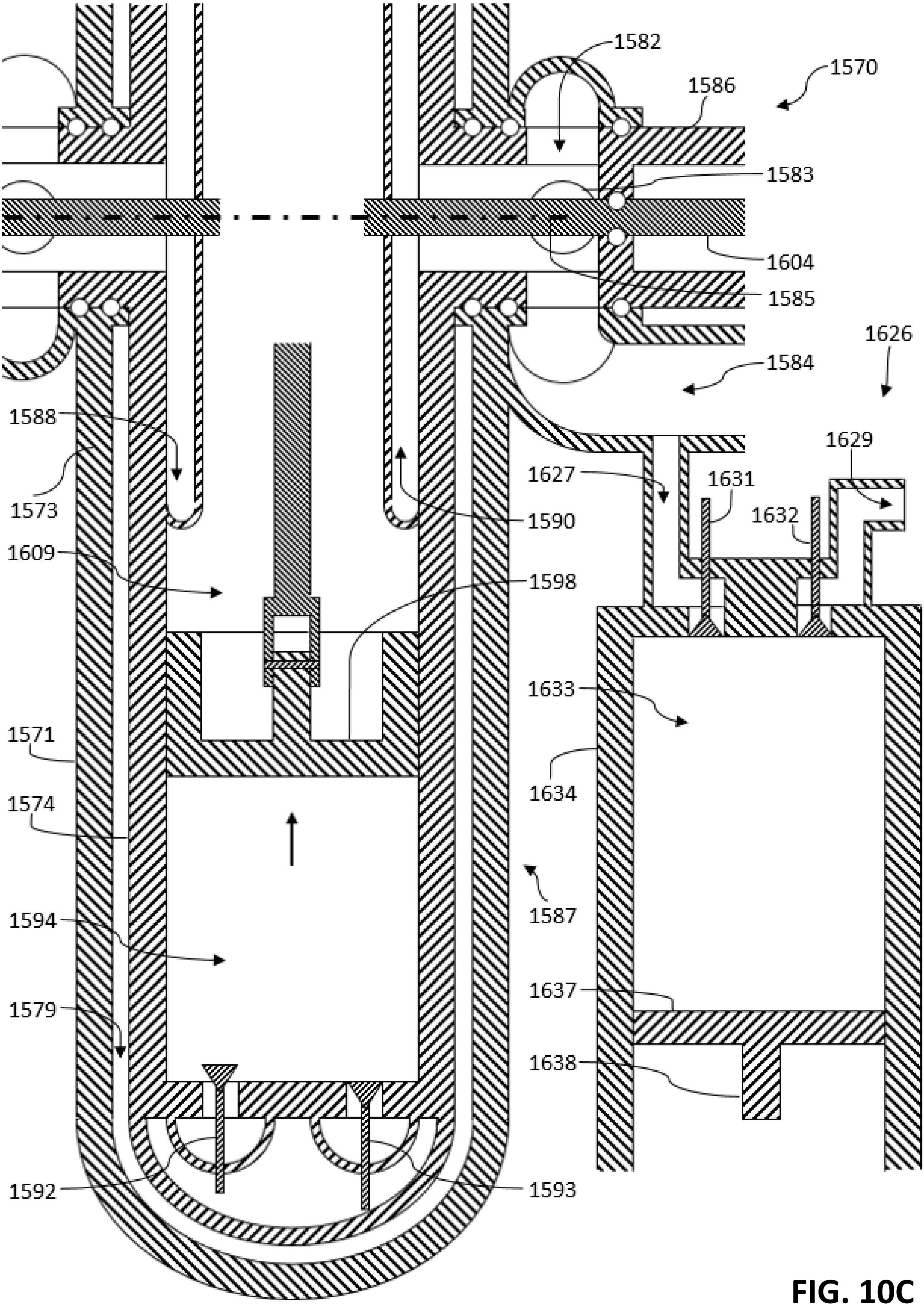
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FIG. 10C

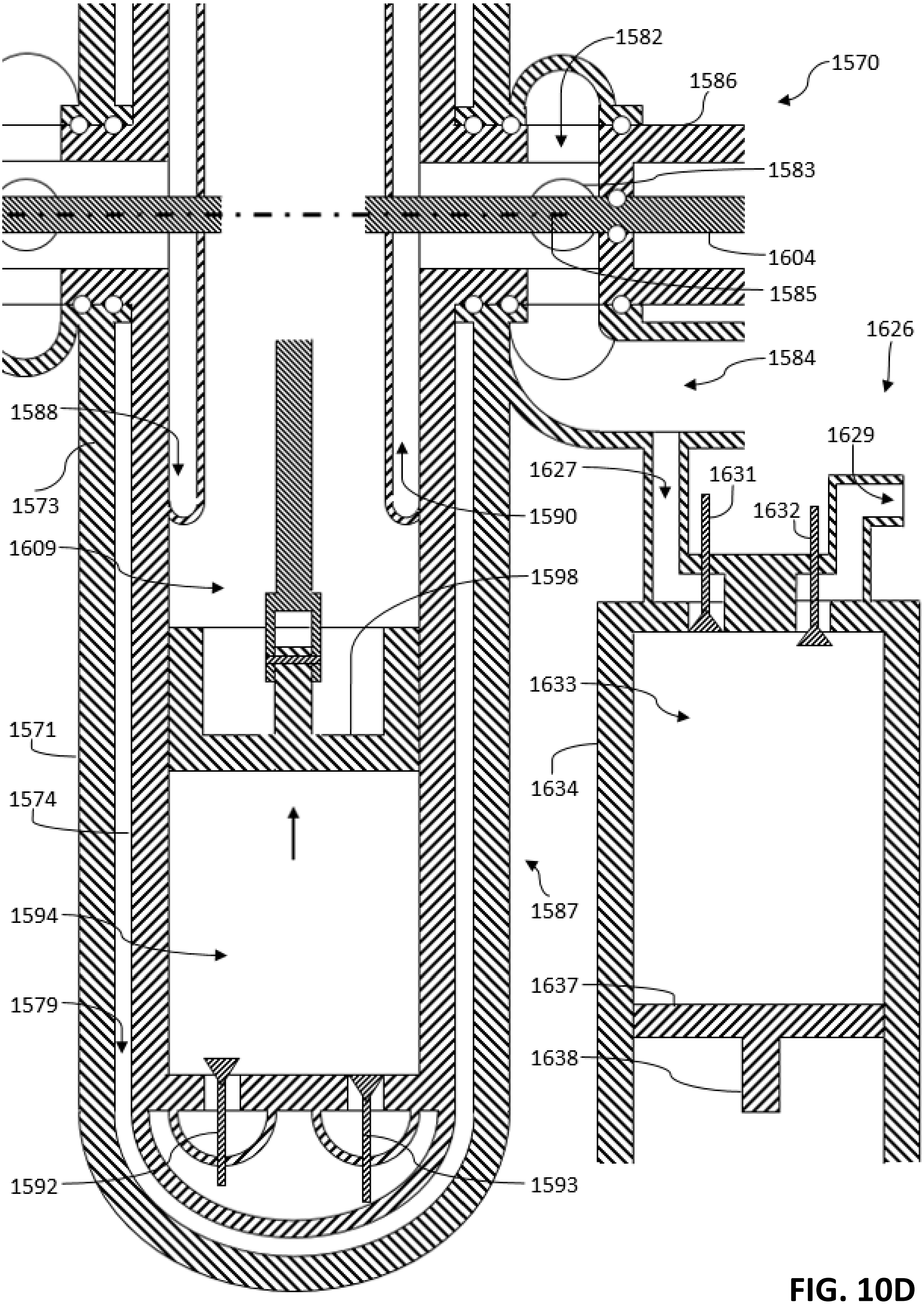
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FIG. 10D

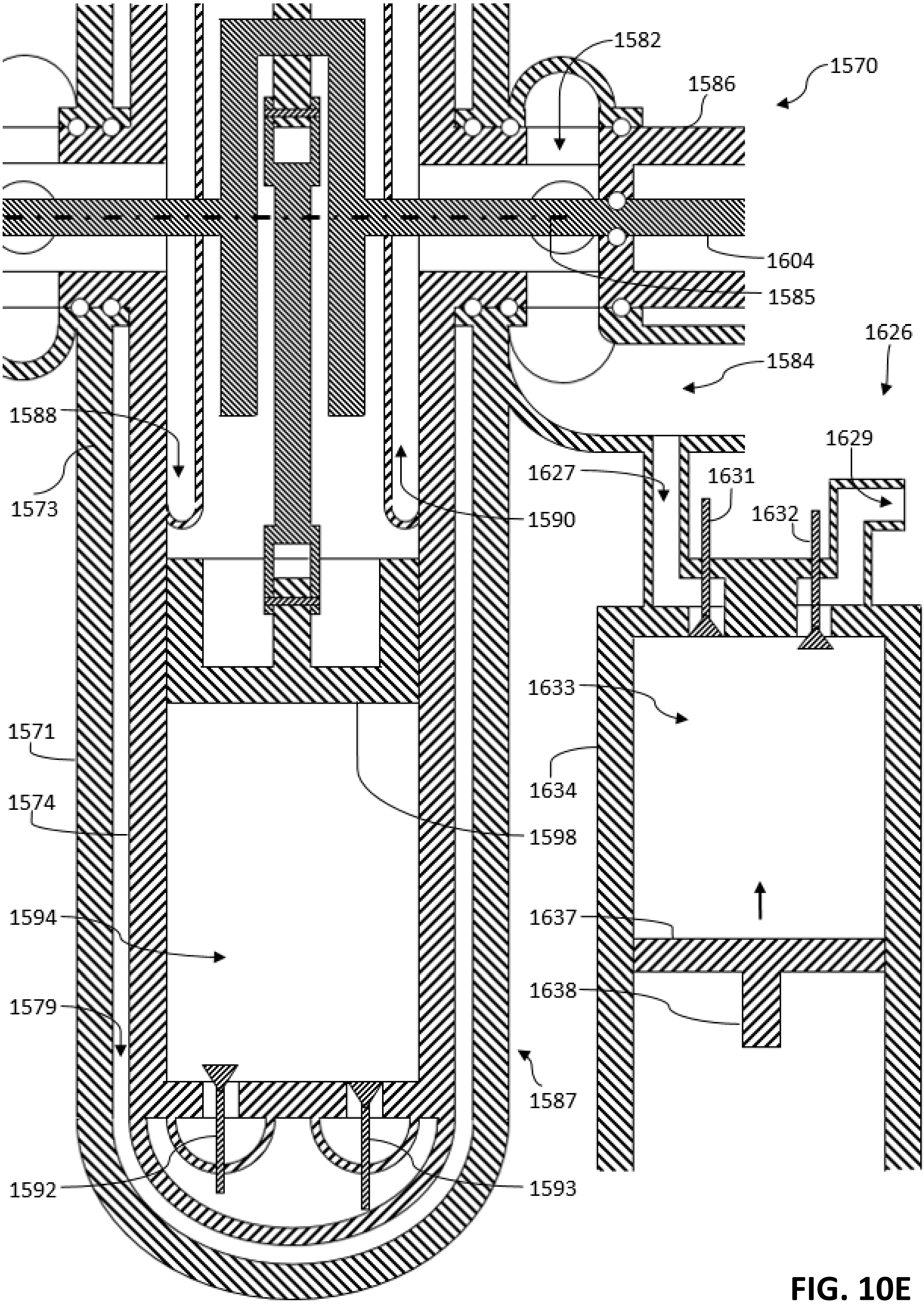
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FIG. 10E

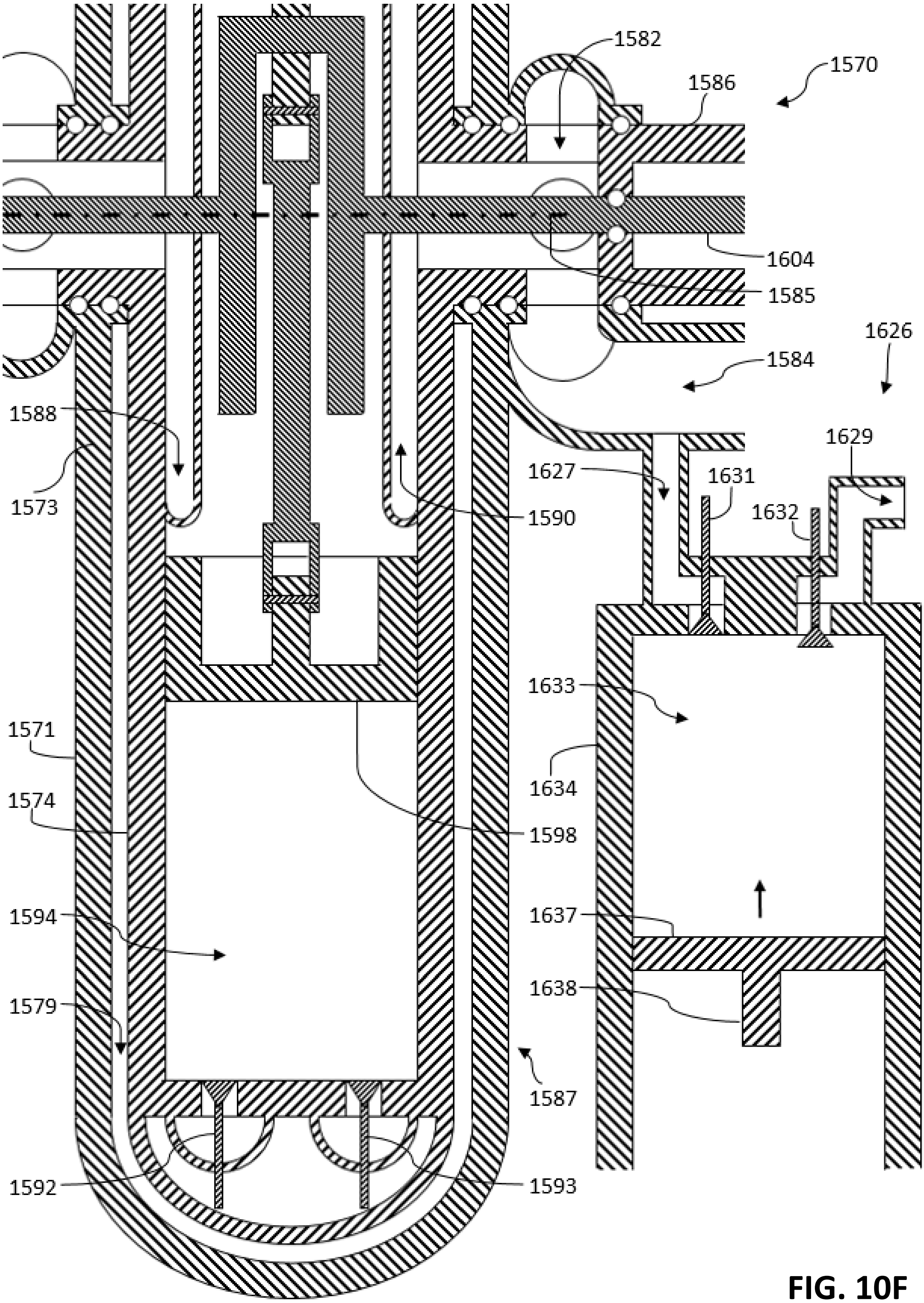
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FIG. 10F

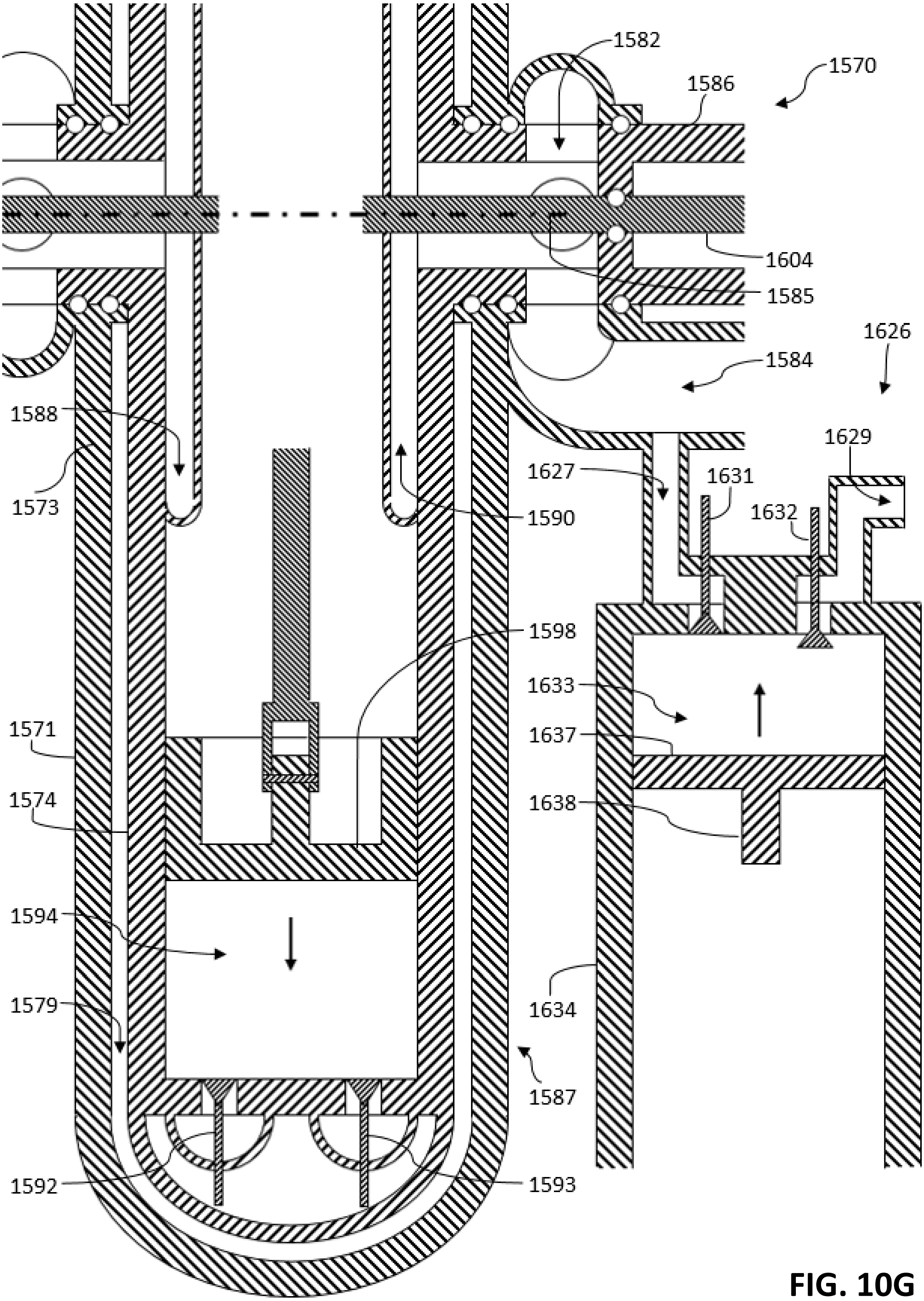
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FIG. 10G

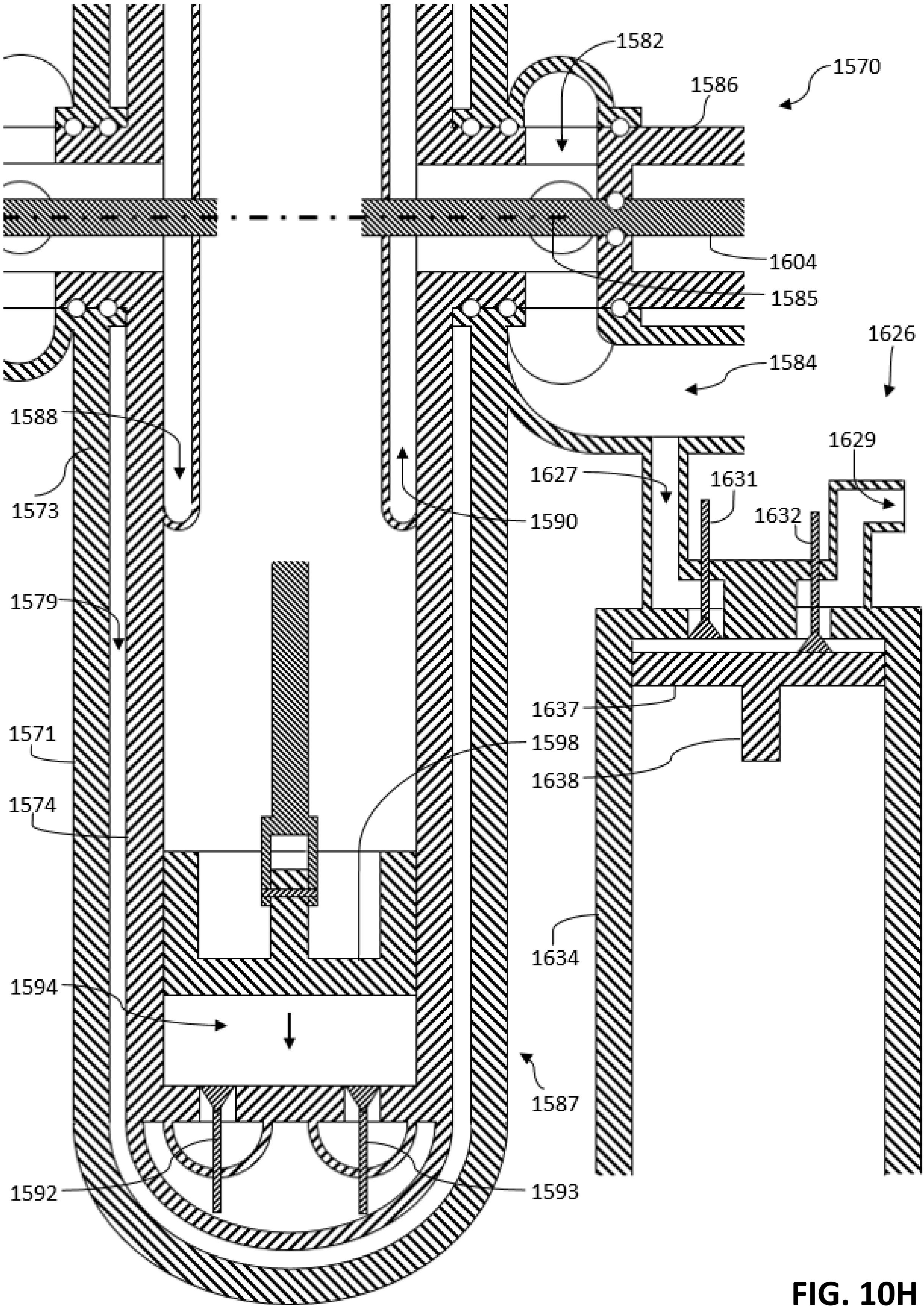
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FIG. 10H

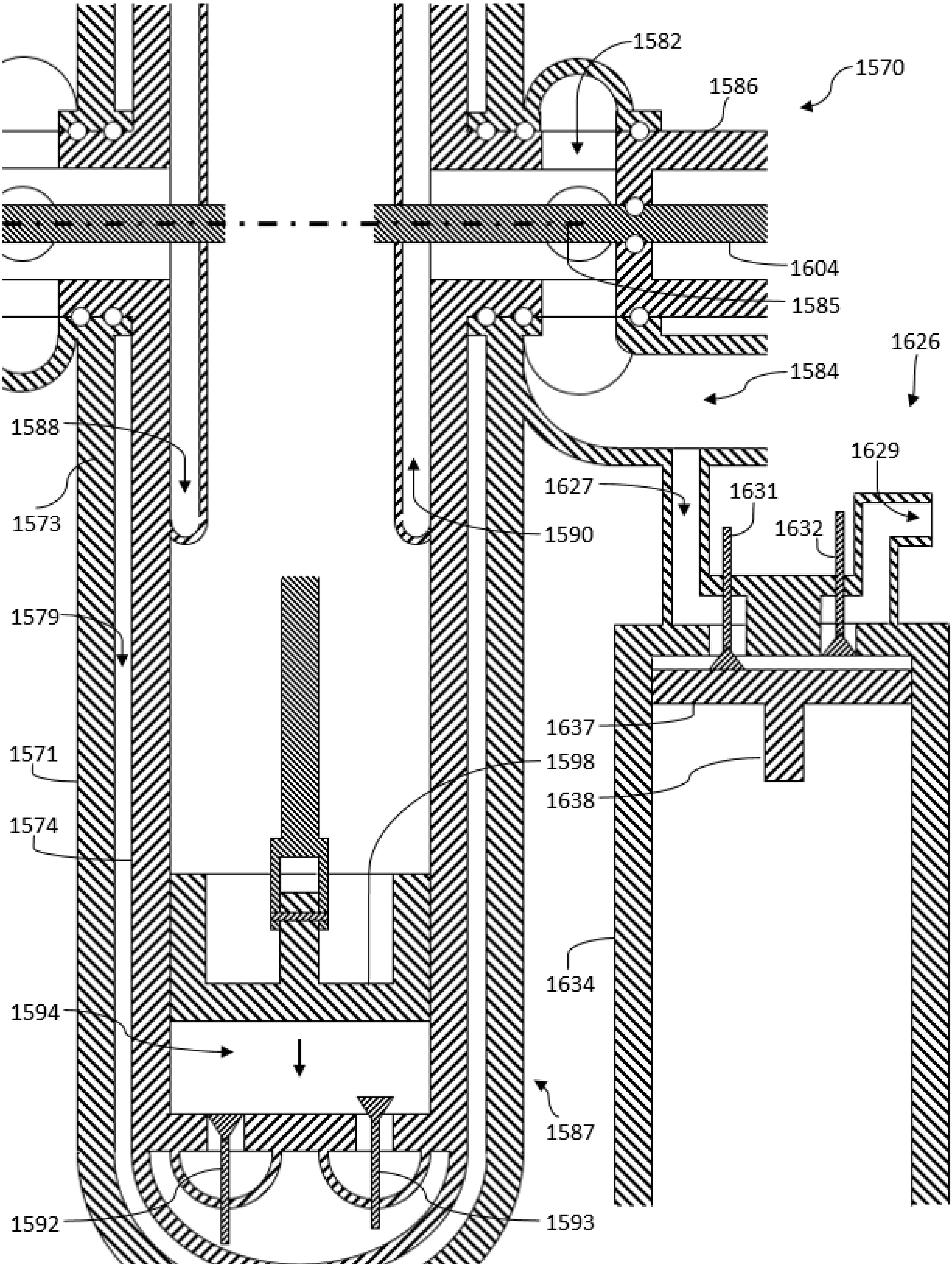
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FIG. 10I

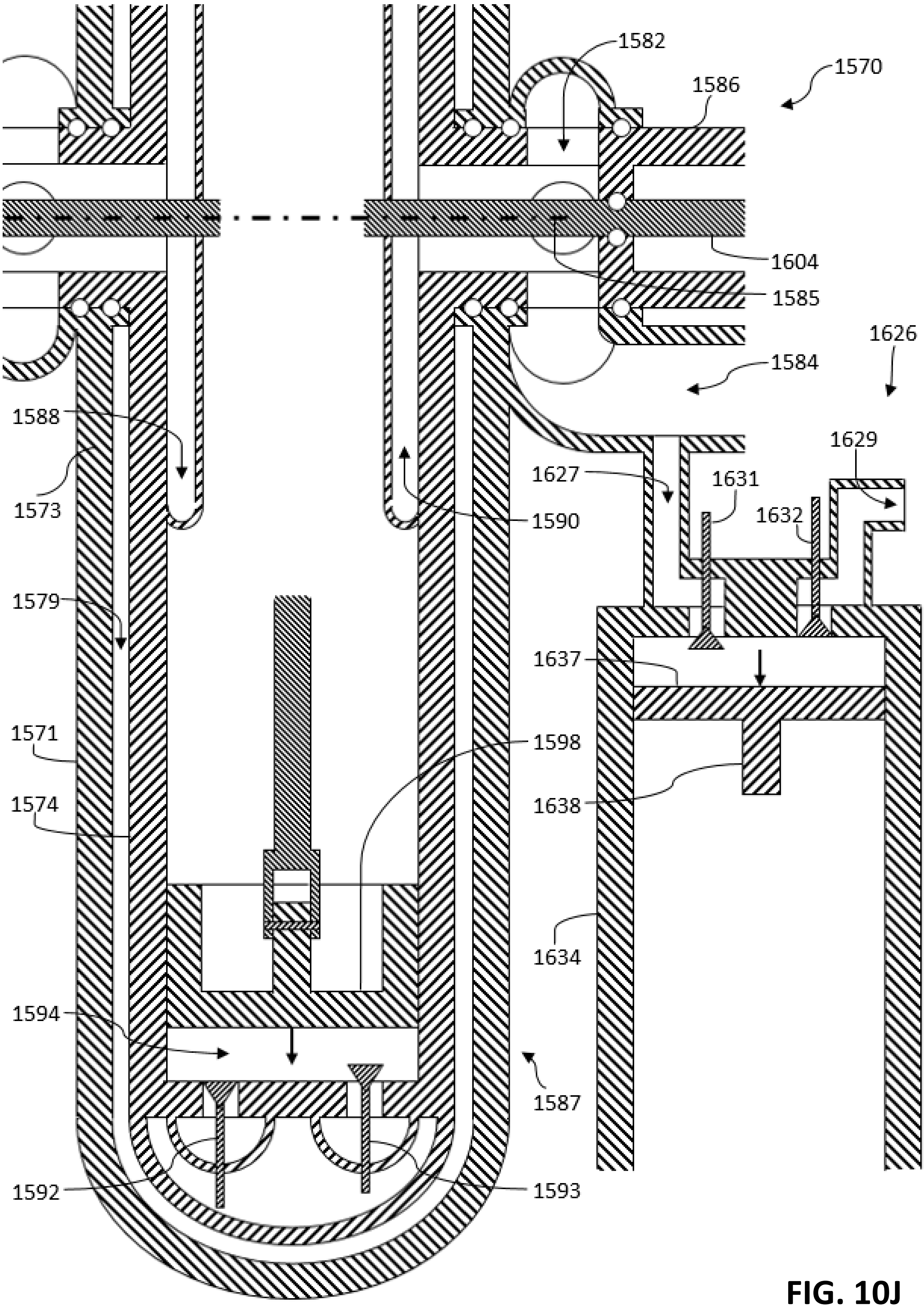
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FIG. 10J

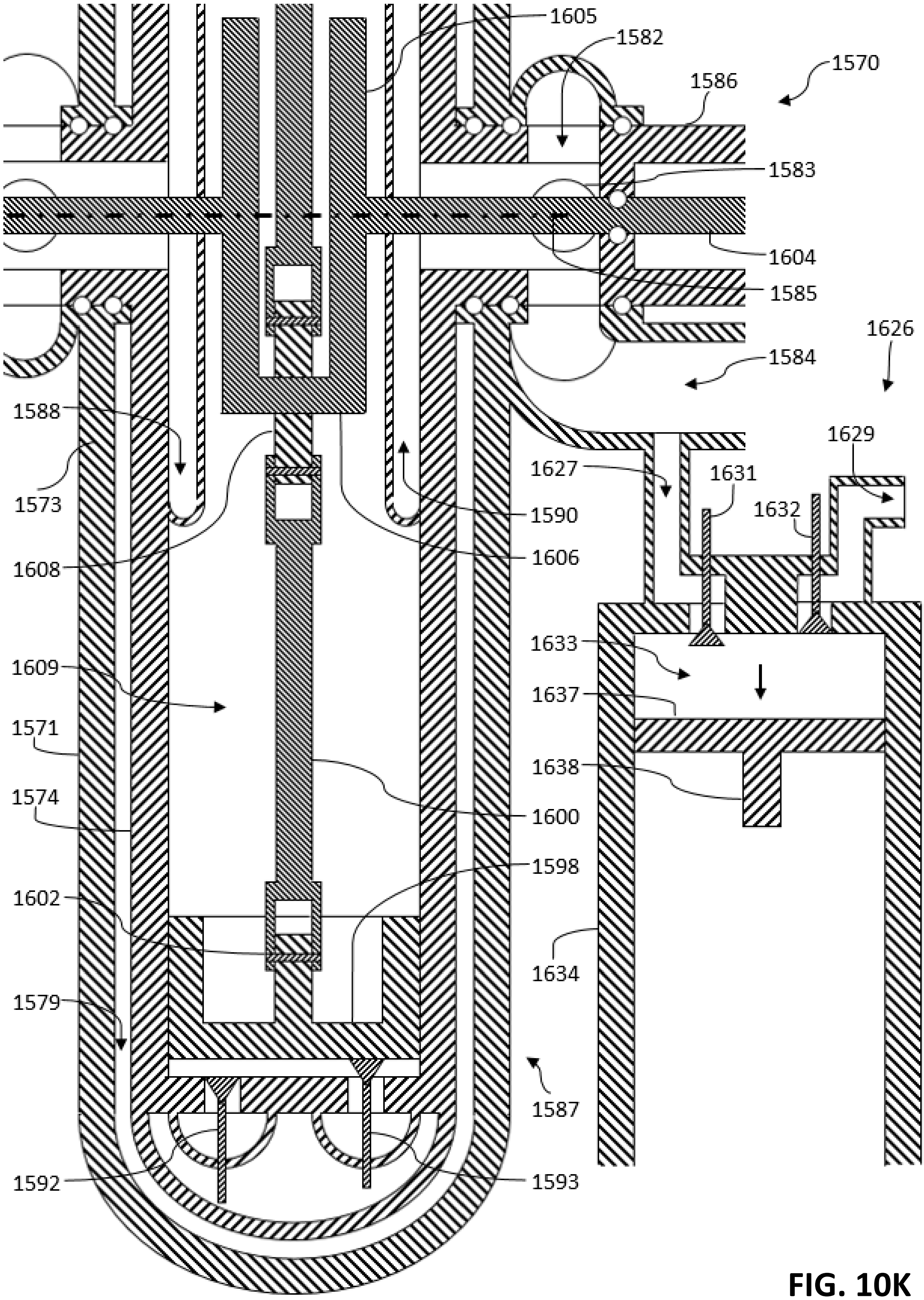
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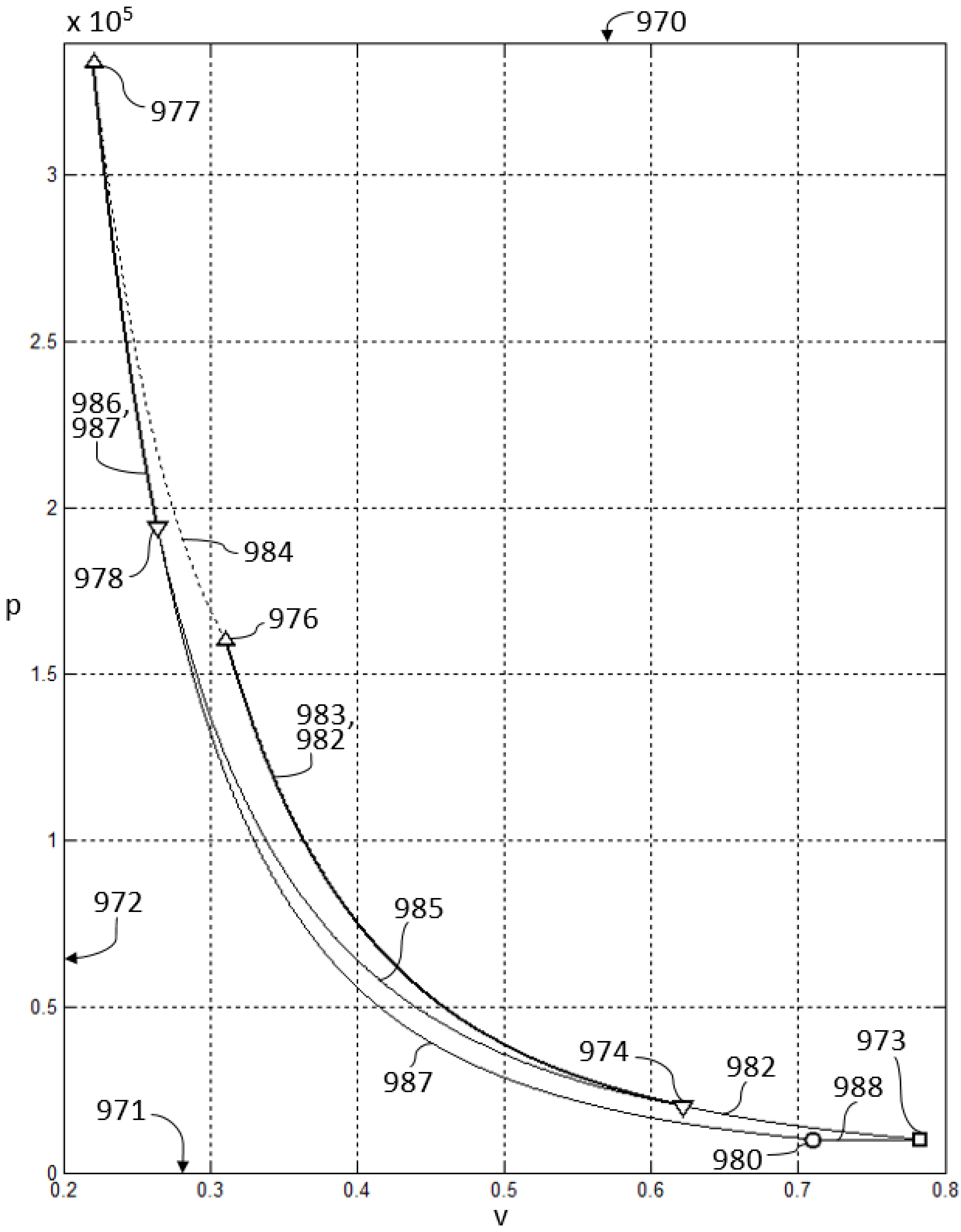
FIG. 10K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982
973
988
987
971
980
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0.3
0.4
0.5
0.6
0.7
0.8
v

FIG. 11

ABSTRACT

By subjecting a volume or a bulk of a working material to a body force per unit mass, such as gravity, inertial forces, electric forces, or magnetic forces, the perceived specific heat capacity of the volume of the working material can be increased or decreased as desired. The artificial modification of the perceived specific heat capacity of a material can be employed in a thermodynamic cycle to convert thermal energy directly into useful mechanical work, and vice versa.

REFRIGERATING METHOD AND APPARATUS

CLAIM OF PRIORITY

[0001] The present patent application is a non-provisional of, and claims the benefit of priority of US Provisional Patent Application No. 62/858,986 filed on June 8, 2019, US Provisional Patent Application No. 62/872,258 filed on July 10, 2019, each of which is hereby incorporated by reference herein in its entirety.

FIELD

[0002] The present invention relates to apparatuses and methods for refrigeration, heating, power generation, and propulsion.

BACKGROUND

[0001] Heat typically flows from a hot thermal reservoir to a cold thermal reservoir when these two thermal reservoirs are in thermal contact with each other. This heat can be transferred via conduction, for instance.

[0002] A conventional heat pump requires mechanical work to be done in order to transfer heat from a cold reservoir to a hot reservoir. For example, a conventional refrigerator consumes electricity in order to remove heat from the cold interior and deliver heat to the warm exterior, such as the room in which the refrigerator is located.

[0003] A conventional heat engine performs mechanical work by absorbing heat from a hot reservoir and transferring heat to a cold reservoir. For example, in a marine steam engine, the working material absorbs heat from a hot reservoir in the boiler, and subsequently performs mechanical work, e.g. on a steam turbine, whereupon the steam transfers heat to a cold reservoir, e.g. the ocean, in the condenser.

[0004] It would be desirable to employ devices which can directly convert thermal energy into useful mechanical work.

SUMMARY

[0003] By subjecting a volume or a bulk of a working material to a body force per unit mass, such as gravity, inertial forces, electric forces, or magnetic forces, the perceived specific heat capacity of the volume of the working material can be increased or decreased as desired. The artificial modification of the perceived macroscopic specific heat capacity of a material can be employed in a thermodynamic cycle to convert thermal energy directly into useful mechanical work, and vice versa. The entropy of a working fluid can be increased and decreased as desired.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. 1A is a cross-sectional view one exemplary embodiment of the invention during an exemplary nominal operating condition. FIG. 1A also contains schematic plots of pressure versus position along the Y-axis at corresponding points along the X-axis within channel 722 of exemplary embodiment 720. This embodiment can be described as a ramjet.

[0005] FIG. 1B is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction.

[0006] FIG. 1C is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction.

[0007] FIG. 2 is a cross-sectional view one exemplary embodiment of the invention during an exemplary nominal operating condition. FIG. 2 also contains schematic plots of pressure versus position along the Y-axis at corresponding points along the X-axis within channel 792 of exemplary embodiment 790. This embodiment can also be described as a ramjet.

[0008] FIGS. 3A-B each show a cross-sectional view of an exemplary embodiment of the invention during an exemplary nominal operating condition. This embodiment can be described as a subsonic and supersonic ramjet.

[0009] FIGS. 4A-C schematically show a cross-sectional view of exemplary embodiments of individual rotor discs and associated rotor blades of exemplary embodiments of the invention, such as the embodiments shown in FIGS. 3A-B, FIGS. 5A-B, and FIGS. 6A-B.

[00010] FIGS. 5A-B each show a cross-sectional view of an exemplary embodiment of the invention during an exemplary nominal operating condition. This embodiment can be described as a subsonic and supersonic ramjet.

[00011] FIGS. 6A-B each show a cross-sectional view of an exemplary embodiment of the invention during an exemplary nominal operating condition. This embodiment can be described as a turbojet engine, or the core of a turbofan engine, for example.

[00012] FIGS. 7A-J schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition. This embodiment can be considered to comprise a rotating radial engine, or a rotary engine, in which the working material does work against the piston.

[00013] FIG. 8 shows a plot of pressure versus specific volume for the working material in a subset of embodiments of the invention for an example method of operation, such as the example method of operation shown in FIGS. 7A-J, or FIGS. 9A-C.

[00014] FIG. 9A shows a cross-sectional view of an exemplary embodiment of the invention employing the principles described in the context of FIGS. 7A-J and FIG. 8. This embodiment can be considered to comprise a rotating radial engine, or a rotary engine, as well as two centrifugal compressors being driven by the main drive shaft.

[00015] FIGS. 9B-C show cross-sectional views of components of a coaxial differential shown in FIG. 9A.

[00016] FIGS. 10A-K schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition. This embodiment can be considered to comprise a rotating radial engine, or a rotary engine, in which the piston does work on the working material.

[00017] FIG. 11 shows a plot of pressure versus specific volume for the working material in a subset of embodiments of the invention for an example method of operation.

DETAILED DESCRIPTION OF THE INVENTION

[00018] FIG. 1A is a cross-sectional view of some embodiments of the invention. The exemplary embodiment 720 shown is cylindrically symmetric about an axis parallel to the X-axis and coincident with the center of exemplary embodiment 720. Outside surface 737 is therefore the shape of a tapered cylinder. In other embodiments, outside surface 737 can be elliptical, rectangular, square, for instance.

[00019] Exemplary embodiment 720 comprises a channel 722 with inside surface 739 located between a first opening 723 and a second opening 728, where the channel comprises a first contraction 724, a first expansion 725, a second contraction 726, and a second expansion 727. The cross-sectional geometry of channel 722 is circular when viewed along the X-direction. Note that the terms “contraction” and “expansion” refer to the magnitude of the radius of the axially symmetric channel. Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions. For example, in other embodiments, the cross-sectional geometry of channel 722 can be annular or ring-shaped. In other embodiments the cross-sectional geometry of channel 722 or outside surface 737 can be square or rectangular. In other embodiments, the cross-sectional geometry of channel 722 or outside surface 737 can be polygonal, such as pentagonal, hexagonal. In some embodiments, the cross-sectional geometry of channel 722 can change from square to circular in the positive X-direction, for example.

[00020] Bulk material 721 can comprise a metal such as aluminium or titanium. Bulk material 721 can also comprise ceramics. In some embodiments, bulk material 721 comprises composites, such as carbon fiber or fiberglass. Bulk material 721 can also comprise electrical insulators such as glass.

[00021] Note that the apparatus contained within inside surface 739 and outside surface 737 does not have to be a solid material, but can contain empty or open spaces in order to not unnecessarily increase the mass or cost of exemplary embodiment 720.

[00022] In FIG. 1, exemplary embodiment 720 moves with constant velocity magnitude and direction relative to a working material in the free stream. The velocity direction of the upstream working material relative to exemplary embodiment 720 is aligned with the X-axis on average, i.e. directed from the left of the page to the right of the page. For clarity of description, the velocity magnitude and direction of the upstream working material relative to exemplary embodiment 720 is assumed to be constant in space and time. In other modes of operation, the upstream relative velocity magnitude and direction need not be constant in space or time. For example, the upstream relative velocity magnitude can increase or decrease as a function of time.

[00023] A working material can be a gas, such as air, helium, or nitrogen, for example. A working material can also be a liquid such as water. Note that water is compressible, although it is often treated as incompressible. In the embodiment shown in the figures, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability are explained herein.

[00024] The working material upstream of exemplary embodiment 720, such as at station 729, is moving faster relative to exemplary embodiment 720 than the speed of sound in the working material in the configuration shown in FIG. 1A. Both the first contraction 724 and the first expansion 725 of channel 722 are configured to decelerate and compress the working material flowing through channel 722 in the positive X-direction relative to exemplary embodiment 720. The first throat 730 is defined to be the portion of channel 722 with the smallest cross-sectional area of channel 722 between first contraction 724 and first expansion 725 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 720 at the first throat 730 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 729, the average relative speed is larger than the speed of sound, and further downstream, such as at station 731, the average relative speed is smaller than the speed of sound within the working material in this embodiment. In some embodiments, there can be a shock wave located between the first throat 730 and station 731. In other words, the relative flow speed of the working material downstream of the first throat 730 can be faster than the speed of sound within the working material, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave. The compression of working material between stations 729 and 731 can be described as a substantially adiabatic compression in this embodiment, where the compression is adiabatic in the sense that no heat is exchanged between the working material in channel 722 and the outside environment in this idealized scenario. As explained below, the adiabatic compression between station 729 and 731 is not isentropic, even in the absence of a shock wave between station 730 and 731. The specific entropy of the working material is reduced between stations 729 and 733 for the depicted operating condition. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 729 and 733 compared to the nominal specific heat capacity of the gas.

[00025] In other embodiments, the compression between stations 729 and 731 can comprise heat transfer from or to the working material. In other embodiments, this compression can at least in part be carried out by an axial compressor, such as an axial compressor found in conventional jet engines. In other embodiments, this compression can at least in part be carried out by a centrifugal compressor, for instance. In some such embodiments, the working material upstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material.

[00026] Both the second contraction 726 and the second expansion 727 of channel 722 are configured to expand the working material flowing through channel 722 in the positive X-direction. The second throat 732 is defined to be the portion of channel 722 with the smallest cross-sectional area of channel 722 between second contraction 726 and second expansion 727 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 720 at the second throat 732 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 731, the average relative speed is smaller than the speed of sound, and downstream, such as at station 733, the average relative speed is larger than the speed of sound within the working material in this embodiment. The expansion of working material between stations 731 and 733 can be described as a substantially adiabatic expansion in this embodiment, where the expansion is adiabatic in the sense that no heat is exchanged between the working material in channel 722 and the outside environment in this idealized scenario. As explained below, the adiabatic expansion between station 731 and 733 is not isentropic.

[00027] In other embodiments, the expansion can comprise heat transfer from or to the working material. In other embodiments, this expansion can at least in part be carried out by an axial turbine, such as an axial turbine found in conventional jet engines. In other embodiments, this expansion can at least in part be carried out by a centrifugal turbine, for instance. In some such embodiments, the working material downstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material.

[00028] Dashed lines 735 and 736 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of exemplary embodiment 720. Streamlines 735 and 736 are therefore part of a streamsurface, or streamtube, which separate working material flowing around exemplary embodiment 720 from working material flowing through channel 722 of exemplary embodiment 720. In this embodiment, the steamtube is circular in cross-section when viewed along the X-direction. The flow direction of the working material relative to exemplary embodiment 720 is indicated by arrow 769.

[00029] A first body force per unit mass generating apparatus, or a first “BFGA”, 740 is located adjacent to channel 722. First BFGA 740 is configured to be able to apply at least one body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this body force can be regulated in this embodiment. The first BFGA 740 comprises a first charge collection 741 and a second charge collection 742. In the configuration shown, first charge collection 741 is negatively charged, and second charge collection 742 is positively charged. In other embodiments, the polarity of the charge in the charge collections can be reversed, i.e. a first charge collection 741 is positively charged, and a second charge collection 742 is negatively charged. The cross-section of first charge collection 741 is annular or ring-shaped when viewed along the X-direction. First charge collection 741 encloses channel 722. First charge collection 741 is electrically insulated from the working material in channel 722 by an electrical insulator such as glass, ceramic, or plastic, in this embodiment. In other embodiments, the first charge collection 741 need not be electrically insulated from the working material in channel 722.

[00030] Second charge collection 742 is circular in cross-section when viewed along the X-direction. Second charge collection 742 is electrically insulated from the working material in channel 722 by an electrical insulator such as glass, ceramic, or plastic, in this embodiment. In other embodiments, the second charge collection 742 need not be electrically insulated from the working material in channel 722. Second charge collection 742 is located within an elongated cylindrical body at the center of channel 722 in this embodiment, and at least in part configured to reduce any drag forces acting on the second charge collection 742 due to the motion of the working material around the second charge collection 742. Second charge collection 742 is structurally supported by two support beams, such as support beam 743. The support beams are configured to rigidly connect the second charge collection 742 to the inside wall surface 739 of exemplary embodiment 720. The streamwise geometry of the support beams is streamlined in order to reduce and drag forces acting on the support beams due to the motion or flow of the working material around the support beams. In other embodiments, there can be only one support beam supporting second charge collection 742. In other embodiments, there can be a plurality of support beams supporting second charge collection 742, such as three or four support beams.

[00031] A third BFGA 751 is configured in a similar manner as first BFGA 740, and will therefore not be described in the same detail as first BFGA 740. Third BFGA 751 comprises a first charge collection 752 configured in a similar manner as first charge collection 741 of first BFGA 740. Third BFGA 751 comprises a second charge collection 753 configured in a similar manner as second charge collection 742. Second charge collection 753 is structurally supported by two support beams.

[00032] The first BFGA 740 and third BFGA 751 are configured to generate a body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 722, where the body force comprises a non-zero component in the YZ-plane and directed towards the center of channel 722, i.e. towards the X-axis. The action of the body force per unit mass reduces the pressure on at least a portion of interior surface 739 throughout the first contraction 724 or the second contraction 726, thereby reducing the retarding force, or drag force, acting on the exemplary embodiment 720 in the positive X-direction. This is due to the surface normal of the interior surface 739 having a component in the negative X-direction throughout the first contraction 724 or the second contraction 726. An artificial reduction in pressure on surfaces with a surface normal which has a non-zero component in the negative X-direction can be employed to artificially reduce the retarding force, or drag force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The direction of the body force per unit mass acting on objects of the working material within channel 722 is indicated by bold arrows, such as bold arrow 772 or bold arrow 773 in FIG. 1A. In some embodiments, the component of the body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the body force acting on the working material within the first contraction 724 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material is carried out by the first BFGA 740. In another example, the body force acting on the working material within the second contraction 726 can comprise a component in the positive X-direction. In this case, at least a portion of the expansion and acceleration of the working material is carried out by the third BFGA 751.

[00033] Due to the action of the body force per unit mass within the first contraction 724 and the second contraction 726, the pressure within the working material within the first contraction 724 and the second contraction 726 decreases in a radially outwards direction, as indicated by line 762 and line 766 in the plot of pressure versus position along the Y-axis at the corresponding point along the X-axis, i.e. at a point in the first contraction 724 and in the second contraction 726. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. The change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic expansion along the radial direction in highly simplified, idealized models, for example.

[00034] In the first contraction 724 and the second contraction 726 the first BFGA 740 and third BFGA 751 are configured to electrically polarize atoms or molecules within the working material. The atoms or molecules can be polarized by an application of an external electric field, for instance. The first BFGA 740 and third BFGA 751 are also configured to exert a force on these polarized molecules, where the force arises from a spatial or temporal gradient in the electric field, or a spatially or temporally non-uniform electric field strength. For instance, the magnitude of the electric field strength produced by the first BFGA 740 or third BFGA 751 can increase in a radially decreasing direction, i.e. in a direction perpendicular to the X-axis and directed towards the X-axis. For instance, the positive or negative radially outward component of the electric field can decrease, i.e. become less positive or more negative, in the radially increasing direction in the case in which the electric polarization axis of the objects within the working material comprises a non-zero component the positive radial direction. For instance, the positive or negative radial component of the electric field can increase, i.e. become less negative or more positive, in the radially increasing direction in the case in which the electric polarization axis of the objects within the working material comprises a non-zero component the negative radial direction. Note that the polarization axis of a polarized molecule typically features a large component in the direction of the local electric field. This can result in a body force per unit mass acting in the negative radial direction, i.e. towards the X-axis, as indicated by the bold arrows in FIG. 1A in the first contraction 724 and the second contraction 726.

[00035] A second BFGA 746 is located adjacent to channel 722. Second BFGA 746 is configured to be able to apply at least one body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this body force can be regulated in this embodiment. The second BFGA 746 comprises several insulated collections of charge, such as charge collection 747, or charge collection 748. The longitudinal axis of each elongated collection of charge is aligned in the streamwise direction. Individual, electrically insulated collections of charge are arranged adjacent to each other in an annular or circumferential fashion around channel 722, as shown in FIG. 1C and FIG. 1A. Adjacent collections of charge, such as collection of charge 747 and collection of charge 750, or collection of charge 748 and collection of charge 749, are oppositely charged.

[00036] In other embodiments, the individual collections of charge need not be longitudinal in a streamwise direction, but can be annular in shape around channel 722. In such embodiments the individual charge collections can be arranged adjacent to each other in a streamwise direction. In yet other embodiments, the individual charge collections can be finite in their extent along the streamwise direction and along the circumferential direction. Adjacent collections of charge can be arranged adjacent to each other in both a streamwise direction and a circumferential or annular direction around channel 722. As before, immediately adjacent collections of charge can comprise charge of opposite polarity. The individual collections of charge of second BFGA 746 are electrically insulated from the working material in channel 722 by an electrical insulator such as glass, ceramic, or plastic, in this embodiment. In other embodiments, the individual collections of charge need not be electrically insulated from the working material in channel 722. In other embodiments, adjacent charge collections need not be oppositely charged, but can be of the same charge.

[00037] A fourth BFGA 755 is configured in a similar manner as second BFGA 746, and will therefore not be described in the same detail as second BFGA 746. Fourth BFGA 755 comprises a charge collection 757 configured in a similar manner as charge collection 748 of second BFGA 746. Third BFGA several longitudinal charge collections with a longitudinal axis oriented in a streamwise direction and arranged adjacent to each other in a circumferential or annular fashion around channel 722. Adjacent collections of charge are oppositely charged.

[00038] The second BFGA 746 and fourth BFGA 755 are configured to generate a body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 722, where the body force comprises a non-zero component in the YZ-plane and directed away from the center of channel 722, i.e. away from the X-axis or in the radially outwards direction. The action of the body force per unit mass increases the pressure on at least a portion of interior surface 739 throughout the first expansion 725 or the second expansion 727 of channel 722, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 720 in the negative X-direction. This is due to the surface normal of the interior surface 739 having a component in the positive X-direction throughout the first expansion 725 or the second expansion 727 of channel 722. An artificial increase in pressure on surfaces with a surface normal which has a non-zero component in the positive X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The direction of the body force per unit mass acting on objects of the working material within channel 722 is indicated by bold arrows, such as bold arrow 772 or bold arrow 773 in FIG. 1A. In some embodiments, the component of the body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the body force acting on the working material within the first expansion 725 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material is carried out by the second BFGA 746. In another example, the body force acting on the working material within the second expansion 727 can comprise a component in the positive X-direction. In this case, at least a portion of the expansion and acceleration of the working material is carried out by the fourth BFGA 727.

[00039] Due to the action of the body force per unit mass within the first expansion 725 or the second expansion 727 of channel 722, the pressure within the working material within the first expansion 725 or the second expansion 727 of channel 722 increases in a radially outwards direction, as indicated by line 764 and line 768 in the plot of pressure versus position along the Y-axis at the corresponding point along the X-axis, i.e. at a point in the first expansion 725 and in the second expansion 727. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. The change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example.

[00040] In the first expansion 725 or the second expansion 727 of channel 722 the second BFGA 746 and fourth BFGA 755 are configured to electrically polarize atoms or molecules within the working material. The atoms or molecules can be polarized by an application of an external electric field, for instance. The second BFGA 746 and fourth BFGA 755 are also configured to exert a force on these polarized molecules, where the force can arise from a spatial or temporal gradient in the electric field, or a spatially or temporally non-uniform electric field strength. For instance, the magnitude of the electric field strength produced by the second BFGA 746 and fourth BFGA 755 can increase in a radially increasing direction, i.e. in a direction perpendicular to the X-axis and directed away from the X-axis, in a radially outwards direction. For instance, the positive or negative radially outward component of the electric field can decrease, i.e. become less positive or more negative, in the radially increasing direction in the case in which the electric polarization axis of the objects within the working material comprises a non-zero component the negative radial direction. For instance, the positive or negative radial component of the electric field can increase, i.e. become less negative or more positive, in the radially increasing direction in the case in which the electric polarization axis of the objects within the working material comprises a non-zero component the positive radial direction. Note that the polarization axis of a polarized molecule typically features a large component in the direction of the local electric field. This can result in a body force per unit mass acting in the positive radial direction, i.e. away from the X-axis, as indicated by the bold arrows in FIG. 1A in the first expansion 725 or the second expansion 727 of channel 722.

[00041] In the embodiment shown in FIG. 1A, the amount of charge in a charge collection in a first BFGA 740, a second BFGA 746, a third BFGA 751, or a fourth BFGA 755 can be regulated by charging or discharging, or reducing the charge in a charge collection. In such embodiments, the charge collections can comprise electrical conductors which are able to facilitate the accumulation of charge, or the reduction in the amount of charge contained within the conductor. In some instances in time the amount of charge in a charge collection can be configured to be zero in some of such embodiments. The charging process can comprise the application of a voltage difference across charge collections of opposite polarity, such as first charge collection 741 and second charge collection 742 of first BFGA 740, or charge collection 747 and charge collection 750. This voltage difference can be supplied by a battery, a capacitor, an inductor, or an electric generator, for example. Oppositely charged charge collections are electrically insulated from each other as well as from portions of bulk material 721. Electrical conductors, such as insulated copper wires, can electrically connect a charge collection to the voltage source. These electrical conductors are not shown. In between a charge collection and the channel 722 the bulk material 721 is an electrical insulator. In effect, charge collections which are oppositely charged can be considered to be the opposite plates of a capacitor, with the dielectric in between these plates comprising the working material as well as the relevant portion of bulk material 721 between the charge collections. In the embodiment shown, the charge collections are configured in a manner in which the majority of electric field lines pass through the working material within channel 722. To that end, an individual charge collection can comprise several insulated conductors. These conductors can be wires, for instance, and can be arranged perpendicular to the streamwise direction, or arranged parallel to a radial direction. This can serve to prevent or diminish any undesirable redistribution of charge within a charge collection.

[00042] In other embodiments, the amount of charge contained within a charge collection is constant in time. In such embodiments, a charge collection can comprise electrons, ions or other charged particle embedded within an electrical insulator. In some such embodiments, a separate voltage source for regulating the amount of charge in a charge collection is not required.

[00043] FIG. 1B is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction. FIG. 1B shows the support beams of second collection of charge 742 of first BFGA 740, such as support beam 738 and support beam 743. The electric field lines, such as electric field line 760, schematically indicate the direction and strength of the electric field within channel 722 at the first contraction 724. The electric field lines are directed from the positive charge within the second collection of charge 742 towards the annular first collection of charge 741, i.e. in a positive radially outward direction. The electric field outside of the first collection of charge 741 is not shown for clarity. Due to the annular geometry of the first collection of charge 741 and the longitudinal geometry and location of the second collection of charge 742 along the center of channel 722, the radially outward component of the electric field decreases in a radially outward direction. Objects within the working material in channel 722 can be electrically polarized by the electric field. The polarization can be proportional to the local electric field for a subset of objects within a working material, for example, as can be the case for a working material comprising monatomic molecules, for instance. The positive radially outward component of the electric field thus decreases, i.e. become less positive, in the radially increasing direction in the case in which the electric polarization axis of the objects within the working material comprises a non-zero component the positive radial direction. This can result in a body force per unit mass acting on objects within the working material, where the body force per unit mass is directed in the radially inwards direction, towards, the X-axis, towards the region of increased electric field strength, away from interior surface 739, and towards the second collection of charge 742. The second collection of charge is structurally supported and electrically insulated from the working material in channel 722 by bulk material 744. The interface between bulk material 744 and the working material is described by surface 745.

[00044] FIG. 1C is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction. As shown, several collections of charge, such as collections of charge 750, 747, 749, or 748, are arranged in circumferential fashion around channel 722. The collections of charge are configured to increase the electric field strength along the radially outward direction within channel 722. This electric field strength can electrically polarize molecules within the working material, and generate a body force per unit mass acting on the polarized molecules in the radially outward direction, away from the X-axis, towards the region of increased electric field strength, towards interior surface 739, and towards the collections of charge or the concentrations of charge.

[00045] FIG. 2 is a cross-sectional view of some embodiments of the invention. The exemplary embodiment 790 shown is cylindrically symmetric about an axis parallel to the X-axis and coincident with the center of exemplary embodiment 790. Outside surface 813 is therefore the shape of a tapered cylinder. In other embodiments, outside surface 813 can be elliptical, rectangular, square, for instance.

[00046] Exemplary embodiment 790 comprises a channel 792 with inside surface 815 located between a first opening 793 and a second opening 801, where the channel comprises a first contraction 794, a first expansion 795, a spin-up segment 796, a second expansion 797, a spin-down segment 798, a second contraction 799, and a third expansion 800. The cross-sectional geometry of channel 792 is circular when viewed along the X-direction. Note that the terms “contraction” and “expansion” refer to the magnitude of the radius of the axially symmetric channel. Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions. For example, in other embodiments, the cross-sectional geometry of channel 792 can be annular or ring-shaped. In other embodiments the cross-sectional geometry of channel 792 or outside surface 813 can be square or rectangular. In other embodiments, the cross-sectional geometry of at least a portion of channel 792 or outside surface 813 can be polygonal, such as pentagonal, hexagonal. In some embodiments, the cross-sectional geometry of channel 792 can change from square to circular, or vice versa, in the positive X-direction, for example.

[00047] Bulk material 791 can comprise a metal such as aluminium, steel, or titanium. Bulk material 791 can also comprise ceramics. In some embodiments, bulk material 791 comprises composites, such as carbon fiber or fiberglass. Bulk material 791 can also comprise electrical insulators such as glass.

[00048] In some embodiments, the apparatus contained within inside surface 815 and outside surface 813 does not have to be a solid material, but can contain empty or open spaces, as is common practice in conventional ramjet or jet engine construction. This can serve to avoid an unnecessarily large mass or cost of exemplary embodiment 790, for instance.

[00049] In FIG. 2, exemplary embodiment 790 moves with constant velocity magnitude and direction relative to a working material in the free stream. The velocity direction of the upstream working material relative to exemplary embodiment 790 is aligned with the X-axis on average, i.e. directed from the left of the page to the right of the page. For clarity of description, the velocity magnitude and direction of the upstream working material relative to exemplary embodiment 790 is assumed to be constant in space and time. In other modes of operation, the upstream relative velocity magnitude and direction need not be constant in space or time. For example, the upstream relative velocity magnitude can increase or decrease as a function of time.

[00050] A working material can be a gas, such as air, helium, or nitrogen, for example. A working material can also be a liquid such as water. In the embodiment shown in the figures, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability are explained herein.

[00051] The working material upstream of exemplary embodiment 790, such as at station 802, is moving faster relative to exemplary embodiment 790 than the speed of sound in the working material in the configuration shown in FIG. 2. The first contraction 794, the second expansion 795, and the third expansion 797 of channel 792 are configured to decelerate and compress the working material flowing through channel 792 in the positive X-direction relative to exemplary embodiment 790. The first throat 803 is defined to be the portion of channel 792 with the smallest cross-sectional area of channel 792 between first contraction 794 and second expansion 795 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 790 at the first throat 803 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 802, the average relative speed is larger than the speed of sound, and further downstream, such as at station 807, the average relative speed is smaller than the speed of sound within the working material in this embodiment. In some embodiments, there can be a shock wave located between the first throat 803 and station 805. In other words, the relative flow speed of the working material downstream of the first throat 803 can be faster than the speed of sound within the working material, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave. During nominal operations a shock wave can be located within the first expansion 795. This can prevent or reduce the probability of an unscheduled engine unstart due to turbulence or variations in the free stream flow velocity of the working material. The compression of the working material between stations 802 and 807 can be described as a substantially adiabatic compression in this embodiment, where the compression is adiabatic in the sense that no heat is exchanged between the working material in channel 792 and the outside environment in this idealized scenario. As explained below, the adiabatic compression between station 802 and 807 is not isentropic, even in the absence of a shock wave between station 803 and 807. The specific entropy of the working material is reduced between stations 803 and 807 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 803 and 807 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas.

[00052] In other embodiments, the compression between stations 802 and 807 can comprise heat transfer from or to the working material. For instance, in some embodiments, fuel can be added to the working material and combusted at or before station 807, similar to a conventional ramjet. In some embodiments, there can be heat transfer from the working material to the bulk material 791 due to temperature differences. In other embodiments, the compression between stations 802 and 803 can at least in part be carried out by an axial compressor, such as an axial compressor found in conventional jet engines. In other embodiments, the compression between stations 802 and 803 can at least in part be carried out by a centrifugal compressor, for instance. In some embodiments, the working material upstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material. In other words, the free stream flow can be subsonic in some embodiments for some modes of operation.

[00053] Both the second contraction 799 and the third expansion 800 of channel 792 are configured to expand and accelerate the working material flowing through channel 792 in the positive X-direction. The second throat 808 is defined to be the portion of channel 792 with the smallest cross-sectional area of channel 792 between second contraction 799 and third expansion 800 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 790 at the second throat 808 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 807, the average relative speed is smaller than the speed of sound, and downstream, such as at station 809, the average relative speed is larger than the speed of sound within the working material in this embodiment. The expansion of the working material between stations 807 and 809 can be described as a substantially adiabatic expansion in this embodiment, where the expansion is adiabatic in the sense that no heat is exchanged between the working material in channel 792 and the outside environment in this idealized scenario. In the embodiment shown in FIG. 2, the adiabatic expansion between station 807 and 809 can also be described as a substantially isentropic expansion.

[00054] In other embodiments, the expansion between station 807 and 809 can comprise heat transfer from or to the working material. In other embodiments, this expansion can at least in part be carried out by an axial turbine, such as an axial turbine found in conventional jet engines. In other embodiments, this expansion can at least in part be carried out by a centrifugal turbine, for instance. In some such embodiments, the working material downstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material.

[00055] Dashed lines 811 and 812 indicate stagnation streamlines which are incident on the leading edge or originate at the trailing edge of exemplary embodiment 790. Streamlines 811 and 812 are therefore part of a streamsurface, or streamtube, which separate working material flowing around exemplary embodiment 790 from working material flowing through channel 792 of exemplary embodiment 790. In this embodiment, the steamtube is circular in cross-section when viewed along the X-direction. The flow direction of the working material relative to exemplary embodiment 790 is indicated by arrow 841.

[00056] A first body force per unit mass generating apparatus, or a first "BFGA", 816 is located within channel 792. First BFGA 816 is configured to be able to apply an effective body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this effective body force can be regulated in this embodiment. The first BFGA 816 comprises a rotating drum 817 which rotates relative to bulk material 791 about axis 822. The drum 817 comprises a bulk material which is annular in cross-section when viewed along the X-axis and which encloses channel 792. The drum 817 is axially symmetric about axis 822, and can thus be considered to be in the shape of a tapered cylinder, or a cylinder of variable radius along the longitudinal length of the cylinder. The drum 817 comprises a first opening 818 and a second opening 819 through which the working material can flow into and out of the volume enclosed by the annular drum 817. The rotating drum can be structurally supported by bulk material 791 or the remainder of exemplary embodiment 790 via bearings, such as ball or roller bearings, fluid bearings, or magnetic bearings, for example.

[00057] The first BFGA 816 comprises a spin-up segment 796 which is configured to induce or increase the rate of rotation in the bulk flow of the working material in channel 792 about axis 822. The spin-up segment 796 comprises at least one rotor disc, such as rotor disc 826. In FIG. 2 there are five rotor discs, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the rotor disc is at least in part structurally supported by drum 817. In other embodiments, the rotor blades can be at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The axis of the central shaft or support disc can be coincident with axis 822, and the radius of the outer surface of the central shaft or the support disc can be smaller than the radius of channel 792 at the location of the central shaft or support disc. At least a portion of the working material can be configured to flow around the central shaft or support disc through channel 792. In some embodiments, at least a portion of the working material can be configured to flow through the central shaft or through the support disc.

[00058] The rate of rotation of the bulk flow of the working material through channel 792 about axis 822 can be configured to be very large, or substantially increased, at station 805 compared to station 803 due to the action of the spin-up segment 796.

[00059] The rotor blades in a rotor disc can be configured in a similar manner as the rotor blades or baffles in a conventional centrifugal compressor. Note that, apart from the deflection of fluid flow in the radially outwards direction by the rotor blades of the rotor discs of the spin-up segment 796 and by the effective centrifugal forces, the axial flow direction of the working material is maintained throughout the spin-up segment 796. This is in contrast to conventional centrifugal compressors, in which the bulk flow of the working material is typically twice deflected through ninety degrees, at the inlet and outlet of a centrifugal compressor, such as a centrifugal compressor found in a conventional turboprop engine. The spin-up segment 796 can thus be considered to be an axial flow centrifugal compressor.

[00060] The rotor blades in a rotor disc in the spin-up segment 796 can also be configured in a similar manner as the rotor blades or baffles in a conventional axial compressor. In some such configurations, an absence of stator discs or stator blades in the spin-up segment 796 can facilitate the increase of the rate of rotation or swirl of the bulk flow of the working material about axis 822 throughout the spin-up segment 796. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-up segment 796, such as between rotor disc 826 and the rotor disc immediately downstream of rotor disc 826, can be employed to enhance the increase of the rate of rotation or swirl of the bulk flow of the working material about axis 822 throughout the spin-up segment 796. In a subset of embodiments, the first expansion 795 of channel 792 can be employed to reduce the maximum local relative flow velocity of the working material relative to the rotor blades of the rotor disc of spin-up segment 796 to subsonic speeds during nominal operations. This can reduce the wave drag associated with the formation of shock waves at the rotor discs of spin-up segment 796.

[00061] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about axis 822 in the spin-up segment 796 can be provided by a separate electrical motor, for example. The electrical motor can be configured to rotate drum 817, and thereby rotate, and supply mechanical power to, the rotor discs of spin-up segment 826. The electrical power supplied to the electrical motor can be provided by a battery, or by an electrical generator which is driven by a separate turbine, such as the turbine in an auxiliary power unit. For instance, an electrical motor can be employed to power the first BFGA 798 and increase the rate of rotation of drum 817 and the associated rotor discs of the spin-up segment 796 during the starting of the engine 790, i.e. the increase of the net thrust of the exemplary embodiment 790 from a value which is zero or less than zero, i.e. directed in the positive X-direction, to a value which is above zero, i.e. directed in the negative X-direction.

[00062] The working material flowing through second expansion 797 comprises an axial flow component as well as a rotational or swirl component due to the rotation about axis 822 imparted to the working material by the spin-up segment 796. In order to maintain the rate of rotation of the bulk flow of the working material about axis 822, second expansion 797 can comprise baffles arranged in a streamwise direction, i.e. along the X-direction. The baffles can be rigidly connected to drum 817, and therefore rotate about axis 822. The baffles can be configured to prohibit, or restrict or reduce, the circumferential motion of the working material about the X-axis relative to the drum 817 or relative to the baffles. In this scenario, since the drum 817 and the baffles are rotating, the angular rate of rotation of the bulk flow of the working material in the second expansion 797 is substantially equal to the angular rate of rotation of the drum 817 and the baffles about axis 822. Thus the baffles can be employed to control and regulate the rate of rotation of the working material flowing through second expansion 797.

[00063] The first BFGA 816 comprises a spin-down segment 798 which is configured to decrease the rate of rotation in the bulk flow of the working material in channel 792 about axis 822. The spin-down segment 798 comprises at least one rotor disc, such as rotor disc 832. The rotor discs in the spin-down segment 798 can be configured in a similar manner as the rotor discs in the spin-up segment 796. In FIG. 2 there are three rotor discs in spin-down segment 798, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the rotor disc is at least in part structurally supported by drum 817. In other embodiments, the rotor blades can be at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines, and as described in the context of the spin-up segment 796.

[00064] The rate of rotation of the bulk flow of the working material through channel 792 about axis 822 can be configured to be negligible, or substantially reduced, at station 807 compared to station 806 or station 805 due to the action of the spin-down segment 798.

[00065] The rotor discs of spin-down segment 798 can be configured in a similar manner as the rotor blades or baffles in a conventional centrifugal turbine. As described in the context of the spin-up segment 796, the spin-down segment 798 can be considered to be an axial flow centrifugal turbine.

[00066] The rotor discs of spin-down segment 798 can also be configured in a similar manner as the rotor blades or baffles in a conventional axial turbine. In some such configurations, an absence of stator discs or stator blades in the spin-down segment 798 can facilitate the decrease of the rate of rotation or swirl of the bulk flow of the working material about axis 822 throughout the spin-down segment 798. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-down segment 798, such as between rotor disc 832 and the rotor disc immediately upstream of rotor disc 832, can be employed to enhance the decrease of the rate of rotation or swirl of the bulk flow of the working material about axis 822 throughout the spin-down segment 798.

[00067] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about axis 822 in the spin-up segment 796 can be provided by the mechanical power extracted from the working material during the decrease in the rate of rotation of the working material about axis 822 in the spin-down segment 798. This decrease in the rate of rotation of the working material in spin-down segment 798 can be generate a torque which acts on the rotor discs of spin-down segment 798 about axis 822, and which can be mechanically transferred to drum 817, and to the rotor discs of spin-up segment 796. In other embodiments, the rotor discs in spin-down segment 8798 can be configured to drive an electrical generator. At least a portion of the energy recovered by the electrical generator can be employed to deliver electrical power to an electrical motor configured to drive the rotor discs of spin-up segment 796.

[00068] In the embodiment shown in FIG. 790, the first BFGA 816 is comprises a single spool connecting the rotor discs of the spin-up segment 796 with the rotor discs of the spin-down segment 798 via a single shaft 817. In other embodiments, the first BFGA can comprise two spools, three spools, or a larger number of spools. For example, a first drive shaft can connect the rotor disc 826 of spin-up segment 796 to the rotor disc 832 of spin-down segment 798, thereby forming a first spool. A second drive shaft can connect the remaining rotor discs of spin-up segment 796 to the remaining rotor discs of spin-down segment 798, thereby forming a second spool. The first drive shaft can be configured to pass through the center of the second drive shaft. Such multi-spool architectures are common in conventional turbofan engines, for example.

[00069] The first BFGA 816 is configured to generate an effective body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 792, where the effective body force comprises a non-zero component in the YZ-plane and directed away from the center of channel 792, i.e. away from the X-axis or in the radially outwards direction. The effective body force per unit mass acting on the working material arises from the rotation of the working material in an inertial frame, about axis 822, within the second expansion 797 of channel 722. Due to the lack of a centripetal body force per unit mass acting on the objects of a working material in the negative radial direction, there is an effective or perceived centrifugal body force per unit mass acting in the positive radial direction on objects in the working material, as indicated by the bold arrows, such as bold arrow 843. In the steady state, the effective centrifugal force is balanced by the interior surface 815 of drum 817 of BFGA 816, and an increase in the pressure and density of the working material in the radially increasing direction, i.e. in the direction in the YZ-plane and away from axis 822, or away from the X-axis.

[00070] The action of the effective body force per unit mass increases the pressure on at least a portion of interior surface 815 throughout the second expansion 797 of channel 792, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 790 in the negative X-direction. This is due to the surface normal of the interior surface 815 having a component in the positive X-direction throughout the second expansion 797 of channel 792. An artificial increase in pressure on surfaces with a surface normal which has a non-zero component in the positive X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The direction of the effective body force per unit mass acting on objects of the working material within channel 792 is indicated by bold arrows, such as bold arrow 843 in FIG. 2. In some embodiments, the component of the effective body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the effective body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the effective body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the effective body force acting on the working material within the second expansion 797 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material is carried out by the first BFGA 816.

[00071] Due to the action of the effective body force per unit mass within the second expansion 797 of channel 792, the pressure within the working material within the second expansion 797 of channel 792 increases in a radially outwards direction, as indicated by line 836 in the plot of pressure versus position along the Y-axis at the corresponding point along the X-axis, i.e. at a point in the second expansion 797. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. The change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example. Upstream of the spin-up segment 796 and downstream of the spin-down segment 798 the rate of rotation of the working material is negligible in the simplified embodiment shown in FIG. 2. The radial variation of the pressure at these locations is approximately uniform, as indicated by lines 834, 838, and 840 in the plots of pressure versus position along the Y-axis at the corresponding point along the X-axis, i.e. at a point along the X-axis in the first contraction 794, the second contraction 799, and the third expansion 800, respectively.

[00072] A wide variety of body force generating apparatuses, or combinations thereof, can be employed in embodiments of the invention. For example, in other embodiments, the pressure at a point along the X-axis in the first contraction 794, the second contraction 799, or the third expansion 800 need not be substantially uniform in the radial direction, but can vary in the radial direction, as exemplified by the embodiment shown in FIG. 1A. For example, a second BFGA configured in a similar manner as the first BFGA 816 can be located within at least a portion of the third expansion 800 and configured to generate a body force on the working material directed in the radially outward direction, as is the case in the first BFGA 816. In another example, other types of BFGA, such as the type of BFGA described in FIG. 1A can be used in place of, or concurrently with, the first BFGA 816 in the exemplary embodiment shown in FIG. 2, or throughout portions of channel 792 in which no dedicated BFGA is being employed, such as the first contraction 794, the second contraction 799, or the third expansion 800. As discussed in the context of FIG. 1A, a BFGA can be employed to generate a body force on the working material in the first contraction 794 or the second contraction 799, where the body force can comprise a component in a radially inward direction, away from interior surface 815. As discussed in the context of FIG. 1A and FIG. 2, a BFGA can be employed to generate a body force on the working material in the first expansion 795, the second expansion 797, or the third expansion 800, where the body force can comprise a component in a radially outward direction, towards interior surface 815.

[00073] In another example, several embodiments, such as embodiment 790, or embodiment 720, can be connected in series. For example, an embodiment of the invention can comprise a first and a second embodiment 790 of the type shown in FIG. 2 connected in series, such that the station 808 of the first embodiment is coincident with station 803 of the second embodiment. Due to the cooling of the working material throughout successive embodiments, and the unchanged maximum cross-sectional area of channel 722 or channel 792, the amount of thrust produced by two embodiments connected in series can exceed the thrust produced by two identical and equivalent embodiments connected in parallel, i.e. operated independently of each other.

[00074] The exemplary embodiment 720 and the exemplary embodiment 790, as well as other embodiments operated in accordance with the invention, can be employed to reduce the specific entropy of the working material interacting with the embodiments. This can be employed to convert thermal energy of the working material directly into useful work. For instance, embodiment 720 can generate a net thrust force in the negative X-direction. The power associated with the generation of this force can be provided by the thermal energy of the working material flowing through channel 722. Thus, the working material at station 733 is at a lower temperature than the working material at station 729, and the relative velocity of the working material at station 733 is larger than the relative velocity of the working material at station 729 relative to embodiment 720. The acceleration of the working material and the cooling of the working material is a consequence of the work done by the working material on embodiment 720. Embodiment 790 can interact with the working material flowing through channel 792 in similar fashion.

[00075] FIGS. 3A-B show a cross-sectional view of one embodiment of the invention. This embodiment can be described as a subsonic and supersonic ramjet. The embodiment shown in FIGS. 3A-B is configured in a similar manner as the embodiment shown in FIG. 2, and will therefore not be described in the same detail.

[00076] The exemplary embodiment 100 shown is substantially cylindrically symmetric about an axis parallel to the long axis of the embodiment, denoted the X-axis, and coincident with the center of exemplary embodiment 100. The X-axis is parallel to, and coincident with, a line connecting the tip 105 of the spike 104 with the tip 108 of the exit fairing 109, and directed to the right of the page. Outside surface 129 is therefore the shape of a tapered cylinder. In other embodiments, outside surface 129 can be elliptical, rectangular, or square, for instance.

[00077] Exemplary embodiment 100 comprises a channel 102 with inside surface of drum 133 located between a first opening 103 and a second opening 117, where the channel comprises a first contraction 110, a first expansion 111, a spin-up segment 112, a second expansion 113, a spin-down segment 114, a second contraction 115, and a third expansion 116. The cross-sectional geometry of channel 102 is circular when viewed along the X-direction. Note that the terms “contraction” and “expansion” refer to the magnitude of the maximum radius of the axially symmetric channel.

[00078] Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions. For example, in other embodiments, the cross-sectional geometry of channel 102 can be annular or ring-shaped. In other embodiments the cross-sectional geometry of channel 102 or outside surface 129 can be square or rectangular. In other embodiments, the cross-sectional geometry of at least a portion of channel 102 or outside surface 129 can be polygonal, such as pentagonal, hexagonal. In some embodiments, the cross-sectional geometry of channel 102 can change from square to circular, or vice versa, in the positive X-direction, for example. For instance, the channel can be rectangular at the first opening 103, annular at the opening 134 to the spin-up segment 112 and station 123, and rectangular again at station 124 and exit 117. The rectangular opening and exit can facilitate easier modification of the channel cross-sectional area, since the cross-sectional area of a rectangular channel can be modified by simple ramps, as exemplified by the rectangular variable area inlet of the Concorde engines or the F-14 Tomcat engines. By contrast, the cross-sectional area of a circular channel can be modified by the mechanically more complex circular or polygonal variable area nozzles, as exemplified by the exhaust nozzles of the Concorde engines. The modification of the cross-sectional area of the channel is particularly relevant for flight at variable subsonic and supersonic speeds. Engines with different channel geometries, as well as different methods for modifying the cross-sectional area of a channel, are within the scope of the invention.

[00079] In the embodiment shown in FIGS. 3A-B, the inlet is configured to be able to modify the smallest cross-sectional area of the channel 102. This is accomplished by a translating spike 104 which is able to move along the positive and negative X-direction along support shaft 107 inside slot 106. In FIG. 3A the spike is shown in an extended position, which facilitates an increased cross-sectional area at the inlet of channel 102. The spike can be in this position at low subsonic speeds, high subsonic speeds, and low supersonic speeds, for example. In FIG. 3B the spike is shown in a retracted position, which facilitates a reduced cross-sectional area at the inlet of channel 102 and at throat 119. The spike can be in such a position at low and high supersonic speeds, for example. The mode of operation of the spike and the purpose of the spike is similar to the spike at the inlet of the engines of the Lockheed SR-71 Blackbird.

[00080] In the embodiment shown in FIGS. 3A-B, the exhaust nozzle 150 is configured to be able to modify the smallest cross-sectional area of the channel 102. This is facilitated by variable cross-sectional area nozzles, such as primary nozzle 151, secondary nozzle 153, and fairing nozzle 155. In FIG. 3B, the primary nozzle 151 is configured to reduce the cross-sectional area of the channel 102, while secondary nozzle 153 is configured to increase the cross-sectional area of the channel 102.

The exhaust nozzle 150 can be in such a position at high subsonic speeds, as well as low and high supersonic speeds, for example. The elements of secondary nozzle 153 are rotably coupled to the tip of primary nozzle 151. The individual primary nozzle 151, secondary nozzle 153, and fairing nozzle 155 are configured with overlapping leaves or panels, as is the case for exhaust nozzles of conventional supersonic turbojet engines, such as the engines on the Eurofighter Typhoon. In other embodiments, the variable geometry exhaust nozzle of engine 100 can be configured in a similar manner as the variable geometry exhaust nozzle of conventional supersonic turbojet engines, such as the ejector type exhaust nozzle of the SR-71. In FIG. 3B, the exhaust nozzle is configured to accelerate the flow in channel 102 to supersonic speeds. In FIG. 3A, the exhaust nozzle 150 is shown in a stored configuration. The primary nozzle 151 and the secondary nozzle 153 are folded in a radially outward direction. The exhaust nozzle 150 can be in such a position at low and high subsonic speeds, or low supersonic speeds, for example.

[00081] Bulk material 101 can comprise a metal such as aluminium, steel, or titanium. Bulk material 101 can also comprise ceramics. In some embodiments, bulk material 101 comprises composites, such as carbon fiber or fiberglass.

[00082] In some embodiments, the apparatus contained within inside surface of drum 133 and outside surface 129 does not have to be a solid material, but can contain empty or open spaces, as is common practice in conventional ramjet or jet engine construction. This can serve to avoid an unnecessarily large mass or cost of exemplary embodiment 100, for instance.

[00083] In FIGS. 3A-B, exemplary embodiment 100 moves with constant velocity magnitude and direction relative to a working material in the free stream. The velocity direction of the upstream working material relative to exemplary embodiment 100 is aligned with the X-axis on average, i.e. directed from the left of the page to the right of the page. For clarity of description, the velocity magnitude and direction of the upstream working material relative to exemplary embodiment 100 is assumed to be constant in space and time. In other modes of operation, the upstream relative velocity magnitude and direction need not be constant in space or time. For example, the upstream relative velocity magnitude can increase or decrease as a function of time.

[00084] A working material can be a gas, such as air, helium, or nitrogen, for example. A working material can also be a liquid such as water. In the embodiment shown in the figures, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability are explained herein.

[00085] The working material upstream of exemplary embodiment 100, such as at station 118, is moving faster relative to exemplary embodiment 100 than the speed of sound in the working material in the configuration shown in FIG. 3B. The first contraction 110, the second expansion 111, and the third expansion 113 of channel 102 are configured to decelerate and compress the working material flowing through channel 102 in the positive X-direction relative to exemplary embodiment 100. The first throat 119 is defined to be the portion of channel 102 with the smallest cross-sectional area of channel 102 between first contraction 110 and second expansion 111 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 100 at the first throat 119 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 118, the average relative speed is larger than the speed of sound, and further downstream, such as at station 123, the average relative speed is smaller than the speed of sound within the working material in this embodiment. In some embodiments, there can be a shock wave located between the first throat 119 and station 120. In other words, the relative flow speed of the working material downstream of the first throat 119 can be faster than the speed of sound within the working material, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave. During nominal operations a shock wave can be located within the first expansion 111. This can prevent or reduce the probability of an unscheduled engine unstart due to turbulence or variations in the free stream flow velocity of the working material. The compression of the working material between stations 118 and 123 can be described as a substantially adiabatic compression in this embodiment, where the compression is adiabatic in the sense that no heat is exchanged between the working material in channel 102 and the outside environment in this idealized scenario. The adiabatic compression between station 121 and 122 is not isentropic, even in the absence of a shock wave between stations 121 and 122. The specific entropy of the working material is reduced between stations 121 and 122 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 120 and 123 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas.

[00086] In other embodiments, the compression between stations 118 and 123 can comprise heat transfer from or to the working material. For instance, in some embodiments, fuel can be added to the working material and combusted at or before station 123, similar to a conventional ramjet. In some embodiments, there can be heat transfer from the working material to the bulk material 101 due to temperature differences. In other embodiments, the compression between stations 118 and 120 can at least in part be carried out by an axial compressor, such as an axial compressor found in conventional jet engines. In other embodiments, the compression between stations 118 and 120 can at least in part be carried out by a centrifugal compressor, for instance. In some embodiments, the working material upstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material. In other words, the free stream flow can be subsonic in some embodiments for some modes of operation.

[00087] Both the second contraction 115 and the third expansion 116 of channel 102 are configured to expand and accelerate the working material flowing through channel 102 in the positive X-direction. The second throat 124 is defined to be the portion of channel 102 with the smallest cross-sectional area of channel 102 between second contraction 115 and third expansion 116 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 100 at the second throat 124 is approximately equal to the speed of sound within the working material at that location. Upstream, such as at station 123, the average relative speed is smaller than the speed of sound, and downstream, such as at station 125, the average relative speed is larger than the speed of sound within the working material in this embodiment. The expansion of the working material between stations 123 and 125 can be described as a substantially adiabatic expansion in this embodiment, where the expansion is adiabatic in the sense that no heat is exchanged between the working material in channel 102 and the outside environment in this idealized scenario. In the embodiment shown in FIGS. 3A-B, the adiabatic expansion between station 123 and 125 can also be described as a substantially isentropic expansion.

[00088] In other embodiments, there can be heat transfer from or to the working material between stations 120 and 125, or stations 123 and 125. In some embodiments, there can be heat transfer from the working material to the bulk material 101 due to temperature differences, for example. In other embodiments, heat can be deliberately added or removed from the working material. In other embodiments, the expansion between stations 123 and 125 can at least in part be carried out by an axial turbine, such as an axial turbine found in conventional jet engines. In other embodiments, this expansion can at least in part be carried out by a centrifugal turbine, for instance. In some such embodiments, the working material downstream of the embodiment can move relative to the embodiment at a speed slower than the speed of sound in the working material. In other words, the exhaust can be subsonic relative to the engine 100 in some embodiments or some modes of operation.

[00089] A first body force per unit mass generating apparatus, or a first "BFGA", 132 is located within channel 102. First BFGA 132 is configured to be able to apply an effective body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this effective body force can be regulated in this embodiment. The first BFGA 132 comprises a rotating drum 133 which rotates relative to bulk material 101 about the X-axis. The drum 133 comprises a bulk material which is annular in cross-section when viewed along the X-axis and which encloses channel 102. The drum 133 is axially symmetric about the X-axis, and can thus be considered to be in the shape of a tapered cylinder, or a cylinder of variable radius along the longitudinal length of the cylinder. The drum 133 comprises a first opening 134 and a second opening through which the working material can flow into and out of the volume enclosed by the annular drum 133. The rotating drum can be structurally supported by bulk material 101 or the remainder of exemplary embodiment 100 via bearings, such as ball or roller bearings, fluid bearings, or magnetic bearings, for example.

[00090] The first BFGA 132 comprises a spin-up segment 112 which is configured to induce or increase the rate of rotation in the bulk flow of the working material in channel 102 about the X-axis. The spin-up segment 112 comprises at least one rotor disc, such as rotor discs 142, 143, and 144. In FIGS. 3A-B there are three rotor discs, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the rotor disc 144 is at least in part structurally supported by drum 133. The rotor blades of the rotor discs 142 and 143 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 142 are supported by shaft 149. The rotor blades of the rotor disc 143 are supported by shaft 148. The axis of the central shaft or support disc can be coincident with the X-axis, and the radius of the outer surface of the central shaft or the support disc can be smaller than the radius of channel 102 at the location of the central shaft or support disc. At least a portion of the working material can be configured to flow around the central shaft or support disc through channel 102. In some embodiments, at least a portion of the working material can be configured to flow through the central shaft or through the support disc.

[00091] The rate of rotation of the bulk flow of the working material through channel 102 about the X-axis can be configured to be very large, or substantially increased, at station 121 compared to station 119 due to the action of the spin-up segment 112.

[00092] The rotor blades in a rotor disc can be configured in a similar manner as the rotor blades or baffles in a conventional centrifugal compressor. Note that, apart from the deflection of fluid flow in the radially outwards direction by the rotor blades of the rotor discs of the spin-up segment 112 and by the effective centrifugal forces, the axial flow direction of the working material is maintained throughout the spin-up segment 112. This is in contrast to conventional centrifugal compressors, in which the bulk flow of the working material is typically deflected through ninety degrees at least once, at the inlet of a centrifugal compressor, such as a centrifugal compressor found in a conventional turboprop engine. The spin-up segment 112 can thus be considered to be an “axial flow centrifugal compressor”. The rate of rotation of the rotor blades can be modified to regulate the rate of rotation of the working material within the BFGA 132 for a given free stream flow speed and a given desired thrust.

[00093] The rotor blades in a rotor disc in the spin-up segment 112 can also be configured in a similar manner as the rotor blades in a conventional axial compressor. In some such configurations, an absence of stator discs or stator blades in the spin-up segment 112 compared to a conventional axial compressor can facilitate the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 112. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-up segment 112, such as between rotor disc 142 and rotor disc 143, can be employed to enhance the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 112. In a subset of embodiments, the first expansion 111 of channel 102 can be employed to reduce the maximum local relative flow velocity of the working material relative to the rotor blades of the rotor disc of spin-up segment 112 to subsonic speeds during nominal operations. This can reduce the wave drag associated with the formation of shock waves at the rotor discs of spin-up segment 112. In other embodiments, the spin-up segment 112 can consist only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to impart a rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 101 of engine 100. In other embodiments, the stator blades are rotably coupled to the bulk material 101 of the engine 100, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 132 for a given free stream flow speed and a given desired thrust.

[00094] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 112 can be provided by a separate electrical motor, for example. The electrical motor can be configured to rotate drum 133, and thereby rotate, and supply mechanical power to, the rotor discs of spin-up segment 142. The electrical power supplied to the electrical motor can be provided by a battery, or by an electrical generator which is driven by a separate turbine, such as the turbine in an auxiliary power unit, or a turbine located downstream of station 123. For instance, an electrical motor can be employed to power the first BFGA 132 and increase the rate of rotation of drum 133 and the associated rotor discs of the spin-up segment 112 during the starting of the engine 100, i.e. the increase of the net thrust of the exemplary embodiment 100 from a value which is zero or less than zero, i.e. directed in the positive X-direction, to a value which is above zero, i.e. directed in the negative X-direction.

[00095] The working material flowing through second expansion 113 comprises an axial flow component as well as a rotational or swirl component due to the rotation about the X-axis imparted to the working material by the spin-up segment 112. In order to maintain the rate of rotation of the bulk flow of the working material about the X-axis, second expansion 113 can comprise baffles arranged in a streamwise direction, i.e. along the X-direction. The baffles can be rigidly connected to drum 133, and therefore rotate about the X-axis. The baffles can be configured to prohibit, or restrict or reduce, the circumferential motion of the working material about the X-axis relative to the drum 133 or relative to the baffles. In this scenario, since the drum 133 and the baffles are rotating, the angular rate of rotation of the bulk flow of the working material in the second expansion 113 is substantially equal to the angular rate of rotation of the drum 133 and the baffles about the X-axis. Thus the baffles can be employed to control and regulate the rate of rotation of the working material flowing through second expansion 113. In other embodiments, there need not be any baffles between station 121 and 122, allowing the working material to rotate substantially freely about the X-axis between stations 121 and 122. Note that the viscous drag from drum 133 can also contribute a rate of rotation to the working material flowing through drum 133.

[00096] The first BFGA 132 comprises a spin-down segment 114 which is configured to decrease the rate of rotation in the bulk flow of the working material in channel 102 about the X-axis. The spin-down segment 114 comprises at least one rotor disc, such as rotor disc 146 or rotor disc 147. The rotor discs in the spin-down segment 114 can be configured in a similar manner as the rotor discs in the spin-up segment 112. In FIGS. 3A-B there are three rotor discs in spin-down segment 114, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the upstream rotor disc of spin down segment 114 is at least in part structurally supported by drum 133. The rotor blades of the rotor discs 146 and

147 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 147 are supported by shaft 149. The rotor blades of the rotor disc 146 are supported by shaft 148.

[00097] The rate of rotation of the bulk flow of the working material through channel 102 about the X-axis can be configured to be negligible, or substantially reduced, at station 123 compared to station 122 or station 121 due to the action of the spin-down segment 114.

[00098] As described in the context of the spin-up segment 112, the spin-down segment 114 can be considered to be an axial flow centrifugal turbine.

[00099] The rotor discs of spin-down segment 114 can also be configured in a similar manner as the rotor blades in a conventional axial turbine. In some such configurations, an absence of stator discs or stator blades in the spin-down segment 114 can facilitate the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 114. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-down segment 114, such as between rotor disc 146 and rotor disc 147, can be employed to enhance the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 114. In other embodiments, the spin-down segment 114 can consist only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to reduce the rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 101 of engine 100. In other embodiments, the stator blades are rotably coupled to the bulk material 101 of the engine 100, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 132 for a given free stream flow speed and a given desired thrust. The function of the stator blades is identical to the function of the rotor blades in the spin-down segment 114.

[000100] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 112 can be provided by the mechanical power extracted from the working material during the decrease in the rate of rotation of the working material about the X-axis in the spin-down segment 114. This decrease in the rate of rotation of the working material in spin-down segment 114 can be generate a torque which acts on the rotor discs of spin-down segment 114 about the X-axis, and which can be mechanically transferred to drum 133 and to the drive shafts 148 and 149, and to the rotor discs of spin-up segment 112. In other embodiments, the rotor discs in spin-down segment 114 can be configured to drive an electrical generator. At least a portion of the energy recovered by the electrical generator can be employed to deliver electrical power to an electrical motor configured to drive the rotor discs of spin-up segment 112. In the case in which the spin-up segment comprises stator discs, the torque acting on the stator discs in the spin-down segment 114 can be cancelled by the torque acting on the working material in the spin-up segment 112 during nominal operations, such that there is no net torque on the engine 100.

[000101] In the embodiment shown in FIG. 100, the first BFGA 132 is comprises a three spools connecting the rotor discs of the spin-up segment 112 with the rotor discs of the spin-down segment 114 via external drive shaft or drum 133, and internal drive shafts 149 and 148. In other embodiments, the first BFGA can comprise two spools, four spools, or a larger number of spools. Such multi-spool architectures are common in conventional turbofan engines, for example.

[000102] The first BFGA 132 is configured to generate an effective body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 102, where the effective body force comprises a non-zero component in the YZ-plane and directed away from the center of channel 102, i.e. away from the X-axis or in the radially outwards direction. The effective body force per unit mass acting on the working material arises from the rotation of the working material in an inertial frame, about the X-axis, within the second expansion 113 of channel 722. Due to the lack of a centripetal body force per unit mass acting on the objects of a working material in the negative radial direction, there is an effective or perceived centrifugal body force per unit mass acting in the positive radial direction, i.e. in a radially outward direction, on objects in the working material. In the steady state, the effective centrifugal force is balanced by the interior surface of drum 133 of BFGA 132, and an increase in the pressure and density of the working material in the radially increasing direction, i.e. in the direction in the YZ-plane and away from the X-axis, or away from the X-axis.

[000103] The action of the effective body force per unit mass increases the pressure on at least a portion of interior surface of drum 133 throughout the second expansion 113 of channel 102, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 100 in the negative X-direction. This is due to the surface normal of the interior surface of drum 133 having a component in the positive X-direction throughout the second expansion 113 of channel 102. An artificial increase in pressure on surfaces with a surface normal which has a non-zero component in the positive X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The specific entropy of the working material is reduced between stations 121 and 122 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 121 and 122 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas. The modification of the specific heat capacity between stations 121 and 122 is similar in principle to the modification of the specific heat capacity discussed in the context of FIGS. 7A-J.

[000104] The direction of the effective body force per unit mass acting on objects of the working material within channel 102 is in the radially outward direction. In some embodiments, the component of the effective body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the effective body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the effective body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the effective body force acting on the working material within the second expansion 113 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material would be carried out by the first BFGA 132.

[000105] Due to the action of the effective body force per unit mass within the second expansion 113 of channel 102, the pressure within the working material within the second expansion 113 of channel 102 increases in a radially outwards direction at a given location along the length of the channel. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. At a given location along the length of the channel the change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example. Upstream of the spin-up segment 112 and downstream of the spin-down segment 114 the rate of rotation of the working material about the X-axis is negligible in the simplified embodiment shown in FIGS. 3A-B. The radial variation of the pressure between stations 118 and 120, and between stations 123 and 125 is approximately uniform.

[000106] A wide variety of body force generating apparatuses, or combinations thereof, can be employed in embodiments of the invention. For example, in other embodiments, the pressure at a point along the X-axis in the first contraction 110, the second contraction 115, or the third expansion 116 need not be substantially uniform in the radial direction, but can vary in the radial direction, as exemplified by the embodiment shown in FIG. 1A. For example, a second BFGA configured in a similar manner as the first BFGA 132 can be located within at least a portion of the third expansion 116 and configured to generate a body force on the working material directed in the radially outward direction, as is the case in the first BFGA 132. In another example, other types of BFGA, such as the type of BFGA described in FIG. 1A can be used in place of, or concurrently with, the first BFGA 132 in the exemplary embodiment shown in FIGS. 3A-B, or throughout portions of channel 102 in which no dedicated BFGA is being employed, such as the first contraction 110, the second contraction 115, or the third expansion 116. As discussed in the context of FIG. 1A, a BFGA can be employed to generate a body force on the working material in the first contraction 110 or the second contraction 115, where the body force can comprise a component in a radially inward direction, away from interior surface 131. As discussed in the context of FIG. 1A and FIGS. 3A-B, a BFGA can be employed to generate a body force on the working material in the first expansion 111, the second expansion 113, or the third expansion 116, where the body force can comprise a component in a radially outward direction, towards interior surface 131.

[000107] In another example, several embodiments, such as embodiment 100, can be connected in series. For example, an embodiment of the invention can comprise a first and a second embodiment 100 of the type shown in FIGS. 3A-B connected in series, such that the station 124 of the first embodiment is coincident with station 119 of the second embodiment, or such that station 124 of the first embodiment is coincident with station 120 of the second embodiment. Due to the cooling of the working material throughout successive embodiments, and the unchanged maximum cross-sectional area of channel 102, the amount of thrust produced by two embodiments connected in series can exceed the thrust produced by two identical and equivalent embodiments connected in parallel, i.e. operated independently of each other.

[000108] The exemplary embodiment 100, as well as other embodiments operated in accordance with the invention, can be employed to reduce the specific entropy of the working material interacting with the embodiments. This can be employed to convert thermal energy of the working material directly into useful work. For instance, embodiment 100 can generate a net thrust force in the negative X-direction. The power associated with the generation of this force can be provided by the thermal energy of the working material flowing through channel 102. Thus, the working material at station 125 is at a lower temperature than the working material at station 118, and the relative velocity of the working material at station 125 is larger than the relative velocity of the working material at station 118 relative to embodiment 100. The acceleration of the working material and the cooling of the working material is a consequence of the work done by the working material on embodiment 100.

[000109] FIGS. 4A-C schematically show a cross-sectional view of exemplary embodiments of individual rotor discs and associated rotor blades of exemplary embodiments of the invention, such as the embodiments shown in FIGS. 3A-B, FIGS. 5A-B, and FIGS. 6A-B.

[000110] FIG. 4A schematically shows a circumferential cross-section of 5 rotor discs, namely rotor discs 180, 182, 186, 191, and 193. The radially inward direction is directed into the page, and the flow direction is directed from the left of the page to the right of the page. Each rotor disc comprises several rotor blades, such as rotor blades 181, 183, 190, 192, and 194. All rotor blades rotate in a downwards direction, i.e. from the top of the page towards the bottom of the page during nominal operations. A spin-up segment apparatus can be considered to comprise rotor discs 180 and 182, as well as spin-up segment 187 and baffle segment 188 of rotor disc 186. A spin-down segment apparatus can be considered to comprise rotor discs 191 and 193, as well as spin-down segment 189 of rotor disc 186. The spin-up segment apparatus, i.e. the first rotor disc 180, the second rotor disc 182, and the spin-up portion 187 of the third rotor disc 186 as well as the baffle portion 188 of the third rotor disc 186 are configured to increase the rate of rotation of the working material in an inertial frame in the direction towards the bottom of the page, or in a positive sense according to the right hand rule about the X-axis. Recall that the X-axis is coincident with the axis of rotation and directed from the left of the page to the right of the page. The spin-down segment apparatus, i.e. the spin-down portion 189 of the third rotor disc 186, as well as the fourth rotor disc 191 and the fifth rotor disc 193 are configured to decrease the rate of rotation of the working material in an inertial frame. For some embodiments, such as the embodiments shown in FIGS. 3A-B, the rate of rotation of the working material about the X-axis upstream of rotor disc 180 and downstream of the rotor disc 193 is negligible or zero during nominal operations. For some embodiments, or some modes of operation, the rate of rotation of the working material about the X-axis upstream of rotor disc 180 and/or downstream of the rotor disc 193 can be non-zero.

[000111] Rotor disc 180 can correspond to rotor disc 142 in FIGS. 3A-B, rotor disc 404 in FIGS. 5A-B, or rotor disc 694 in FIGS. 6A-B, for example. Rotor disc 182 can correspond to rotor disc

143 in FIGS. 3A-B, rotor disc 406 in FIGS. 5A-B, or rotor disc 696 in FIGS. 6A-B. Rotor disc 186 can correspond to rotor disc 144 in FIGS. 3A-B, rotor disc 408 in FIGS. 5A-B, or rotor disc 698 in FIGS. 6A-B. Note that FIGS. 3A-B, FIGS. 5A-B, and FIGS. 6A-B only show the spin-up segment 187 and the spin down-segment 189 of rotor disc 186 in cross-sectional view for simplicity and clarity, as indicated by spin-up segment 698 and spin-down segment 712 in FIGS. 6A-B. As indicated in FIGS. 3A-B, FIGS. 5A-B, and FIGS. 6A-B, rotor disc 180 can be driven by a drive shaft coupled to rotor disc 193, and rotor disc 182 can be driven by a drive shaft coupled to rotor disc 191. The rotor blades of rotor disc 186 can be structurally supported by a drive shaft as well, where the drive shaft can be located at the center of the channel, or at the outside surface of the channel. Thus at least a portion of the mechanical power extracted by the spin-down segment apparatus can be delivered mechanically to the spin-up segment apparatus via the drive shafts.

[000112] The axial flow speed of the working material in the X-direction can vary along the length of the X-axis throughout the rotor discs. For example, the axial flow speed can increase or decrease in the positive X-direction. The axial flow speed of the working material in the X-direction throughout a spin-up segment apparatus or a spin-down segment apparatus can vary along the length of the X-axis. Note that the axial flow speed is a function of the cross-sectional area of a channel comprising the rotor discs. The axial flow speed of the working material in the X-direction throughout a spin-up segment apparatus or a spin-down segment apparatus can also remain substantially constant along the length of the X-axis.

[000113] In order to increase the rate of rotation of the working material in the spin-up segment apparatus, the rate of rotation of the third rotor disc 186 is typically larger than the rate of rotation of the second rotor disc 182, which in turn is larger than the rate of rotation of the first rotor disc 180 during nominal operations.

[000114] The embodiment shown in FIG. 4B is configured in a similar manner as the embodiment shown in FIG. 4A, and will therefore not be described in the same detail. FIG. 4B schematically shows a circumferential cross-section of 5 rotor discs, namely rotor discs 210, 212, 216, 221, and 223. The radially inward direction is directed into the page, and the flow direction is directed from the left of the page to the right of the page. Each rotor disc comprises several rotor blades, such as rotor blades 221, 213, 220, 222, and 224. All rotor blades rotate in a downwards direction, i.e. from the top of the page towards the bottom of the page during nominal operations. A spin-up segment apparatus can be considered to comprise rotor discs 210 and 212, as well as spin-up segment 217 and baffle segment 218 of rotor disc 216. A spin-down segment apparatus can be considered to comprise rotor discs 221 and 223, as well as spin-down segment 219 of rotor disc 216. The spin-up segment apparatus is configured to increase the rate of rotation of the working material in an inertial frame in the direction towards the bottom of the page, or in a positive sense according to the right hand rule about the X-axis. Recall that the X-axis is coincident with the axis of rotation and directed from the left of the page to the right of the page. The spin-down segment apparatus is configured to decrease the rate of rotation of the working material in an inertial frame. For some embodiments, such as the embodiments shown in FIGS. 3A-B, the rate of rotation of the working material about the X-axis upstream of rotor disc 210 and downstream of the rotor disc 223 is negligible or zero during nominal operations. For some embodiments, or some modes of operation, the rate of rotation of the working material about the X-axis upstream of rotor disc 210 and/or downstream of the rotor disc 223 can be non-zero.

[000115] Compared to FIG. 4A the rotor blades of rotor discs 210 and 212 have a stronger camber. Note that the trailing edges of the rotor blades of rotor discs 210 and 212 are substantially parallel to the X-axis. This can enhance the rate of rotation of the working material downstream of rotor disc 212 and upstream of rotor disc 216 compared to the embodiment shown in FIG. 4A for some modes of operation, ceteris paribus. Note that the camber of the rotor blades of rotor discs 251 and 253 is configured to reduce the rate of rotation of the working material about the X-axis by a desired amount for a given rotational speed of the rotor discs.

[000116] The embodiment shown in FIG. 4C is configured in a similar manner as the embodiment shown in FIG. 4A and FIG. 4B, and will therefore not be described in the same detail. FIG. 4C schematically shows a circumferential cross-section of 5 rotor discs, namely rotor discs 240, 242, 246, 251, and 253. The radially inward direction is directed into the page, and the flow direction is directed from the left of the page to the right of the page. Each rotor disc comprises several rotor blades, such as rotor blades 241, 243, 250, 252, and 254. All rotor blades rotate in a downwards direction, i.e. from the top of the page towards the bottom of the page during nominal operations. A spin-up segment apparatus can be considered to comprise rotor discs 240 and 242, as well as spin-up segment 247 and baffle segment 248 of rotor disc 246. A spin-down segment apparatus can be considered to comprise rotor discs 251 and 253, as well as spin-down segment 249 of rotor disc 246. The spin-up segment apparatus is configured to increase the rate of rotation of the working material in an inertial frame in the direction towards the bottom of the page, or in a positive sense according to the right hand rule about the X-axis. Recall that the X-axis is coincident with the axis of rotation and directed from the left of the page to the right of the page. The spin-down segment apparatus is configured to decrease the rate of rotation of the working material in an inertial frame. For some embodiments, such as the embodiments shown in FIGS. 3A-B, the rate of rotation of the working material about the X-axis upstream of rotor disc 240 and downstream of the rotor disc 253 is negligible or zero during nominal operations. For some embodiments, or some modes of operation, the rate of rotation of the working material about the X-axis upstream of rotor disc 240 and downstream of the rotor disc 253 can be non-zero.

[000117] Compared to FIG. 4A and FIG. 4B, the rotor blades of rotor discs 240 and 242 have a stronger camber. This can enhance the rate of rotation of the working material downstream of rotor disc 242 and upstream of rotor disc 246 compared to the embodiment shown in FIG. 4A and FIG. 4B, ceteris paribus. Note that the camber of the rotor blades of rotor discs 251 and 253 is configured to reduce the rate of rotation of the working material about the X-axis by a desired amount for a given rotational speed of the rotor discs.

[000118] FIGS. 5A-B show a cross-sectional view of one embodiment of the invention. This embodiment can be described as a subsonic and supersonic ramjet. The embodiment shown in FIGS. 5A-B is configured in a similar manner as the embodiment shown in in FIG. 2 and FIGS. 3A-B, and will therefore not be described in the same detail.

[000119] The exemplary embodiment 360 shown is substantially cylindrically symmetric about an axis parallel to the long axis of the embodiment, denoted the X-axis, and coincident with the center of exemplary embodiment 360. The X-axis is parallel to, and coincident with, a line connecting the tip 365 of the spike 364 with the tip 368 of the exit fairing 369, and directed to the right of the page. Outside surface 391 is therefore the shape of a tapered cylinder. In other embodiments, outside surface 391 can be elliptical, rectangular, or square, for instance.

[000120] Exemplary embodiment 360 comprises a channel 362 with inside surface of drum 395 located between a first opening 363 and a second opening 378, where the channel comprises a first contraction 370, a first expansion 371, a spin-up segment 372, a second expansion 373, a second contraction 374, a spin-down segment 375, a third contraction 376, and a third expansion 377. The cross-sectional geometry of channel 362 is circular when viewed along the X-direction. Note that the terms “contraction” and “expansion” refer to the magnitude of the maximum radius of the axially symmetric channel.

[000121] Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions, as described in the context of FIGS. 3A-B.

[000122] In the embodiment shown in FIGS. 5A-B, the inlet is configured to be able to modify the smallest cross-sectional area of the channel 362. This is accomplished by a translating spike 364 which is able to move along the positive and negative X-direction along support shaft 367 inside slot 366. In FIG. 5A the spike is shown in an extended position, which facilitates an increased cross-sectional area at the inlet of channel 362. The spike can be in this position at low subsonic speeds, high subsonic speeds, and low supersonic speeds, for example. In FIG. 5B the spike is shown in a retracted position, which facilitates a reduced cross-sectional area at the inlet of channel 362 and at throat 380. The spike can be in such a position at low and high supersonic speeds, for example. The mode of operation of the spike and the purpose of the spike is similar to the spike at the inlet of the engines of the Lockheed SR-71 Blackbird, for example.

[000123] In the embodiment shown in FIGS. 5A-B, the exhaust nozzle is configured to be able to modify the smallest cross-sectional area of the channel 362. This is facilitated by variable cross-sectional area nozzles, such as primary nozzle 421, and annular sliding ring 424. In FIG. 5B, the annular sliding ring 424 is moved in a negative X-direction relative to the embodiment shown in FIG. 5A. This reduces the cross-sectional area of the channel 362 to a local minimum at throat 386. Downstream of the throat 386, the cross-sectional area of the channel 362 is increased again by primary nozzle 421 and exit fairing 369. The exhaust nozzle can be in a similar position at high subsonic speeds, as well as low and high supersonic speeds, for example. The elements of primary nozzle 421 are rotably coupled to the bulk material 361. The primary nozzle 421 is configured with overlapping leaves or panels, as is the case for exhaust nozzles of conventional supersonic turbojet engines, such as the engines on the Eurofighter Typhoon. In other embodiments, the variable geometry exhaust nozzle of engine 360 can be configured in a similar manner as the variable geometry exhaust nozzle of conventional supersonic turbojet engines, such as the ejector type exhaust nozzle of the SR-71, or the type of nozzle shown in FIGS. 3A-B. In FIG. 5B, the exhaust nozzle is configured to accelerate the subsonic flow in channel 362 to supersonic speeds. In FIG. 5A, the exhaust nozzle is shown in a stored configuration. The primary nozzle 421 are folded in a radially outward direction compared to the configuration shown in FIG. 5A. The exhaust nozzle can be in such a position at low and high subsonic speeds, or low supersonic speeds, for example. Annular sliding ring 424 is configured to slide on rails along inside surface 393 of channel 362 in the positive and negative X-direction. Due to the sloping surface of exit fairing 369, the cross-sectional area of throat 386 can be regulated in flight during nominal operations in this manner.

[000124] Bulk material 361 can comprise a metal such as aluminium, steel, or titanium. Bulk material 361 can also comprise ceramics. In some embodiments, bulk material 361 comprises composites, such as carbon fiber or fiberglass.

[000125] In some embodiments, the apparatus contained within inside surface of drum 395 and outside surface 391 does not have to be a solid material, but can contain empty or open spaces, as is common practice in conventional ramjet or jet engine construction. This can serve to avoid an unnecessarily large mass or cost of exemplary embodiment 360, for instance.

[000126] In FIGS. 5A-B, exemplary embodiment 360 moves with constant velocity magnitude and direction relative to a working material in the free stream. The velocity direction of the upstream working material relative to exemplary embodiment 360 is aligned with the X-axis on average, i.e. directed from the left of the page to the right of the page. For clarity of description, the velocity magnitude and direction of the upstream working material relative to exemplary embodiment 360 is assumed to be constant in space and time. In other modes of operation, the upstream relative velocity magnitude and direction need not be constant in space or time. For example, the upstream relative velocity magnitude can increase or decrease as a function of time.

[000127] A working material can be a gas, such as air, helium, or nitrogen, for example. In the embodiment shown in the figures, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability comprise compressibility, for example. Note that all materials are compressible to some extent.

[000128] The working material upstream of exemplary embodiment 360, such as at station 379, is moving faster relative to exemplary embodiment 360 than the speed of sound in the working material in the configuration shown in FIG. 5B. The first contraction 370, the first expansion 371, and the second expansion 373 of channel 362 are configured to decelerate and compress the working material flowing through channel 362 in the positive X-direction relative to exemplary embodiment 360. The first throat 380 is defined to be the portion of channel 362 with the smallest cross-sectional area of channel 362 between first contraction 370 and first expansion 371 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 360 at the first throat 380 is approximately equal to the speed of sound within working material at that location. Upstream, such as at station 379, the average relative speed is larger than the speed of sound, and further downstream, such as at station 385, the average relative speed is smaller than the speed of sound within the working material in this embodiment. In some embodiments, there can be a shock wave located between the first throat 380 and station 381. In other words, the relative flow speed of the working material downstream of the first throat 380 can be faster than the speed of sound within the working material, where the relative flow speed is reduced to a speed slower than the speed of sound throughout the shock wave. During nominal operations a shock wave can be located within the first expansion 371. This can prevent or reduce the probability of an unscheduled engine unstart due to turbulence or variations in the free stream flow velocity of the working material. The compression of the working material between stations 379 and 385 can be described as a substantially adiabatic compression in this embodiment, where the compression is adiabatic in the sense that no heat is exchanged between the working material in channel 362 and the outside environment in this idealized scenario. The specific entropy of the working material is reduced between stations 382 and 384 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 381 and 385 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas.

[000129] Both the third contraction 376 and the third expansion 377 of channel 362 are configured to expand and accelerate the working material flowing through channel 362 in the positive X-direction. The second throat 386 is defined to be the portion of channel 362 with the smallest cross-sectional area of channel 362 between third contraction 376 and third expansion 377 when viewed along the X-direction. The average speed of the working material relative to exemplary embodiment 360 at the second throat 386 is approximately equal to the speed of sound within the working material at that location. Upstream, such as at station 385, the average relative speed is smaller than the speed of sound, and downstream, such as at station 387, the average relative speed is larger than the speed of sound within the working material in this embodiment. The expansion of the working material between stations 385 and 387 can be described as a substantially adiabatic expansion in this embodiment, where the expansion is adiabatic in the sense that no heat is exchanged between the working material in channel 362 and the outside environment in this idealized scenario. In the embodiment shown in FIGS. 5A-B, the adiabatic expansion between station 385 and 387 can also be described as a substantially isentropic expansion.

[000130] A first body force per unit mass generating apparatus, or a first “BFGA”, 394 is located within channel 362. First BFGA 394 is configured to be able to apply an effective body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this effective body force can be regulated in this embodiment. This can be accomplished by controlling the rate of rotation of drive shafts 412, 413, and drum 395, relative to bulk material 361 or engine 360 or an inertial frame, for example. The first BFGA 394 comprises a rotating drum 395 which rotates relative to bulk material 361 about the X-axis. The drum 395 comprises a bulk material which is annular in cross-section when viewed along the X-axis and which encloses channel 362. The drum 395 is substantially axially symmetric about the X-axis, and can thus be considered to be in the shape of a tapered cylinder, or a cylinder of variable radius along the longitudinal length of the cylinder. The drum 395 comprises a first opening 396 and a second opening through which the working material can flow into and out of the volume enclosed by the annular drum 395. The rotating drum can be structurally supported by bulk material 361 or the remainder of exemplary embodiment 360 via bearings, such as ball or roller bearings, fluid bearings, or magnetic bearings, for example.

[000131] The first BFGA 394 comprises a spin-up segment 372 which is configured to induce or increase the rate of rotation in the bulk flow of the working material in channel 362 about the X-axis. The spin-up segment 372 comprises at least one rotor disc, such as rotor discs 404, 406, and 408. In FIGS. 5A-B there are three rotor discs, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the rotor disc 408 is at least in part structurally supported by drum 395. The rotor blades of the rotor discs 404 and 406 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 404 are supported by shaft 413. The rotor blades of the rotor disc 406 are supported by shaft 412. The axis of the central shaft or support disc can be coincident with the X-axis, and the radius of the outer surface of the central shaft or the support disc can be smaller than the radius of channel 362 at the location of the central shaft or support disc. At least a portion of the working material can be configured to flow around the central shaft or support disc through channel 362. In some embodiments, at least a portion of the working material can be configured to flow through the central shaft or through the support disc.

[000132] The rate of rotation of the bulk flow of the working material through channel 362 about the X-axis can be configured to be very large, or substantially increased, at station 382 compared to station 380 due to the action of the spin-up segment 372.

[000133] The rotor blades in a rotor disc can be configured in a similar manner as the rotor blades in a conventional centrifugal compressor. Note that, apart from the deflection of fluid flow in the radially outwards direction by the rotor blades of the rotor discs of the spin-up segment 372 and by the effective centrifugal forces, the axial flow of the working material is maintained throughout the spin-up segment 372. This is in contrast to conventional centrifugal compressors, in which the bulk flow of the working material is typically deflected through ninety degrees at least once, at the inlet of a centrifugal compressor, such as a centrifugal compressor found in a conventional turboprop engine. The spin-up segment 372 can thus be considered to be an “axial flow centrifugal compressor”. The rate of rotation of the rotor blades can be modified to regulate the rate of rotation of the working material within the BFGA 394 for a given free stream flow speed and a given desired thrust.

[000134] The rotor blades in a rotor disc in the spin-up segment 372 can also be configured in a similar manner as the rotor blades in a conventional axial compressor. In some such configurations, an absence of stator discs or stator blades in the spin-up segment 372 compared to a conventional axial compressor can facilitate the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 372. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-up segment 372, such as between rotor disc 404 and rotor disc 406, can be employed to enhance the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 372. In a subset of embodiments, the first expansion 371 of channel 362 can be employed to reduce the maximum local relative flow velocity of the working material relative to the rotor blades of the rotor disc of spin-up segment 372 to subsonic speeds during nominal operations. This can reduce the wave drag associated with the formation of shock waves at the rotor discs of spin-up segment 372. In other embodiments, the spin-up segment 372 can consist only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to impart a rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 361 of engine 360. In other embodiments, the stator blades are rotably coupled to the bulk material 361 of the engine 360, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 394 for a given free stream flow speed and a given desired thrust.

[000135] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 372 can be provided by a separate electrical motor, for example. The electrical motor can be configured to rotate drum 395, and thereby rotate, and supply mechanical power to, the rotor discs of spin-up segment 404. The electrical power supplied to the electrical motor can be provided by a battery, or by an electrical generator which is driven by a separate turbine, such as the turbine in an auxiliary power unit, or a turbine located downstream of station 385. For instance, an electrical motor can be employed to power the first BFGA 394 and increase the rate of rotation of drum 395 and the associated rotor discs of the spin-up segment 372 during the starting of the engine 360, i.e. the increase of the net thrust of the exemplary embodiment 360 from a value which is zero or less than zero, i.e. directed in the positive X-direction, to a value which is above zero, i.e. directed in the negative X-direction.

[000136] The working material flowing through second expansion 373 and second contraction 374 comprises an axial flow component as well as a rotational or swirl component due to the rotation about the X-axis imparted to the working material by the spin-up segment 372. In order to maintain the rate of rotation of the bulk flow of the working material about the X-axis, second expansion 373 and second contraction 374 can comprise baffles arranged in a streamwise direction, i.e. along the X-direction. The baffles can be rigidly connected to drum 395, and therefore rotate about the X-axis. The baffles can be configured to prohibit, or restrict or reduce, the circumferential motion of the working material about the X-axis relative to the drum 395 or relative to the baffles. In this scenario, since the drum 395 and the baffles are rotating, the angular rate of rotation of the bulk flow of the working material in the second expansion 373 is substantially equal to the angular rate of rotation of the drum 395 and the baffles about the X-axis. Thus the baffles can be employed to control and regulate the rate of rotation of the working material flowing through second expansion 373. In other embodiments, there need not be any baffles between station 382 and 384, allowing the working material to rotate substantially freely about the X-axis between stations 382 and 384. Note that the viscous drag from drum 395 can also contribute a rate of rotation to the working material flowing through drum 395.

[000137] The first BFGA 394 comprises a spin-down segment 375 which is configured to decrease the rate of rotation in the bulk flow of the working material in channel 362 about the X-axis. The spin-down segment 375 comprises at least one rotor disc, such as rotor disc 410 or rotor disc 411. The rotor discs in the spin-down segment 375 can be configured in a similar manner as the rotor discs in the spin-up segment 372. In FIGS. 5A-B there are three rotor discs in spin-down segment 375, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the upstream rotor disc of spin down segment 375 is at least in part structurally supported by drum 395. The rotor blades of the rotor discs 410 and

411 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 411 are supported by shaft 413. The rotor blades of the rotor disc 410 are supported by shaft 412.

[000138] The rate of rotation of the bulk flow of the working material through channel 362 about the X-axis can be configured to be negligible, or substantially reduced, at station 385 compared to station 384 or station 382 due to the action of the spin-down segment 375.

[000139] As described in the context of the spin-up segment 372, the spin-down segment 375 can be considered to be an axial flow centrifugal turbine.

[000140] The rotor discs of spin-down segment 375 can also be configured in a similar manner as the rotor blades in a conventional axial turbine. In some such configurations, an absence of stator discs or stator blades in the spin-down segment 375 can facilitate the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 375. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-down segment 375, such as between rotor disc 410 and rotor disc 411, can be employed to enhance the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 375. In other embodiments, the spin-down segment 375 can consist only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to reduce the rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 361 of engine 360. In other embodiments, the stator blades are rotably coupled to the bulk material 361 of the engine 360, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 394 for a given free stream flow speed and a given desired thrust. The function of the stator blades is identical to the function of the rotor blades in the spin-down segment 375.

[000141] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 372 can be provided by the mechanical power extracted from the working material during the decrease in the rate of rotation of the working material about the X-axis in the spin-down segment 375. This decrease in the rate of rotation of the working material in spin-down segment 375 can be generate a torque which acts on the rotor discs of spin-down segment 375 about the X-axis, and which can be mechanically transferred to drum 395 and to the drive shafts 412 and 413, and to the rotor discs of spin-up segment 372. In other embodiments, the rotor discs in spin-down segment 375 can be configured to drive an electrical generator. At least a portion of the energy recovered by the electrical generator can be employed to deliver electrical power to an electrical motor configured to drive the rotor discs of spin-up segment 372. In the case in which the spin-up segment comprises stator discs, the torque acting on the stator discs in the spin-down segment 375 can be cancelled by the torque acting on the working material in the spin-up segment 372 during nominal operations, such that there is no net torque on the engine 360.

[000142] In the embodiment shown in FIG. 360, the first BFGA 394 is comprises a three spools connecting the rotor discs of the spin-up segment 372 with the rotor discs of the spin-down segment 375 via external drive shaft or drum 395, and internal drive shafts 413 and 412. In other embodiments, the first BFGA can comprise two spools, four spools, or a larger number of spools. Such multi-spool architectures are common in conventional turbofan engines, for example.

[000143] The first BFGA 394 is configured to generate an effective body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 362, where the effective body force comprises a non-zero component in the YZ-plane and directed away from the center of channel 362, i.e. away from the X-axis or in the radially outwards direction. The effective body force per unit mass acting on the working material arises from the rotation of the working material in an inertial frame, about the X-axis, within the second expansion 373 of channel 722. Due to the lack of a centripetal body force per unit mass acting on the objects of a working material in the negative radial direction, there is an effective or perceived centrifugal body force per unit mass acting in the positive radial direction, i.e. in a radially outward direction, on objects in the working material. In the steady state, the effective centrifugal force is balanced by the interior surface of drum 395 of BFGA 394, and an increase in the pressure and density of the working material in the radially increasing direction, i.e. in the direction in the YZ-plane and away from the X-axis, or away from the X-axis.

[000144] The action of the effective body force per unit mass increases the pressure on at least a portion of interior surface of drum 395 throughout the second expansion 373 of channel 362, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 360 in the negative X-direction. This is due to the surface normal of the interior surface of drum 395 having a component in the positive X-direction throughout the second expansion 373 of channel 362. An artificial increase in pressure on surfaces with a surface normal which has a non-zero component in the positive X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The specific entropy of the working material is reduced between stations 382 and 383 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 382 and 383 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas. The modification of the specific heat capacity between stations 382 and 383 is similar in principle to the modification of the specific heat capacity discussed in the context of FIGS. 7A-J.

[000145] The direction of the effective body force per unit mass acting on objects of the working material within channel 362 is in the radially outward direction. In some embodiments, the component of the effective body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the effective body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the effective body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the effective body force acting on the working material within the second expansion 373 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material would be carried out by the first BFGA 394.

[000146] Due to the action of the effective body force per unit mass within the second expansion 373 of channel 362, the pressure within the working material within the second expansion 373 of channel 362 increases in a radially outwards direction at a given location along the length of the channel. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. At a given location along the length of the channel the change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example. Upstream of the spin-up segment 372 and downstream of the spin-down segment 375 the rate of rotation of the working material about the X-axis is negligible in the simplified embodiment shown in FIGS. 5A-B. The radial variation of the pressure between stations 379 and 381, and between stations 385 and 387 is approximately uniform.

[000147] The action of the effective body force per unit mass decreases the pressure on at least a portion of interior surface of wall 414 throughout the second contraction 374 of channel 362, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 360 in the negative X-direction. This is due to the surface normal of the interior surface of wall 414 having a component in the negative X-direction throughout the second expansion 373 of channel 362. An artificial decrease in pressure on surfaces with a surface normal which has a non-zero component in the negative X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on engine 360 due to the larger pressure of the working material acting on the other surfaces, such as the surface of exit fairing 369 in third expansion 377, as well as the interior surface of first expansion 371 and second expansion 373. The specific entropy of the working material is reduced between stations 383 and 384 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 383 and 384 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas. The modification of the specific heat capacity between stations 383 and 384 is similar in principle to the modification of the specific heat capacity discussed in the context of FIGS. 10A-K.

[000148] Due to the action of the effective body force per unit mass within the second contraction 374 of channel 362, the pressure within the working material within the second contraction 374 of channel 362 increases in a radially outwards direction at a given location along the length of the channel. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. At a given location along the length of the channel the change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example.

[000149] A wide variety of body force generating apparatuses, or combinations thereof, can be employed in embodiments of the invention. For example, in other embodiments, the pressure at a point along the X-axis in the first contraction 370, the third contraction 376, or the third expansion 377 need not be substantially uniform in the radial direction, but can vary in the radial direction, as exemplified by the embodiment shown in FIG. 1A and discussed in the context of FIGS. 3A-B. For example, a second BFGA configured in a similar manner as the first BFGA 394 can be located within at least a portion of the third expansion 377 and configured to generate a body force on the working material directed in the radially outward direction, as is the case in the first BFGA 394. In another example, other types of BFGA, such as the type of BFGA described in FIG. 1A can be used in place of, or concurrently with, the first BFGA 394 in the exemplary embodiment shown in FIGS. 5A-B, or throughout portions of channel 362 in which no dedicated BFGA is being employed, such as the first contraction 370, the third contraction 376, or the third expansion 377. As discussed in the context of FIG. 1A, a BFGA can be employed to generate a body force on the working material in the first contraction 370 or the third contraction 376, where the body force can comprise a component in a radially inward direction, away from interior surface 393. As discussed in the context of FIG. 1A and FIGS. 5A-B, a BFGA can be employed to generate a body force on the working material in the first expansion 371, the second expansion 373, or the third expansion 377, where the body force can comprise a component in a radially outward direction, towards interior surface 393.

[000150] In another example, several embodiments, such as embodiment 360, can be connected in series. For example, an embodiment of the invention can comprise a first and a second embodiment 360 of the type shown in FIGS. 5A-B connected in series, such that the station 386 of the first embodiment is coincident with station 380 of the second embodiment, or such that station 386 of the first embodiment is equivalent to station 381 of the second embodiment. An annular duct can direct the working material from the exit of a spin-down segment of a first BFGA to the entrance of a spin-up segment of a second BFGA. Due to the cooling of the working material throughout successive embodiments, and the unchanged maximum cross-sectional area of channel 362, the amount of thrust produced by two embodiments connected in series can exceed the thrust produced by two identical and equivalent embodiments connected in parallel, i.e. operated independently of each other.

[000151] The exemplary embodiment 360, as well as other embodiments operated in accordance with the invention, can be employed to reduce the specific entropy of the working material interacting with the embodiments. This can be employed to convert thermal energy of the working material directly into useful work. For instance, embodiment 360 can generate a net thrust force in the negative X-direction. The power associated with the generation of this force can be provided by the thermal energy of the working material flowing through channel 362. Thus, the working material at station 387 is at a lower temperature than the working material at station 379, and the relative velocity of the working material at station 387 is larger than the relative velocity of the working material at station 379 relative to embodiment 360. The acceleration of the working material and the cooling of the working material is a consequence of the work done by the working material on embodiment 360.

[000152] FIGS. 6A-B show a cross-sectional view of one embodiment of the invention. This embodiment can be described as a subsonic and supersonic ramjet. The embodiment shown in FIGS. 6A-B is configured in a similar manner as the embodiment shown in FIG. 2, FIGS. 3A-B, and FIGS. 6A-B, and will therefore not be described in the same detail.

[000153] The exemplary embodiment 630 shown is substantially cylindrically symmetric about an axis parallel to the long axis of the embodiment, denoted the X-axis, and coincident with the center of exemplary embodiment 630. The X-axis is parallel to, and coincident with, a line connecting the tip 719 of the hub 634 with the tip 635 of the exit fairing 636, and directed to the right of the page. Outside surface 661 is therefore the shape of a tapered cylinder. In other embodiments, outside surface 661 can be elliptical, rectangular, or square, for instance.

[000154] Exemplary embodiment 630 comprises a channel 632 with inside surface 659 located between a first opening 633 and a second opening 644, where the channel comprises a first contraction 637, a spin-up segment 638, a first expansion 639, a second contraction 640, a spin-down segment 641, and a second expansion 642. The cross-sectional geometry of channel 632 is circular or annular when viewed along the X-direction. Note that the terms “contraction” and “expansion” refer to the magnitude of the maximum radius of the axially symmetric channel.

[000155] Note that the channel radius or geometry can change in a different manner as a function of position along the X-axis, or be configured differently, for other embodiments, or other operating conditions, as described in the context of FIGS. 3A-B.

[000156] Embodiment 630 comprises a compressor with a first compressor spool 661 and a second compressor spool 669. The first spool 661 comprises 3 stages, such as a first stage consisting of a first rotor disc 663 and a first stator disc 664. The first compressor spool 661 is driven by drive shaft 668. The second compressor spool 669 comprises 6 stages, such as fourth stage consisting of a first rotor disc 674 and a first stator disc 675. The second compressor spool 669 is driven by drive shaft 668.

[000157] Embodiment 630 comprises a turbine 677 with a first turbine spool 678 and a second turbine spool 681. The first spool 678 comprises 1 stage consisting of a first rotor disc 679 and a first stator disc 680. The first turbine spool 678 drives drive shaft 676. The second turbine spool 681 comprises 1 stage, consisting of a first rotor disc 682 and a first stator disc 683. The second turbine spool 681 drives drive shaft 668.

[000158] In the embodiment shown in FIGS. 6A-B, the inlet is configured to be able to modify the smallest cross-sectional area of the channel 632. This is accomplished by a sliding annular ring 714 which is able to move along the positive and negative X-direction along shaft 676, into and out of slot 718. In FIG. 6A the annular ring 714 is shown in an extended position, which facilitates a reduced cross-sectional area in channel 632. The annular ring 714 can be in this position at engine start, and at low subsonic speeds, for example. In FIG. 6B the annular ring 714 is shown in a retracted position, which facilitates an increased cross-sectional area at the inlet of channel 632 and at throat 647. The annular ring 714 can be in such a position at high subsonic speeds, for example. The annular ring 714 can be configured to regulate the mass flow rate of air through the first BFGA 684 by choking the channel 632 for some modes of operation. In other words, the local speed of the working material at the smallest cross-sectional area of the channel 632 at the annular ring 714 relative to the engine 630 can be approximately equal to the speed of sound during some modes of operation. In some such modes of operation, the local speed of the working material downstream of the smallest cross-sectional area of the channel 632 at the annular ring 714 relative to the engine 630 can be larger than the local speed of sound until a shock wave decelerates the flow to subsonic speeds again before inlet 686. The regulation of the mass flow rate of the working material flowing through channel 632 by the constriction of channel 632 by annular ring 714 can be employed to regulate the thrust and the performance of first BFGA 684 for some modes of operation. In other embodiments, there need not be a variable geometry inlet to first BFGA 684, i.e. there need not be a device such as sliding ring 714.

[000159] Bulk material 631 can comprise a metal such as aluminium, steel, or titanium. Bulk material 631 can also comprise ceramics. In some embodiments, bulk material 631 comprises composites, such as carbon fiber or fiberglass.

[000160] In some embodiments, the apparatus contained within inside surface of drum 685 and outside surface 661 does not have to be a solid material, but can contain empty or open spaces, as is common practice in conventional ramjet or jet engine construction. This can serve to avoid an unnecessarily large mass or cost of exemplary embodiment 630, for instance.

[000161] In FIGS. 6A-B, exemplary embodiment 630 moves with constant velocity magnitude and direction relative to a working material in the free stream 645. The velocity direction of the upstream working material relative to exemplary embodiment 630 is aligned with the X-axis on average, i.e. directed from the left of the page to the right of the page. For clarity of description, the velocity magnitude and direction of the upstream working material relative to exemplary embodiment 630 is assumed to be constant in space and time. In other modes of operation, the upstream relative velocity magnitude and direction need not be constant in space or time. For example, the upstream relative velocity magnitude can increase or decrease as a function of time.

[000162] A working material can be a gas, such as air, helium, or nitrogen, for example. In the embodiment shown in the figures, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability comprise compressibility, for example. Note that all materials are compressible to some extent.

[000163] The working material upstream of exemplary embodiment 630, such as at station 645, is moving slower relative to exemplary embodiment 630 than the speed of sound in the working material in the configuration shown in FIG. 6B. Note that, in some embodiments, the engine 630 can move supersonically through the atmosphere, where the flow is decelerated by a suitably configured inlet, such as the inlet with translating inlet spike shown in FIGS. 5A-B. Typically, the local free stream flow at station 645 is subsonic, such that the local free stream flow at the rotor tips of the rotor discs, such as rotor disc 663, is below Mach 1. In other embodiments, or other modes of operation, the tip speed can be above Mach 1. The compression of the working material between stations 645 and 647 can be described as a substantially adiabatic compression in this embodiment, where the compression is adiabatic in the sense that no heat is exchanged between the working material in channel 632 and the outside environment in this idealized scenario. The specific entropy of the working material is reduced between stations 648 and 650 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 648 and 650 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas.

[000164] The average speed of the working material relative to exemplary embodiment 630 in the free stream, i.e. at station 645, is approximately equal to the speed of sound within the working material at that location. Upstream, such as at station 651, the average relative speed is smaller than the speed of sound, and downstream, such as at station 653, the average relative speed is larger than the speed of sound within the working material in this embodiment. The expansion of the working material between stations 651 and 653 can be described as a substantially adiabatic expansion in this embodiment, where the expansion is adiabatic in the sense that no heat is exchanged between the working material in channel 632 and the outside environment in this idealized scenario. In the embodiment shown in FIGS. 6A-B, the adiabatic expansion between station 651 and 653 can also be described as a substantially isentropic expansion.

[000165] A first body force per unit mass generating apparatus, or a first "BFGA", 684 is located within channel 632. First BFGA 684 is configured to be able to apply an effective body force per unit mass on objects, e.g. atoms or molecules, of the working material. The magnitude of this effective body force can be regulated in this embodiment. This can be accomplished by controlling the rate of rotation of drive shafts 702, 676, and drum 685, relative to bulk material 631 or engine 630 or an inertial frame, for example. The first BFGA 684 comprises a rotating drum 685 which rotates relative to bulk material 631 about the X-axis. The drum 685 comprises a bulk material which is annular in cross-section when viewed along the X-axis and which encloses channel 632. The drum 685 is substantially axially symmetric about the X-axis, and can thus be considered to be in the shape of a tapered cylinder, or a cylinder of variable radius along the longitudinal length of the cylinder. The drum 685 comprises a first opening 686 and a second opening through which the working material can flow into and out of the volume enclosed by the annular drum 685. The rotating drum can be structurally supported by bulk material 631 or the remainder of exemplary embodiment 630 via bearings, such as ball or roller bearings, fluid bearings, or magnetic bearings, for example.

[000166] The first BFGA 684 comprises a spin-up segment 638 which is configured to induce or increase the rate of rotation in the bulk flow of the working material in channel 632 about the X-axis. The spin-up segment 638 comprises at least one rotor disc, such as rotor discs, 696, and 698. In FIGS. 6A-B there are three rotor discs in the spin-up segment, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the rotor disc 698 is at least in part structurally supported by drum 685. The rotor blades of the rotor discs 694 and 696 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 694 are supported by shaft 676. The rotor blades of the rotor disc 696 are supported by shaft 702. The axis of the central shaft or support disc can be coincident with the X-axis, and the radius of the outer surface of the central shaft or the support disc can be smaller than the radius of channel 632 at the location of the central shaft or support disc. At least a portion of the working material can be configured to flow around the central shaft or support disc through channel 632. In some embodiments, at least a portion of the working material can be configured to flow through the central shaft or through the support disc.

[000167] The rate of rotation of the bulk flow of the working material through channel 632 about the X-axis can be configured to be very large, or substantially increased, at station 648 compared to station 647 due to the action of the spin-up segment 638.

[000168] The rotor blades in a rotor disc can be configured in a similar manner as the rotor blades in a conventional centrifugal compressor. Note that, apart from the deflection of fluid flow in the radially outwards direction by the rotor blades of the rotor discs of the spin-up segment 638 and by the effective centrifugal forces, the axial flow of the working material is maintained throughout the spin-up segment 638. This is in contrast to conventional centrifugal compressors, in which the bulk flow of the working material is typically deflected through ninety degrees at least once, at the inlet of a centrifugal compressor, such as a centrifugal compressor found in a conventional turboprop engine. The spin-up segment 638 can thus be considered to be an "axial flow centrifugal compressor". The rate of rotation of the rotor blades can be modified to regulate the rate of rotation of the working material within the BFGA 684 for a given free stream flow speed and a given desired thrust.

[000169] The rotor blades in a rotor disc in the spin-up segment 638 can also be configured in a similar manner as the rotor blades in a conventional axial compressor. In some such configurations, an absence of stator discs or stator blades in the spin-up segment 638 compared to a conventional axial compressor can facilitate the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 638. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-up segment 638, such as between rotor disc 694 and rotor disc 696, can be employed to enhance the increase of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-up segment 638. In other embodiments, the spin-up segment 638 can consist of only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to impart a rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 631 of engine 630. In other embodiments, the stator blades are rotably coupled to the bulk material 631 of the engine 630, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 684 for a given free stream flow speed and a given desired thrust.

[000170] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 638 can be provided by a separate electrical motor, for example. The electrical motor can be configured to rotate drum 685, and thereby rotate, and supply mechanical power to, the rotor discs of spin-up segment 694. The electrical power supplied to the electrical motor can be provided by a battery, or by an electrical generator which is driven by a separate turbine, such as the turbine in an auxiliary power unit, or a turbine located downstream of station 651. For instance, an electrical motor can be employed to power the first BFGA 684 and increase the rate of rotation of drum 685 and the associated rotor discs of the spin-up segment 638 during the starting of the engine 630, i.e. the increase of the net thrust of the exemplary embodiment 630 from a value which is zero or less than zero, i.e. directed in the positive X-direction, to a value which is above zero, i.e. directed in the negative X-direction.

[000171] The working material flowing through first expansion 639 and second contraction 640 comprises an axial flow component as well as a rotational or swirl component due to the rotation about the X-axis imparted to the working material by the spin-up segment 638. In order to maintain the rate of rotation of the bulk flow of the working material about the X-axis, first expansion 639 and second contraction 640 can comprise baffles arranged in a streamwise direction, i.e. along the X-direction. The baffles can be rigidly connected to drum 685, and therefore rotate about the X-axis. The baffles can be configured to prohibit, or restrict or reduce, the circumferential motion of the working material about the X-axis relative to the drum 685 or relative to the baffles. In this scenario, since the drum 685 and the baffles are rotating, the angular rate of rotation of the bulk flow of the working material in the first expansion 639 is substantially equal to the angular rate of rotation of the drum 685 and the baffles about the X-axis. Thus the baffles can be employed to control and regulate the rate of rotation of the working material flowing through first expansion 639. In other embodiments, there need not be any baffles between station 648 and 650, allowing the working material to rotate substantially freely about the X-axis between stations 648 and 650. Note that the viscous drag from drum 685 can also contribute a rate of rotation to the working material flowing through drum 685.

[000172] The first BFGA 684 comprises a spin-down segment 641 which is configured to decrease the rate of rotation in the bulk flow of the working material in channel 632 about the X-axis. The spin-down segment 641 comprises at least one rotor disc, such as rotor disc 700 or rotor disc 701. The rotor discs in the spin-down segment 641 can be configured in a similar manner as the rotor discs in the spin-up segment 638. In FIGS. 6A-B there are three rotor discs in spin-down segment

641, although other embodiments can have one rotor disc, or a plurality of rotor discs, or any suitable number of rotor discs. Each rotor blade of the upstream rotor disc of spin down segment 641 is at least in part structurally supported by drum 685. The rotor blades of the rotor discs 700 and 701 are at least in part structurally supported by a central shaft or a support disc, as is the case in conventional turbofan engines. The rotor blades of the rotor disc 700 are supported by shaft 702. The rotor blades of the rotor disc 701 are supported by shaft 676. Note that the drive shaft 676 being driven by rotor disc 701 is also driven by rotor disc 679. In other embodiments, this need not be the case, i.e. the drive shaft driven by rotor disc 701 and driving rotor disc 694 can be uncoupled from another drive shaft driven by rotor disc 679 and driving second compressor spool 669.

[000173] The rate of rotation of the bulk flow of the working material through channel 632 about the X-axis can be configured to be negligible, or substantially reduced, at station 651 compared to station 650 or station 648 due to the action of the spin-down segment 641.

[000174] As described in the context of the spin-up segment 638, the spin-down segment 641 can be considered to be an axial flow centrifugal turbine.

[000175] The rotor discs of spin-down segment 641 can also be configured in a similar manner as the rotor blades in a conventional axial turbine. In some such configurations, an absence of stator discs or stator blades in the spin-down segment 641 can facilitate the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 641. In other such configurations, stator discs or stator blades between adjacent rotor discs in the spin-down segment 641, such as between rotor disc 700 and rotor disc 701, can be employed to enhance the decrease of the rate of rotation or swirl of the bulk flow of the working material about the X-axis throughout the spin-down segment 641. In other embodiments, the spin-down segment 641 can consist only one stator disc, or only a plurality of stator discs. In such embodiments, the individual blades or guide vanes of the stator disc are configured to reduce the rate of rotation on the flow about the X-axis. In some embodiments, the stator blades are rigidly connected to the bulk material 631 of engine 630. In other embodiments, the stator blades are rotably coupled to the bulk material 631 of the engine 630, where the axis of rotation can be substantially parallel to the radial direction. This allows the angle of attack of the individual stator blades to be adjusted during nominal operations. The angle of attack of the stator blades can be employed to regulate the rate of rotation of the working material within the BFGA 684 for a given free stream flow speed and a given desired thrust. The function of the stator blades is identical to the function of the rotor blades in the spin-down segment 641.

[000176] At least a portion of the mechanical power required for the increase in the rate of rotation of the working material about the X-axis in the spin-up segment 638 can be provided by the mechanical power extracted from the working material during the decrease in the rate of rotation of the working material about the X-axis in the spin-down segment 641. This decrease in the rate of rotation of the working material in spin-down segment 641 can generate a torque which acts on the rotor discs of spin-down segment 641 about the X-axis, and which can be mechanically transferred to drum 685 and to the drive shafts 702 and 676, and to the rotor discs of spin-up segment 638. In other embodiments, the rotor discs in spin-down segment 641 can be configured to drive an electrical generator. At least a portion of the energy recovered by the electrical generator can be employed to deliver electrical power to an electrical motor configured to drive the rotor discs of spin-up segment 638. In the case in which the spin-up segment comprises stator discs, the torque acting on the stator discs in the spin-down segment 641 can be cancelled by the torque acting on the working material in the spin-up segment 638 during nominal operations, such that there is no net torque on the engine 630.

[000177] In the embodiment shown in FIG. 630, the first BFGA 684 is comprises a three spools connecting the rotor discs of the spin-up segment 638 with the rotor discs of the spin-down segment 641 via external drive shaft or drum 685, and internal drive shafts 676 and 702. In other embodiments, the first BFGA can comprise two spools, four spools, or a larger number of spools. Such multi-spool architectures are common in conventional turbofan engines, for example.

[000178] The first BFGA 684 is configured to generate an effective body force per unit mass which acts on objects, such as atoms or molecules, in the working material, such as air, within channel 632, where the effective body force comprises a non-zero component in the YZ-plane and directed away from the center of channel 632, i.e. away from the X-axis or in the radially outwards direction. The effective body force per unit mass acting on the working material arises from the rotation of the working material in an inertial frame, about the X-axis, within the first expansion 639 of channel 722. Due to the lack of a centripetal body force per unit mass acting on the objects of a working material in the negative radial direction, there is an effective or perceived centrifugal body force per unit mass acting in the positive radial direction, i.e. in a radially outward direction, on objects in the working material. In the steady state, the effective centrifugal force is balanced by the interior surface of drum 685 of BFGA 684, and an increase in the pressure and density of the working material in the radially increasing direction, i.e. in the direction in the YZ-plane and away from the X-axis, or away from the X-axis.

[000179] The action of the effective body force per unit mass increases the pressure on at least a portion of interior surface of drum 685 throughout the first expansion 639 of channel 632, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 630 in the negative X-direction. This is due to the surface normal of the interior surface of drum 685 having a component in the positive X-direction throughout the first expansion 639 of channel 632. An artificial increase in pressure on surfaces with a surface normal which has a non-zero component in the positive X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on these surfaces due to the pressure of the working material acting on these surfaces. The specific entropy of the working material is reduced between stations 648 and 649 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 648 and 649 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas. The modification of the specific heat capacity between stations 648 and 649 is similar in principle to the modification of the specific heat capacity discussed in the context of FIGS. 7A-J.

[000180] The direction of the effective body force per unit mass acting on objects of the working material within channel 632 is in the radially outward direction. In some embodiments, the component of the effective body force per unit mass along the X-direction is negligible, resulting in no direct contribution to thrust or drag by the BFGA acting on the working material. In other embodiments, the component of the effective body force per unit mass long the positive or negative X-direction can be non-zero. In such embodiments, the effective body force per unit mass can be employed to decelerate or compress the working material, or to accelerate or expand the working material. For example, the effective body force acting on the working material within the first expansion 639 can comprise a component in the negative X-direction. In this case, at least a portion of the compression and deceleration of the working material would be carried out by the first BFGA 684.

[000181] Due to the action of the effective body force per unit mass within the first expansion 639 of channel 632, the pressure within the working material within the first expansion 639 of channel 632 increases in a radially outwards direction at a given location along the length of the channel. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. At a given location along the length of the channel the change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example. Upstream of the spin-up segment 638 and downstream of the spin-down segment 641 the rate of rotation of the working material about the X-axis is negligible in the simplified embodiment shown in FIGS. 6A-B. The radial variation of the pressure between stations 645 and 647, and between stations 651 and 653 is approximately uniform.

[000182] The action of the effective body force per unit mass decreases the pressure on at least a portion of interior surface of wall 704 throughout the second contraction 640 of channel 632, thereby increasing the propulsive force, or thrust force, acting on the exemplary embodiment 630 in the negative X-direction. This is due to the surface normal of the interior surface of wall 704 having a component in the negative X-direction throughout the first expansion 639 of channel 632. An artificial decrease in pressure on surfaces with a surface normal which has a non-zero component in the negative X-direction can be employed to artificially increase the propulsive force, or thrust force, acting on engine 630 due to the larger pressure of the working material acting on the other surfaces, such as the surface of exit fairing 636 in second expansion 642, as well as the interior surface of first expansion 639. The specific entropy of the working material is reduced between stations 649 and 650 for the depicted operating condition, while the stagnation pressure is increased. As explained below, this is due to a modification of the perceived specific heat capacity of the gas between stations 649 and 650 compared to the nominal specific heat capacity of the gas due to the rotation of the gas about the X-axis and the associated centrifugal body forces acting on the gas. The modification of the specific heat capacity between stations 649 and 650 is similar in principle to the modification of the specific heat capacity discussed in the context of FIGS. 10A-K.

[000183] Due to the action of the effective body force per unit mass within the second contraction 640 of channel 632, the pressure within the working material within the second contraction 640 of channel 632 increases in a radially outwards direction at a given location along the length of the channel. A radial direction is a direction which is perpendicular to the X-axis and directed away from the X-axis. At a given location along the length of the channel the change in pressure, density, or temperature can be modelled as a conventional, isentropic and adiabatic compression along the radial direction in highly simplified, idealized models, for example.

[000184] A wide variety of body force generating apparatuses, or combinations thereof, can be employed in embodiments of the invention. For example, in other embodiments, the pressure at a point along the X-axis in the first contraction 637, or the second expansion 642 need not be substantially uniform in the radial direction, but can vary in the radial direction, as exemplified by the embodiment shown in FIG. 1A and discussed in the context of FIGS. 3A-B. For example, a second BFGA configured in a similar manner as the first BFGA 684 can be located within at least a portion of the second expansion 642 and configured to generate a body force on the working material directed in the radially outward direction, as is the case in the first BFGA 684. In another example, other types of BFGA, such as the type of BFGA described in FIG. 1A can be used in place of, or concurrently with, the first BFGA 684 in the exemplary embodiment shown in FIGS. 6A-B, or throughout portions of channel 632 in which no dedicated BFGA is being employed, such as the first contraction 637, or the second expansion 642. As discussed in the context of FIG. 1A, a BFGA can be employed to generate a body force on the working material in the first contraction 637, where the body force can comprise a component in a radially inward direction, away from interior surface 659. As discussed in the context of FIG. 1A and FIGS. 6A-B, a BFGA can be employed to generate a body force on the working material in the first expansion 639, or the second expansion 642, where the body force can comprise a component in a radially outward direction, towards interior surface 659.

[000185] In another example, several embodiments, such as embodiment 630, can be connected in series. For example, an embodiment of the invention can comprise a first and a second embodiment 630 of the type shown in FIGS. 6A-B connected in series, such that the station 651 of the first embodiment is coincident with station 647 of the second embodiment. An annular duct can direct the working material from the exit of a spin-down segment of a first BFGA to the entrance of a spin-up segment of a second BFGA. Due to the cooling of the working material throughout successive embodiments, and the unchanged maximum cross-sectional area of channel 632, the amount of thrust produced by two embodiments connected in series can exceed the thrust produced by two identical and equivalent embodiments connected in parallel, i.e. operated independently of each other.

[000186] The exemplary embodiment 630, as well as other embodiments operated in accordance with the invention, can be employed to reduce the specific entropy of the working material interacting with the embodiments. This can be employed to convert thermal energy of the working material directly into useful work. For instance, embodiment 630 can generate a net thrust force in the negative X-direction. The power associated with the generation of this force can be provided by the thermal energy of the working material flowing through channel 632. Thus, the working material at station 653 is at a lower temperature than the working material at station 645, and the relative velocity of the working material at station 653 is larger than the relative velocity of the working material at station 645 relative to embodiment 630. The acceleration of the working material and the cooling of the working material is a consequence of the work done by the working material on embodiment 630.

[000187] FIGS. 7A-J schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition.

[000188] Exemplary embodiment 860 comprises a first work exchange apparatus 873 comprising a first chamber 880 and a second work exchange apparatus 895 comprising a second chamber 903. The working material within the first chamber is subject to a body force per unit mass provided by a body force generating apparatus during nominal operations. A wide variety of body force generating apparatuses can be used. In embodiment 860, the body force per unit mass is inertial in nature. First chamber 880 is configured to rotate about axis 872, thereby experiencing an effective centrifugal acceleration, as described in the context of FIG. 2. An axis coincident with and parallel to axis 872 and directed from the left of the page to the right of the page is denoted the "X-axis". An axis perpendicular to the X-axis and in the plane of the page and directed from the bottom of the page to the top of the page is denoted the "Y-axis". A radial direction is a direction perpendicular to the X-axis, lying in the YZ-plane, and directed away from the X-axis. Due to the rotation of the first chamber 880, an effective body force per unit mass is acting on the working material within first chamber 880 in the positive radial direction. In the steady state, this results in a temperature gradient within the working material in chamber 880, where the temperature increases in an increasing, or outward, or positive, radial direction. The pressure and density also increases in a positive radial direction in this scenario. The first and second work exchange apparatuses comprise reciprocating pistons. The second work exchange apparatus can comprise an axial compressor, a centrifugal compressor, or a different type of compressor in other embodiments, for example.

[000189] In order to enhance the change in temperature throughout first chamber 880 in the positive radial direction, the walls of chamber 880, such as the walls 864, can comprise thermally insulating material. The insulating material can comprise polystyrene, ceramics, or fiberglass, and can encompass chamber 880. This can minimize or reduce the flow of heat from the regions of large temperature within chamber 880 to regions of low temperature within chamber 880 through the walls of chamber 880. This can increase the magnitude of the temperature difference or the magnitude of the spatial temperature gradient within chamber 880.

[000190] The first work exchange apparatus 873 is contained within a rotating apparatus 864 which is configured to rotate about axis 872 relative to apparatus 861. Rotating apparatus 864 is supported by ball bearings, such as ball bearing 867 or ball bearing 866. The bulk material 865 of rotating apparatus 864 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic. The bulk material 863 of apparatus 861 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic. A drive flange 868 can allow external apparatuses, such as electric generators, propellers, or drive shafts to be mechanically coupled to the rotating apparatus 864. The volume 869 between the rotating apparatus 864 and apparatus 861 is evacuated, i.e. forms a vacuum, in the depicted embodiment. In other embodiments, the volume 869 can comprise a low pressure gas or a fluid specially configured or selected to reduce the viscous drag associated with the relative motion of the rotating apparatus 864 relative to apparatus 861.

[000191] The rotating apparatus 864 can comprise several work exchange apparatuses of the same type as the first work exchange apparatus 873. These work exchange apparatuses can be arranged adjacent to each other in circumferential fashion about axis 872. The work exchange apparatuses within rotating apparatus 864, such as first work exchange apparatus 873, can be considered to be the cylinders of a rotary engine, i.e. a radial engine rotating about a central axis, or axis 872. For instance, rotating apparatus 864 can comprise six or seven work exchange apparatuses of the same type and general construction as the first work exchange apparatus 873 arranged in circumferential fashion in the YZ-plane about axis 872. In other embodiments, rotating apparatus 864 can comprise one such work exchange apparatus, where the centrifugal loads are balanced by a counterweight. In other embodiments, rotating apparatus 864 can comprise eight or nine such work exchange apparatuses. In other embodiments, rotating apparatus 864 can comprise a plurality of such work exchange apparatuses. In FIG. 7G and FIG. 7H, the connecting rod 892 and the piston shaft 893 of another first work exchange apparatus are shown, where the other first work exchange apparatus is part of the rotating apparatus 864 and configured in a similar manner as the first work exchange apparatus 873. Another second work exchange apparatus configured in a similar manner as the second work exchange apparatus 895 can be employed to compress the working material from the other first work exchange apparatus, in a similar manner in which the second work exchange apparatus 895 is employed to compress the working material from the first work exchange apparatus. In other embodiments, a single second work exchange apparatus can be employed to compress the working material of more than one first work exchange apparatus of rotating apparatus 864.

[000192] Some embodiments can comprise more than one rotating apparatus of the same type as rotating apparatus 864. In some such embodiments, the rotating apparatuses can be configured to rotate in opposite directions. This can mitigate or at least partially cancel any gyroscopic effects associated with the rotation of the masses associated with the rotating apparatuses and the change in the orientation of the associated axes of rotation of the rotating masses in an inertial space. In a subset of such embodiments, the axis of rotation of a first rotating apparatus is parallel to and coincident with an axis of rotation of a second rotating apparatus.

[000193] The bulk material 905 of second work exchange apparatus 895 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic.

[000194] A working material can be a gas, such as air, helium, or nitrogen, for example. A working material can also be a liquid such as water. In the embodiment shown in FIGS. 7A-J, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability are explained herein.

[000195] Upstream of first opening 870 the working material can be compressed by an upstream compressor. This can increase the power output of embodiment 860 during nominal operations. The upstream compressor can be a centrifugal or axial flow compressor, or a reciprocating engine, for example. The upstream compressor can also be configured in a similar manner as a turbocharger or a supercharger in a conventional internal combustion engine, or a compressor in a conventional turbojet engine. The upstream compressor can also be referred to as a third work exchange apparatus. Downstream of the upstream compressor and upstream of first opening 870, heat can also be removed from the working material in a heat exchanger. The heat exchanger can be configured in a similar manner as an intercooler, for example. Embodiments in which an expander, such as an axial or centrifugal turbine, is located upstream of first opening 870 are also within the scope of the invention. The upstream expander can also be referred to as a third work exchange apparatus. Embodiments in which a heat exchanger downstream of the third work exchange apparatus and upstream of the first opening 870 is configured to deliver heat to the working material are also within the scope of the invention. In some embodiments, the second work exchange apparatus 895 and the aforementioned third work exchange apparatus can be the same. In other words, the second work exchange apparats 895 can also be employed to expand or compress the working material prior to entering chamber 880.

[000196] In the embodiment shown in FIGS. 7A-J, and throughout one thermodynamic cycle during nominal operation, the volume 882 beyond the piston 883 is maintained at a vacuum. In other embodiments, the volume 882 need not comprise a vacuum, but can comprise a gas of suitable pressure. The average pressure of the gas in volume 882 can be selected and maintained by a pressure regulating apparatus in a manner in which the structural loads on the components of the reciprocating apparatus are reduced, where the reciprocating apparatus comprises the piston 883, the piston shaft 884, connecting rod 888, connecting plate 891, or crankshaft 885, for example. The volume located on the opposite side of piston 907 of the second work exchange apparatus 895 compared to chamber 903 can be configured in a similar manner. The volume can comprise a vacuum, or comprise a gas, where the average pressure of the gas throughout one thermodynamic cycle during nominal operations can be selected and regulated to optimize the performance, or maximize the length of the lifecycle, or minimize the total cost of maintenance, of the second work exchange apparatus 895.

[000197] In the embodiment shown in FIGS. 7A-J, the crankshaft 885 does rotate in an inertial frame during nominal operations. In some such embodiments, crankshaft 885 can rotate about axis 872. In such embodiments, crankshaft 885 can comprise a counterweight, such as counterweight 886. In some such embodiments, the rate of rotation of crankshaft 885 about axis 872 can be at a different angular frequency compared to the rate of rotation of rotating apparatus 864. This allows the transfer of mechanical power from rotating apparatus 864 to the crankshaft, or vice versa. In other embodiments, or other methods of operation, or other operating conditions, crankshaft 885 need not rotate in an inertial frame.

[000198] A connecting plate 891 is rotably coupled to crank 887 of crankshaft 885, where the axis of relative rotation is parallel to axis 872. A connecting rod, such as connecting rod 891, is rotably coupled to connecting plate 891 via a connecting pin 890, where the axis of relative rotation is parallel to axis 872. Connecting rod 891 is also rotably coupled to piston shaft 884 via connecting pin 889 in the crankcase 894.

[000199] The nominal operation of the exemplary embodiment 860 for a nominal operating condition throughout one thermodynamic cycle can be described as follows. Throughout this nominal operating condition, the rate of rotation of the first work exchange apparatus 873, and in particular of chamber 880, is constant in time and greater than zero.

[000200] As shown in FIG. 7A, FIG. 7B, and FIG. 7C, at the beginning of the thermodynamic cycle, the first valve 878 of the first work exchange apparatus 873 is opened, and the piston 883 is moved in the radially outward direction, while the second valve 879 remains closed. This increases the volume of first chamber 880 and draws working material through the annular pipe at first opening 870 of the rotating apparatus 864, through the inlet pipe 874 with pipe wall 875, and through the open first valve 878 into first chamber 880. The motion of piston 883 in the radially outward direction is indicated by the bold arrow in chamber 880 in FIG. 7B. Due to the body force acting on the working material in chamber 880, there is an increase in temperature, pressure, and density of the working material along the radially outward direction throughout chamber 880.

[000201] Between the configurations shown in FIG. 7C and FIG. 7D, the first valve 878 of the first work exchange apparatus 873 is closed while the second valve 879 remains closed. At this point, the piston 883 has increased the volume of chamber 880 to slightly less than half the total available volume of chamber 880 in this embodiment, and this example method of operation. The ratio of the volume of chamber 880 at the point at which the first valve 878 is closed at this stage in the thermodynamic cycle to the total available volume of chamber 880 is denoted the "initial volume fraction". In other embodiments, or other example methods of operation, the initial volume fraction can be less than the magnitude of the volume fraction shown in FIG. 7D. In other embodiments, or other example methods of operation, the initial volume fraction can be larger than the magnitude of the volume fraction shown in FIG. 7D. In other embodiments, or other example methods of operation, the initial volume fraction can be less than or equal to 0.5. In other embodiments, or other example methods of operation, the initial volume fraction can be larger than 0.5. The optimal initial volume fraction, or the most suitable initial volume fraction, for a given embodiment of the invention, for a given operating condition, and for a given application, can be readily determined using theoretical or empirical methods known in the art.

[000202] As shown in FIG. 7E, FIG. 7F, and FIG. 7G, the working material within chamber 880 is subsequently expanded as the volume within chamber 880 is increased further while the first valve 878 and the second valve 879 remain closed. Throughout this expansion the working material does work on piston 883 in this embodiment. In a simplified model this expansion can be described as an adiabatic expansion in the sense that no heat is exchanged between the working material and the environment, such as bulk material 865. Due to the effective body force per unit mass acting on the working material within chamber 880 in the negative Y-direction, or, in this case, in the radially outward direction, this expansion is associated with a reduction in the specific entropy of the working material within chamber 880.

[000203] Between the configurations shown in FIG. 7G and FIG. 7H, the second valve 879 of the first work exchange apparatus 873, and the first valve 901 of the second work exchange apparatus

895 are opened, while the first valve 878 of the first work exchange apparatus 873, and the second valve 902 of the second work exchange apparatus 895 remain closed.

[000204] As shown in FIG. 7I, and FIG. 7J, the piston 883 is subsequently moved in the radially inward direction, and the piston 907 and piston shaft 908 is moved in the negative Y-direction, while the first valve 878 and the second valve 902 remain closed. This decreases the volume of first chamber 880 and increases the volume of the second chamber 903 and pushes the working material out of first chamber 880 through the open second valve 879, through outlet pipe 876 with pipe wall 877, through the annular pipe at second opening 871 of the rotating apparatus 864, through the inlet pipe 896 with pipe wall 897 of the second work exchange apparatus 895, through the open first valve 901 and into second chamber 903 of the second work exchange apparatus 895. The motion of piston 883 in the radially inward direction and the motion of piston 907 in the negative Y-direction is indicated by the bold arrow in chamber 880 and the bold arrow in chamber 903 in FIG. 7I.

[000205] Between the configurations shown in FIG. 7J and FIG. 7A, the first valve 901 of the second work exchange apparatus 895 and the second valve 879 of the first work exchange apparatus 873 are subsequently closed. The first valve 878 of the first work exchange apparatus 873 is subsequently opened, as shown in FIG. 7A.

[000206] As shown in FIGS. 7A-E, the working material within chamber 903 is subsequently compressed as the volume within chamber 903 is decreased while the first valve 901 and the second valve 902 remain closed. Throughout this compression piston 907 does work on the working material in chamber 903 in this embodiment. In a simplified model this compression can be described as an adiabatic and isentropic compression.

[000207] As shown in FIGS. 7A-E, the working material within chamber 903 is subsequently compressed as the volume within chamber 903 is decreased while the first valve 901 and the second valve 902 remain closed. Throughout this compression piston 907 does work on the working material in chamber 903 in this embodiment. In a simplified model this compression can be described as an adiabatic and isentropic compression. Recall that no body force per unit mass is acting on the working material within chamber 903 of second work exchange apparatus 895 in this example. In other embodiments, a body force per unit mass can act on the working material in chamber 903, where the component of the body force can be in the positive Y-direction. In other embodiments, a body force per unit mass can act on the working material in chamber 903, where the component of the body force can be in the negative Y-direction, where the magnitude of the component of the body force per unit mass in the negative Y-direction in chamber 903 is smaller than the component of the body force per unit mass in the negative Y-direction, or the radially outwards direction, in chamber 880. Throughout this compression, the pressure, temperature and density of the working material in chamber 903 increases.

[000208] Once the pressure of the working material in chamber 903 has reached the value of the ambient pressure, or the pressure beyond third opening 900, the second valve 902 can be opened, which occurs between the configurations shown in FIG. 7E and FIG. 7F.

[000209] As shown in FIGS. 7F-G the piston 907 of second work exchange apparatus 895 is subsequently moved further into the positive Y-direction, reducing the volume of chamber 903 and expelling the working material through the open second valve 902, through the outlet pipe 898 with pipe wall 899, and out of third opening 900.

[000210] Following the expulsion out of the third opening 900 the temperature of the working material is lower than the temperature of the working material at the beginning of the thermodynamic cycle. The temperature of the working material can be subsequently increased to the temperature of the working material at the beginning of the thermodynamic cycle. When the working material is expelled into a large reservoir of working material, such as air expelled into the atmosphere, the temperature increase occurs at substantially constant pressure. This completes the thermodynamic cycle described in FIGS. 7A-J. In other embodiments the working material can remain in a closed cycle as opposed to an open cycle. In such embodiments, the increase in temperature can occur isobarically, isochorically, or polytropically, for example.

[000211] As used herein, the term “interaction cycle” describes the properties of the working material throughout its interaction with exemplary embodiment 860. The interaction cycle is equivalent to the aforementioned closed thermodynamic cycle with the exception of the isobaric heating of the working material after having exited through the third opening 900. An exemplary interaction cycle can comprise: the drawing or pulling of working material into a first chamber 880; the subjecting of the working material within the first chamber 880 to a body force per unit mass, where the body force per unit mass comprises a non-zero component in a first direction, e.g. in the negative Y-direction; the expansion of the working material within the first chamber 880, where the expansion comprises a non-zero component in the first direction, e.g. in the negative Y-direction; the expulsion of the working material from the first chamber 880 and the drawing or pulling of the working material into a second chamber 903, where the component of the body force per unit mass is negligible in magnitude along a second direction; the compression of the working material within the second chamber 903, where the compression comprises a non-zero component in the second direction, e.g. in the positive Y-direction; and the expulsion of the working material from the second chamber 903. For instance, the interaction cycle described in FIGS. 7A-J is approximately described by this exemplary interaction cycle. An interaction cycle can be described as an open thermodynamic cycle, or an incomplete thermodynamic cycle. Due to the reduction of the specific entropy of the working material in chamber 880 during the expansion of the working material, the working material experiences a reduction in temperature throughout an interaction cycle in which the pressure of the working material at the beginning and end of the interaction cycle is identical. Throughout such an interaction cycle the working material need not absorb heat from the environment, or deliver heat to the environment. In this case, the interaction cycle can be described as a substantially adiabatic interaction cycle. Throughout such an interaction cycle, the working material can do a net amount of work on its environment, e.g. on piston 883 of first work exchange apparatus 873 and piston 907 of second work exchange apparatus 895. According to the first law of thermodynamics, and in an idealized, frictionless scenario, the amount of work done by the working material on its environment throughout a complete, or closed, thermodynamic cycle is equal to the amount of heat absorbed by the working material throughout the cycle. Thus, embodiments of the invention can be employed to convert thermal energy, or heat, contained within the working material, or provided by an external heat source, directly into useful energy, or mechanical work. In some embodiments the mechanical work can be converted into other forms of useful energy, such as electrical energy, or gravitational potential energy.

[000212] In some embodiments, the interaction cycle also comprises a compression or expansion of the working material upstream of the first opening 870, as described previously. In some embodiments, the second chamber 903 comprises a body force per unit mass directed in a third direction, e.g. in the negative Y-direction, where the component of the body force per unit mass is smaller than the magnitude of an equivalent component of the body force per unit mass in the first chamber 880 in the first direction, e.g. in the negative Y-direction, and where the compression of the working material in the second chamber 903 comprises a component in the negative third direction, i.e. in the positive Y-direction. In some embodiments, the second chamber 903 comprises a body force per unit mass directed in a fourth direction, e.g. in the positive Y-direction, and where the compression of the working material in the second chamber 903 comprises a component in the fourth direction, e.g. in the positive Y-direction.

[000213] Since the working material experiences a reduction in temperature throughout the aforementioned interaction cycle, embodiments of the invention can also be employed in applications requiring refrigeration of a thermal reservoir. For example, a closed thermodynamic cycle can be formed by a heat exchanger, where the heat exchanger is configured to allow the working material to flow through the heat exchanger located between the third opening 900 and the first opening 870. The heat exchanger can be configured to isobarically deliver heat to the working material, for example. The heat exchanger can be configured to remove heat from the interior of a refrigerator, or a room which is to be cooled. The useful mechanical work generated by apparatus 860 can be converted into electrical energy by an electric generator. The electrical energy can be delivered to a national electricity grid, or converted into thermal energy in a different thermal reservoir, such as the atmosphere or outer space, for example. The conversion into thermal energy can comprise Joule heating, or the emission of electromagnetic waves, or photons. In the latter case, the frequencies of the photons can be configured to correspond to the frequencies for which the atmosphere has a low coefficient of absorptivity, such that a large portion of the photons are able to travel through the atmosphere into outer space. Such methods are well known in the field of radiative cooling.

[000214] In some embodiments, or some example methods of operation, the working material can be returned to the first chamber 880 of the first work exchange apparatus 873 after having been compressed in the second chamber 903 of the second work exchange apparatus 895. In this manner the working material can be subjected to several consecutive interaction cycles before being expelled through third opening 900. In other words, several interaction cycles can be connected in series, i.e. arranged sequentially in time. As described in the context of FIG. 2, the cooling of the working material throughout successive interaction cycles, and the unchanged maximum volume of first chamber 880, can result in the amount of work done by the working material throughout at least two consecutive interaction cycles increasing for a subset of embodiments and operating conditions.

[000215] In other embodiments, an exemplary interaction cycle can comprise: the subjecting of the working material within the first chamber to a body force per unit mass, where the body force per unit mass comprises a non-zero component in a first direction; the compression of the working material within the first chamber, where the compression comprises a non-zero component in the first direction. A similar scenario is also described in FIG. 11. For example, the first valve 878 and the second valve 879 can be located at the radially outward location of chamber 882 instead of the radially inward location of chamber 880 shown in FIGS. 7A-J. In other words the first valve 878 and the second valve 879 can be located on the opposing side of piston 883, at the radially outward facing side of chamber 882. Throughout an interaction cycle, the working material can be drawn into chamber 882 through the open first valve. In this case the piston 883 can be drawn back to the innermost radially inward position, such as the position shown in FIG. 7A, before the first valve is closed. As before, the working material in chamber 882 is subject to a body force per unit mass acting in the radially outwards direction, resulting in a decrease in temperature, pressure, and density of the working material along the radially inward direction throughout chamber 882. Following the closure of the first valve the piston 883 can do work on the working material and compress the working material in chamber 882, while the first and second valve to chamber 882 remain closed. Due to the body force acting on the working material throughout this compression, and due to the compression being performed by piston 883 in a radially outward direction, the compression is associated with a reduction in the specific entropy of the working material. Following the compression, the piston 883 can be located at almost the outermost radial position within chamber 882. Subsequently the second valve of chamber 882 can be opened, and the working material can be expelled from chamber 882 and into a second work exchange apparatus such as second work exchange apparatus 895. Following the expulsion of the working material, the piston 883 can be located at the outermost radial position within chamber 882 once more, and the second valve can be closed, and the first valve can be opened in anticipation of the next pull or draw of working material into chamber 882. In the second work exchange apparatus the working material from chamber 883 can be expanded. The expansion can be described as an adiabatic and isentropic expansion in a simplified model. Once the pressure of the working material in the second work exchange apparatus has decreased to a level approximately equivalent to the pressure of the working material in an adjacent thermal reservoir, the working material can be expelled into the adjacent thermal reservoir. The working material can be air, and the adjacent thermal reservoir can be the atmosphere, for example. This completes this interaction cycle. As described in the context of the interaction cycle depicted in FIGS. 7A-J, a wide variety of alternative configurations, alternative methods of operation, and alternative utilizations or applications of such an interaction cycle are within the scope of the invention. For instance, the interaction cycle can be part of a closed thermodynamic cycle. The working material can also be compressed or expanded prior to entering the interaction cycle, or after exiting the interaction cycle. Several such interaction cycles can also be arranged in series or sequentially in time, for example.

[000216] In some embodiments, the first work exchange apparatus 873 can comprise four valves, two for chamber 880, and two for chamber 882. In such embodiments, both chambers, i.e. both chamber 880 and chamber 882, can be employed concurrently to compress and expand the working materials located within both chambers. In other words, the piston 883 can simultaneously interact with working material on both the radially inward side, as described in the context of FIGS. 7A-J, and the working material on the radially outwards side, as described in the preceding paragraph. This can increase the power output of an embodiment of the invention by simultaneously or concurrently utilizing chamber 880 and chamber 882 to reduce the specific entropy of the working material on both sides of piston 883. Similarly, in some embodiments, the second work exchange apparatus 895 can comprise four valves, two for chamber 903, and two for the opposite chamber 906, i.e. the chamber on the opposite side of piston 907, on the side of the piston located in the negative Y-direction. In some such embodiments, both chamber 903 and the opposite chamber 906 can be employed to compress the working material from chamber 880, or expand the working material from chamber 882. In other such embodiments, both chamber 903 can be employed to compress the working material from chamber 880 or expel the working material through the third opening 900, while the opposite chamber 906 is employed to draw or pull working material from chamber 882, or from another chamber of another first work exchange apparatus.

[000217] In some embodiments, or some methods of operation, the second work exchange apparatus 895 can be employed to expand the working material from chamber 880 instead of compressing the working material from chamber 880. In some embodiments, or some methods of operation, a second work exchange apparatus, such as second work exchange apparatus 895, need not be required. In such embodiments, the pressure of the working material at the second opening 871 can already be substantially equal to the ambient pressure, or the pressure in the thermal reservoir into which the working material is to be expelled.

[000218] In some embodiments, the second work exchange apparatus 895 can be part of an inline reciprocating engine. In some embodiments, the second work exchange apparatus 895 can be part of a radial engine. In other embodiments, the second work exchange apparatus 895 can comprise an axial or centrifugal compressor, an axial or centrifugal turbine, or a converging diverging duct, for example.

[000219] FIG. 8 shows a plot 930 of pressure 932 versus specific volume 931 for the working material in a subset of embodiments of the invention for an example method of operation, or an example thermodynamic cycle, such as the example method of operation shown in FIGS. 7A-J.

[000220] Prior to interacting with an embodiment of the invention, the state of the working material is described by station 933 in this example thermodynamic cycle. Station 933 can describe the thermodynamic properties of the working material in a first thermal reservoir, for example. The first thermal reservoir can be the atmosphere of the earth, for example. Between station 933 and station 934, the working material is compressed 942 adiabatically and isentropically in this example. Following the compression 942, the working material is pulled or drawn into a first chamber, in which the working material is subject to a body force per unit mass. As a result, a spatial variation 943 in pressure, temperature, and density of the working material is established within the first chamber. The thermodynamic properties 934 of the working material in the first thermal reservoir provide a boundary condition for the spatial variation 943 of the thermodynamic properties of the working material within the first chamber. The thermodynamic properties of the working material at the opposing side of the first chamber, such as at the side of first chamber facing piston 883, are described by station 936. In other words, station 936 describes the thermodynamic state of the working material in the first chamber as perceived by piston 883.

[000221] Following the pulling or drawing of working material into a first chamber by piston 883, the valves of first chamber are closed. Subsequently, the working material within the first chamber is expanded by the retraction of piston 883 and an increase in the volume within the first chamber. The resulting change in the thermodynamic properties of the working material within the first chamber as perceived by piston 883, i.e. at the location of piston 883, is described by line 944. The change in the thermodynamic properties of the working material within the first chamber as perceived by the opposite side of the first chamber, e.g. the side facing the valves to the first chamber, such as first chamber 880, is described by dashed line 945. Following the completion of the expansion of the working material in the first chamber, the spatial variation of the thermodynamic properties of the working material throughout the first chamber is described by line 946. Station 937 describes the thermodynamic properties of the working material within the first chamber as perceived by piston 883, i.e. at the location of piston 883 at this point in the thermodynamic cycle. Station 938 describes the thermodynamic properties of the working material within the first chamber as perceived by the opposing side of the first chamber, e.g. the side facing the valves to the first chamber, such as first chamber 880, at this point in the thermodynamic cycle.

[000222] Following the completion of the expansion of the working material in the first chamber, the working material can be expelled out of the first chamber and pulled or drawn into a second chamber. In this simplified example, there is no body force per unit mass acting on the working material in the second chamber. The thermodynamic properties of the working material at the location of the valves, i.e. at station 938, provides a boundary condition for the thermodynamic properties of the working material within the second chamber. The thermodynamic properties of the working material within the entirety of the second chamber are therefore described by the thermodynamic properties at station 938 at this stage in the thermodynamic cycle. The valves between the second chamber and the first chamber are closed following the expulsion of the working material from the first chamber. The working material in the second chamber can subsequently be compressed 947 adiabatically and isentropically this simplified model. Note that a portion of line 946 between stations 937 and 938 overlaps with line 947 between stations 938 and 940. Following the adiabatic compression 947, the thermodynamic state of the working material is described by station 940. Following the adiabatic compression 947, the working material can be expelled from the second chamber through a valve into a second reservoir. In some embodiments, the second reservoir and the first reservoir are identical, or one and the same. Within the second reservoir, the working material can be heated isobarically 948 and return to station 933, thus completing the thermodynamic cycle. Throughout this thermodynamic cycle the working material absorbs heat from the environment, and does a net amount of work on the environment.

[000223] At least a portion of the mechanical work done on the working material in the second chamber can be provided by the mechanical work done by the working material during the expansion of the working material in the first chamber. For example, the rotating apparatus 864 or the crankshaft 885 can be employed to deliver mechanical power to the second work exchange apparatus 895 in the embodiment shown in FIGS. 7A-J.

[000224] FIG. 9A shows a cross-sectional view of an exemplary embodiment of the invention employing the principles described in the context of FIGS. 7A-J and FIG. 8. This embodiment can be considered to comprise a rotating radial engine, or a rotary engine, as well as two centrifugal compressors being driven by the main drive shaft. The embodiment shown in FIG. 9A is configured in a similar manner as the embodiment shown in FIGS. 7A-J, and will therefore not be described in the same detail.

[000225] The apparatus 1442 comprises a first centrifugal compressor 1514 with an impeller 1516 with an inlet 1515 and exit 1518 located within casing 1522. The first centrifugal compressor 1514 is configured in a similar manner as conventional centrifugal compressors found in turbochargers and superchargers in conventional automobile and aircraft engines. The first centrifugal compressor 1514 comprises a diffuser 1524 and a volute 1525 and exit pipe 1526. During nominal operations the first centrifugal compressor 1514 compresses the working material after entering through inlet 1515 and before exiting into volute 1525 and pipe 1526. Following the compression in the first centrifugal compressor 1514, the working material enters the rotary engine 1444.

[000226] Note that the first centrifugal compressor 1514 and the compression of the working material therein is not an essential part of embodiments of the invention. The purpose of the first centrifugal compressor 1514 is to increase the density of the working material at the inlet to rotary engine 1444, and thereby increase the mass flow rate of the working material through rotary engine 1444. This can increase the power output of rotary engine 1444. The purpose of the first centrifugal compressor 1514 is therefore similar to the purpose of a conventional turbocharger or supercharger on a conventional piston engine, such as a conventional automobile or aircraft engine. In some embodiments, the working material can also pass through an intercooler between the exit of supercharger 1514 and the inlet to rotary engine 1444. The intercooler can cool down the working material by facilitating a heat exchange with the ambient working material, such as air in the atmosphere, for example. The intercooler can alternatively or concurrently cool down the working material by facilitating a heat exchange with the working material in the exhaust of engine 1442, i.e. the working material exiting the second centrifugal compressor 1501 through pipe 1513, for example. Such methods are well known in the field of turbocharging or supercharging reciprocating engines.

[000227] The apparatus 1442 comprises a rotary engine 1444, which is shown in cross-sectional view in FIG. 9A. The engine is located inside a casing 1443 which contains a volume of reduced pressure, or a vacuum, in order to reduce the viscous drag of rotary engine 1444 rotating within casing 1443 about axis 1448 during nominal operations. The rotary engine 1444 comprises a plurality of cylinders, pistons, or work exchange apparatuses, such as work exchange apparatus 1450 and work exchange apparatus 1459. The rotary engine 1444 can comprise two, eight or twelve work exchange apparatuses, for example. In other embodiments, the rotary engine 1444 can comprise any number of work exchange apparatuses, such as three, seven, ten, or eleven work exchange apparatuses or cylinders. Each work exchange apparatus is configured similarly. Work exchange apparatus 1450 comprises a piston 1451 and piston shaft 1452. Work exchange apparatus 1459 comprises a piston 1470 and piston shaft 1471 rotably coupled to piston rod 1472, which in turn is rotably coupled to connecting plate 1457, which in turn is rotably coupled to crank 1455. Valves 1464 and 1465 allow working material to enter and exit chamber 1466. Counterweight 1454 balances the mass of the crank 1455 of crankshaft 1453.

[000228] Working material can flow through pipe 1526 through several circular channels, such as channel 1446 through exit shaft 1449 of inside casing 1444, and into the cylinders via the valves. Similarly, the working material can flow through several circular channels, such as channel 1447 through exit shaft 1449 of inside casing 1444, out of the cylinders and into centrifugal compressor 1501.

[000229] The apparatus 1442 comprises a second centrifugal compressor 1501 with an impeller 1503 with an inlet 1502 and exit 1505 and back plate 1508 located within a casing. The second centrifugal compressor 1501 is configured in a similar manner as conventional centrifugal compressors found in turbochargers and superchargers in conventional automobile and aircraft engines. The second centrifugal compressor 1501 comprises a diffuser 1511 and a volute 1512 and exhaust pipe 1513. During nominal operations the second centrifugal compressor 1501 compresses the working material after entering through inlet 1502 and before exiting into volute 1512 and pipe 1513. Following the compression in the second centrifugal compressor 1501, the working material is exhausted into the ambient reservoir, such as the atmosphere of earth, at a colder temperature than at inlet 1515 to engine 1442 during nominal operations.

[000230] During nominal operations, i.e. during power production by engine 1442, there is a difference in the rotational speeds of crankshaft 1453 and exit shaft 1449 of inside casing 1444. Note that exit shaft 1449 is rigidly attached to the crankcase and the inside casing 1444. The crankshaft 1453 can rotate faster or slower than exit shaft 1449 in an inertial frame. In order to reduce the centrifugal loads and stresses, it is preferable for the crankshaft 1453 to rotate more slowly than exit shaft 1449 in an inertial frame. The differential rotation between the exit shaft 1449 and the crankshaft 1453 in a rotating frame can be converted into a net rotation in an inertial frame by a differential gear. In the embodiment shown in FIG. 9A, a coaxial differential gear 1475 is employed. The differential gear 1475 comprises two planetary gears.

[000231] The first planetary gear 1476 comprises a sun gear 1477 which is rigidly coupled to the exit shaft 1449. The first planetary gear 1476 also comprises several planet gears, such as planet gear 1478 rotably coupled to support shaft 1479, which in turn is rigidly mounted on support plate 1481, which does not rotate in an inertial frame during nominal operations. The first planetary gear 1476 also comprises other planet gears, such as planet gears 1482 and 1483. The first planetary gear 1476 also comprises a ring gear 1484 which can rotate freely relative to the engine 1442, and is also the ring gear for the second planetary gear 1485.

[000232] The second planetary gear 1485 comprises a sun gear 1486 which is rigidly coupled to the crankshaft 1453. The second planetary gear 1485 also comprises several planet gears, such as planet gear 1487 rotably coupled to a support shaft, which in turn is rigidly mounted on carrier gear 1489, which rotates freely during nominal operations and is rigidly coupled to drive shaft 1490. The second planetary gear 1485 also comprises other planet gears, such as planet gears 1491 and 1492. The second planetary gear 1485 also comprises a ring gear 1484, as mentioned.

[000233] The radius of the sun gear of the first planetary gear 1476 is denoted “R1”. The radius of the planetary gear of the first planetary gear 1476 is denoted “RP1”. The radius of the ring gear of the first planetary gear 1476 is denoted “R1B”. The radius of the sun gear of the second planetary gear 1485 is denoted “R2”. The radius of the planetary gear of the second planetary gear 1485 is denoted “RP2”. The radius of the ring gear of the second planetary gear 1485 is denoted “R2B”. For a typical coaxial differential the ratio of R1 to RP1 is equal to the ratio of R2 to RP2. For a typical coaxial differential the ratio of R1 to R1B is equal to the ratio of R2 to R2B. In other words, the first planetary gear 1476 is geometrically similar to the second planetary gear 1485. In this case, the rate of rotation of the drive shaft 1490 is proportional to the difference in the rates of rotation of the crankshaft 1453 and the exit shaft 1449. The constant of proportionality is a function of the radius R1 and RP1, for example. In this manner, the drive shaft 1490 can be powered by the difference in the rotational speeds of two rotating drive shafts.

[000234] The first centrifugal compressor 1514 and the second centrifugal compressor 1501 are driven by drive shaft 1490 via a gear train. For example, the carrier gear 1489 drives a first gear 1496 mounted on drive shaft 1494. A second gear 1497 is mounted on the drive shaft driven by carrier gear 1489. The second gear 1497 drives a third gear 1498, which drives the impeller 1503 of the second centrifugal compressor 1501. Similarly, impeller 1516 of first centrifugal compressor 1514 is driven by third gear 1500, which is driven by second gear 1499, which in turn is coupled to a drive shaft driven by carrier gear 1489.

[000235] In other embodiments, the gear train coupling the drive shaft 1490 to the impellers of first centrifugal compressor 1514 and the second centrifugal compressor 1501 can be configured differently. For example, the gear train can comprise more gears, clutches, gearboxes or transmissions, and other such mechanical devices.

[000236] FIG. 9B shows the first planetary gear 1476 in cross-sectional view. FIG. 9C shows the second planetary gear 1485 in cross-sectional view.

[000237] FIGS. 10A-K schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition. This embodiment can be considered to comprise a rotating radial engine, or a rotary engine, in which the piston does work on the working material.

[000238] Exemplary embodiment 1570 comprises a first work exchange apparatus 1587 comprising a first chamber 1594 and a second work exchange apparatus 1626 comprising a second chamber 1633. The working material within the first chamber is subject to a body force per unit mass provided by a body force generating apparatus during nominal operations. A wide variety of body force generating apparatuses can be used. In embodiment 1570, the body force per unit mass is inertial in nature. First chamber 1594 is configured to rotate about axis 1585, thereby experiencing an effective centrifugal acceleration, as described in the context of FIG. 2. An axis coincident with and parallel to axis 1585 and directed from the left of the page to the right of the page is denoted the "X-axis". An axis perpendicular to the X-axis and in the plane of the page and directed from the bottom of the page to the top of the page is denoted the "Y-axis". A radial direction is a direction perpendicular to the X-axis, lying in the YZ-plane, and directed away from the X-axis. Due to the rotation of the first chamber 1594, an effective body force per unit mass is acting on the working material within first chamber 1594 in the positive radial direction. In the steady state, this results in a temperature gradient within the working material in chamber 1594, where the temperature increases in an increasing, or outward, or positive, radial direction. The pressure and density also increases in a positive radial direction in this scenario. The first and second work exchange apparatuses comprise reciprocating pistons in this simplified example. The second work exchange apparatus can comprise an axial turbine, a centrifugal turbine, or a different type of expander in other embodiments, for example.

[000239] In order to enhance the change in temperature throughout first chamber 1594 in the positive radial direction, the walls of chamber 1594, such as the walls 1574, can comprise thermally insulating material. The insulating material can comprise polystyrene, ceramics, or fiberglass, and can encompass chamber 1594. This can minimize or reduce the flow of heat from the regions of large temperature within chamber 1594 to regions of low temperature within chamber 1594 through the walls of chamber 1594. This can increase the magnitude of the temperature difference or the magnitude of the spatial temperature gradient within chamber 1594.

[000240] The first work exchange apparatus 1587 is contained within a rotating apparatus 1574 which is configured to rotate about axis 1585 relative to apparatus 1571. Rotating apparatus 1574 is supported by ball bearings, such as ball bearing 1576. The bulk material of rotating apparatus 1574 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic. The bulk material 1573 of apparatus 1571 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic. The differential rotation between exit shaft 1586 and crankshaft 1604 can be employed to drive a differential, which in turn can drive external apparatuses, such as electric generators, propellers, or drive shafts to be mechanically coupled to engine 1570. The volume 1579 between the rotating apparatus 1574 and apparatus 1571 is evacuated, i.e. forms a vacuum, in the depicted embodiment. In other embodiments, the volume 1579 can comprise a low pressure gas or a fluid specially configured or selected to reduce the viscous drag associated with the relative motion of the rotating apparatus 1574 relative to casing apparatus 1571.

[000241] The rotating apparatus 1574 can comprise several work exchange apparatuses of the same type as the first work exchange apparatus 1587. These work exchange apparatuses can be arranged adjacent to each other in circumferential fashion about axis 1585. The work exchange apparatuses within rotating apparatus 1574, such as first work exchange apparatus 1587, can be considered to be the cylinders of a rotary engine, i.e. a radial engine rotating about a central axis, or axis 1585. For instance, rotating apparatus 1574 can comprise six or seven work exchange apparatuses of the same type and general construction as the first work exchange apparatus 1587 arranged in circumferential fashion in the YZ-plane about axis 1585. In other embodiments, rotating apparatus 1574 can comprise one such work exchange apparatus, where the centrifugal loads are balanced by a counterweight. In other embodiments, rotating apparatus 1574 can comprise eight or nine such work exchange apparatuses. In other embodiments, rotating apparatus 1574 can comprise a plurality of such work exchange apparatuses. In FIG. 10A, FIG. 10E, FIG. 10F and FIG. 10K, the connecting rod 1623 of another first work exchange apparatus are shown, where the other first work exchange apparatus is part of the rotating apparatus 1574 and configured in a similar manner as the first work exchange apparatus 1587. Another second work exchange apparatus configured in a similar manner as the second work exchange apparatus 1626 can be employed to expand the working material from the other first work exchange apparatus, in a similar manner in which the second work exchange apparatus 1626 is employed to expand the working material from the first work exchange apparatus. In other embodiments, a single second work exchange apparatus can be employed to expand the working material of more than one first work exchange apparatus of rotating apparatus 1574.

[000242] Some embodiments can comprise more than one rotating apparatus of the same type as rotating apparatus 1574. In some such embodiments, the rotating apparatuses can be configured to rotate in opposite directions. This can mitigate or at least partially cancel any gyroscopic effects associated with the rotation of the masses associated with the rotating apparatuses and the change in the orientation of the associated axes of rotation of the rotating masses in an inertial space. In a subset of such embodiments, the axis of rotation of a first rotating apparatus is parallel to and coincident with an axis of rotation of a second rotating apparatus.

[000243] The bulk material of second work exchange apparatus 1626 can comprise metal such as aluminium, steel, or titanium, or a composite such as carbon fiber or fiberglass, or a ceramic.

[000244] A working material can be a gas, such as air, helium, or nitrogen, for example. A working material can also be a liquid such as water. In the embodiment shown in FIGS. 10A-K, the working material is treated as an ideal gas for simplicity. In other embodiments, the working material can be any suitable material, where the conditions for suitability are explained herein.

[000245] The working material flows from a first opening into inlet pipe 1588, which directs the working material into the cylinders, such as cylinder 1587. Upstream of the first opening the working material can be compressed by an upstream compressor. This can increase the power output of embodiment 1570 during nominal operations. The upstream compressor can be a centrifugal or axial flow compressor, or a reciprocating engine, for example. The upstream compressor can also be configured in a similar manner as a turbocharger or a supercharger in a conventional internal combustion engine, or a compressor in a conventional turbojet engine. The upstream compressor can also be referred to as a third work exchange apparatus. Downstream of the upstream compressor and upstream of the first opening, heat can also be removed from the working material in a heat exchanger. The heat exchanger can be configured in a similar manner as an intercooler, for example. Embodiments in which an expander, such as an axial or centrifugal turbine, is located upstream of the first opening are also within the scope of the invention. The upstream expander can also be referred to as a third work exchange apparatus. Embodiments in which a heat exchanger downstream of the third work exchange apparatus and upstream of the first opening is configured to deliver heat to the working material are also within the scope of the invention. In some embodiments, the second work exchange apparatus 1626 and the aforementioned third work exchange apparatus can be the same. In other words, the second work exchange apparats 1626 can also be employed to expand or compress the working material prior to entering chamber 1594.

[000246] In the embodiment shown in FIGS. 10A-K, and throughout one thermodynamic cycle during nominal operation, the crankcase 1609, or volume 1609 behind the piston 1598, is maintained at a desired pressure. The average pressure of the gas in volume 1609 can be selected and maintained by a pressure regulating apparatus in a manner in which the structural loads on the components of the reciprocating apparatus are reduced, where the reciprocating apparatus comprises the piston 1598, connecting rod 1600, connecting plate 1608, or crankshaft 1585, for example. The volume located on the opposite side of piston 1637 of the second work exchange apparatus 1626 compared to chamber 1633 can be configured in a similar manner. The volume can comprise a vacuum, or comprise a gas, where the average pressure of the gas throughout one thermodynamic cycle during nominal operations can be selected and regulated to optimize the performance, or maximize the length of the lifecycle, or minimize the total cost of maintenance, of the second work exchange apparatus 1626. In other embodiments, the volume 1609 can comprise a vacuum.

[000247] In the embodiment shown in FIGS. 10A-K, the crankshaft 1585 rotates in an inertial frame during nominal operations. In some such embodiments, crankshaft 1585 can rotate about axis 1585. In such embodiments, crankshaft 1585 can comprise a counterweight, such as counterweight 886. In some such embodiments, the rate of rotation of crankshaft 1585 about axis 1585 can be at a different angular frequency compared to the rate of rotation of rotating apparatus 1574 in an inertial frame. This allows the transfer of mechanical power from rotating apparatus 1574 to the crankshaft, or vice versa. In other embodiments, or other methods of operation, or other operating conditions, crankshaft 1585 need not rotate in an inertial frame.

[000248] A connecting plate 1608 is rotably coupled to crank 1606 of crankshaft 1585, where the axis of relative rotation is parallel to axis 1585. A connecting rod, such as connecting rod 1608, is rotably coupled to connecting plate 1608 via a connecting pin, where the axis of relative rotation is parallel to axis 1585. Connecting rod 1608 is also rotably coupled to the piston via connecting pin 1602 in the crankcase 1609.

[000249] The nominal operation of the exemplary embodiment 1570 for a nominal operating condition throughout one thermodynamic cycle can be described as follows. Throughout this nominal operating condition, the rate of rotation of the first work exchange apparatus 1587, and in particular of chamber 1594, is constant in time and greater than zero.

[000250] As shown in FIGS. 10A-E, at the beginning of the thermodynamic cycle, the first valve 1592 of the first work exchange apparatus 1587 is open, and the piston 1598 is moved in the radially inward direction, while the second valve 1593 remains closed. This increases the volume of first chamber 1594 and draws working material through the inlet pipe 1588 at the first opening of the rotating apparatus 1574, through the open first valve 1592 into first chamber 1594. The motion of piston 1598 in the radially inward direction is indicated by the bold arrow in chamber 1594. Due to the body force acting on the working material in chamber 1594, there is an increase in temperature, pressure, and density of the working material along the radially outward direction throughout chamber 1594.

[000251] Between the configurations shown in FIG. 10E and FIG. 10F, the first valve 1592 of the first work exchange apparatus 1587 is closed while the second valve 1593 remains closed. At this point, the piston 1598 has increased the volume of chamber 1594 in this embodiment, and this example method of operation.

[000252] As shown in FIG. 10G, and FIG. 10H, the working material within chamber 1594 is subsequently compressed as the volume within chamber 1594 is decreased while the first valve 1592 and the second valve 1593 remain closed. Throughout this compression the piston 1598 does work on the working material in this embodiment. In a simplified model this compression can be described as an adiabatic compression in the sense that no heat is exchanged between the working material and the environment, such as the bulk material of inside casing 1574. Due to the effective body force per unit mass acting on the working material within chamber 1594 in the negative Y-direction, or, in this case, in the radially outward direction, this compression is associated with a reduction in the specific entropy of the working material within chamber 1594.

[000253] Between the configurations shown in FIG. 10H and FIG. 10I, the second valve 1593 of the first work exchange apparatus 1587, and the first valve 1631 of the second work exchange apparatus 1626 are opened, while the first valve 1592 of the first work exchange apparatus 1587, and the second valve 1632 of the second work exchange apparatus 1626 remain closed.

[000254] As shown in FIG. 10J, and FIG. 10K, the piston 1598 is subsequently moved in the radially outward direction, and the piston 1637 and piston shaft 1638 is moved in the negative Y-direction, while the first valve 1592 and the second valve 1632 remain closed. This decreases the volume of first chamber 1594 and increases the volume of the second chamber 1633 and pushes the working material out of first chamber 1594 through the open second valve 1593, through outlet pipe 1590, through the annular pipe at a second opening, through circular channels, such as channel 1582 and channel 1583, through exit shaft 1586 of the rotating apparatus 1574, through the exit pipe 1584 into inlet pipe 1627 of the second work exchange apparatus 1626, through the open first valve 1631 and into second chamber 1633 of the second work exchange apparatus 1626. The motion of piston 1598 in the radially outward direction and the motion of piston 1637 in the negative Y-direction is indicated by the bold arrow in chamber 1594 and the bold arrow in chamber 1633 in FIG. 10K.

[000255] Between the configurations shown in FIG. 10K and FIG. 10A, the first valve 1631 of the second work exchange apparatus 1626 and the second valve 1593 of the first work exchange apparatus 1587 are subsequently closed. The first valve 1592 of the first work exchange apparatus 1587 is subsequently or concurrently opened, as shown in FIG. 10A.

[000256] As shown in FIGS. 10A-E, the working material within chamber 1633 is subsequently compressed as the volume within chamber 1633 is decreased while the first valve 1631 and the second valve 1632 remain closed. Throughout this compression piston 1637 does work on the working material in chamber 1633 in this embodiment. In a simplified model this compression can be described as an adiabatic and isentropic compression.

[000257] As shown in FIGS. 10A-C, the working material within chamber 1633 is subsequently expanded as the volume within chamber 1633 is increased while the first valve 1631 and the second valve 1632 remain closed. Throughout this expansion the working material in chamber 1633 does work on piston 1637 in this embodiment. In a simplified model this compression can be described as an adiabatic and isentropic compression. Recall that no body force per unit mass is acting on the working material within chamber 1633 of second work exchange apparatus 1626 in this example. In other embodiments, a body force per unit mass can act on the working material in chamber 1633, where the component of the body force can be in the negative Y-direction. In other embodiments, a body force per unit mass can act on the working material in chamber 1633, where the component of the body force can be in the positive Y-direction, where the magnitude of the component of the body force per unit mass in the positive Y-direction in chamber 1633 is smaller than the component of the body force per unit mass in the negative Y-direction, or the radially outwards direction, in chamber 1594. Throughout this expansion, the pressure, temperature and density of the working material in chamber 1633 decreases.

[000258] Once the pressure of the working material in chamber 1633 has reached the value of the ambient pressure, or the pressure beyond third opening of exit pipe 1629, the second valve 1632 can be opened, which occurs between the configurations shown in FIG. 10C and FIG. 10D.

[000259] As shown in FIGS. 10E-H the piston 1637 of second work exchange apparatus 1626 is subsequently moved further into the positive Y-direction, reducing the volume of chamber 1633 and expelling the working material through the open second valve 1632, through the outlet pipe 1629, and out of the third opening.

[000260] Following the expulsion out of the third opening 1629 the temperature of the working material is lower than the temperature of the working material at the beginning of the thermodynamic cycle. The temperature of the working material can be subsequently increased to the temperature of the working material at the beginning of the thermodynamic cycle by absorbing heat. When the working material is expelled into a large reservoir of working material, such as air expelled into the atmosphere, the temperature increase occurs at substantially constant pressure during the absorption of energy from the atmosphere. This completes the thermodynamic cycle described in FIGS. 10A-K. In other embodiments the working material can remain in a closed cycle as opposed to an open cycle. In such embodiments, the increase in temperature can occur isobarically, isochorically, or polytropically, for example. The increase in temperature can be facilitated by a heat exchanger thermally coupled to another thermal reservoir.

[000261] As used herein, the term "interaction cycle" describes the properties of the working material throughout its interaction with exemplary embodiment 1570. The interaction cycle is equivalent to the aforementioned closed thermodynamic cycle with the exception of the isobaric heating of the working material after having exited through the third opening 1629. An exemplary interaction cycle can comprise: the drawing or pulling of working material into a first chamber 1594; the subjecting of the working material within the first chamber 1594 to a body force per unit mass, where the body force per unit mass comprises a non-zero component in a first direction, e.g. in the negative Y-direction; the compression of the working material within the first chamber 1594, where the compression comprises a non-zero component in the first direction, e.g. in the negative Y-direction; the expulsion of the working material from the first chamber 1594 and the drawing or pulling of the working material into a second chamber 1633, where the component of the body force per unit mass is negligible in magnitude along a second direction; the expansion of the working material within the second chamber 1633, where the expansion comprises a non-zero component in the second direction, e.g. in the negative Y-direction; and the expulsion of the working material from the second chamber 1633. For instance, the interaction cycle described in FIGS. 10A-K is approximately described by this exemplary interaction cycle. An interaction cycle can be described as an open thermodynamic cycle, or an incomplete thermodynamic cycle. Due to the reduction of the specific entropy of the working material in chamber 1594 during the compression of the working material, the working material experiences a reduction in temperature throughout an entire interaction cycle in which the pressure of the working material at the beginning and end of the interaction cycle is identical. Throughout such an interaction cycle the working material need not absorb heat from the environment, or deliver heat to the environment. In this case, the interaction cycle can be described as a substantially adiabatic interaction cycle. Throughout such an interaction cycle, the working material can do a net amount of work on its environment, e.g. on piston 1637 of first work exchange apparatus 1587 and piston 1637 of second work exchange apparatus 1626. According to the first law of thermodynamics, and in an idealized, frictionless scenario, the amount of work done by the working material on its environment throughout a complete, or closed, thermodynamic cycle is equal to the amount of heat absorbed by the working material throughout the cycle. Thus, embodiments of the invention can be employed to convert thermal energy, or heat, contained within the working material, or provided by an external heat source, directly into useful energy, or mechanical work. In some embodiments the mechanical work can be converted into other forms of useful energy, such as electrical energy, or gravitational potential energy. In the presence of friction, a fraction of the thermal energy extracted from the working material is converted back into thermal energy or heat.

[000262] In some embodiments, the interaction cycle also comprises a compression or expansion of the working material upstream of the first opening, as described previously. In some embodiments, the second chamber 1633 comprises a body force per unit mass directed in a third direction, e.g. in the positive Y-direction, where the component of the body force per unit mass is smaller than the magnitude of an equivalent component of the body force per unit mass in the first chamber 1594 in the first direction, e.g. in the negative Y-direction, and where the expansion of the working material in the second chamber 1633 comprises a component in the negative third direction, i.e. in the negative Y-direction. In some embodiments, the second chamber 1633 comprises a body force per unit mass directed in a fourth direction, e.g. in the negative Y-direction, and where the compression of the working material in the second chamber 1633 comprises a component in the fourth direction, e.g. in the negative Y-direction.

[000263] Since the working material experiences a reduction in temperature throughout the aforementioned interaction cycle, embodiments of the invention can also be employed in applications requiring refrigeration of a thermal reservoir. For example, a closed thermodynamic cycle can be formed by a heat exchanger, where the heat exchanger is configured to allow the working material to flow through the heat exchanger located between the third opening 1629 and the first opening upstream of pipe 1588. The heat exchanger can be configured to isobarically deliver heat to the working material, for example. The heat exchanger can be configured to remove heat from the interior of a refrigerator, or a room which is to be cooled. The useful mechanical work generated by apparatus 1570 can be converted into electrical energy by an electric generator. The electrical energy can be delivered to a national electricity grid, or converted into thermal energy in a different thermal reservoir, such as the atmosphere or outer space, for example. The conversion into thermal energy can comprise Joule heating, or the emission of electromagnetic waves, or photons, for example. In the latter case, the frequencies of the photons can be configured to correspond to the frequencies for which the atmosphere has a low coefficient of absorptivity, such that a large portion of the photons are able to travel through the atmosphere into outer space. Such methods are well known in the field of radiative cooling.

[000264] FIG. 11 shows a plot 970 of pressure 972 versus specific volume 971 for the working material in a subset of embodiments of the invention for an example method of operation.

[000265] Prior to interacting with an embodiment of the invention, the state of the working material is described by station 973 in this example thermodynamic cycle. Station 973 can describe the thermodynamic properties of the working material in a first thermal reservoir, for example. The first thermal reservoir can be the atmosphere of the earth, and the working material can be air, for example. Station 976 immediately follows station 973. Between station 973 and station 976, the working material is compressed 982 adiabatically and isentropically in this example. Following the compression 982, the working material is pulled or drawn into a first chamber, in which the working material is subject to a body force per unit mass. As a result, a spatial variation 983 in pressure, temperature, and density of the working material is established within the first chamber. Note that a portion of line 982 between stations 973 and 976 overlaps with line 983 between stations 976 and 974. The thermodynamic properties 976 of the working material in the first thermal reservoir provide a boundary condition for the spatial variation 983 of the thermodynamic properties of the working material within the first chamber. The thermodynamic properties of the working material at the opposing side of the first chamber, such as at the side of first chamber, such as chamber 882, facing piston 883, are described by station 974. Note that the reference designators refer to an embodiment adapted from the embodiment shown in FIGS. 7A-J for the purposes of the thermodynamic cycle shown in FIG. 11. The principles of one such exemplary adaptation are discussed in the context of FIGS. 7A-J. In other words, station 974 describes the thermodynamic state of the working material in the first chamber 882 as perceived by piston 883 of the adapted embodiment.

[000266] Following the pulling or drawing of working material into a first chamber by piston 883, the valves of first chamber are closed. Subsequently, the working material within the first chamber is compressed by the extension of piston 883 and a decrease in the volume within the first chamber. The resulting change in the thermodynamic properties of the working material within the first chamber 882 as perceived by piston 883, i.e. at the location of piston 883, is described by line 985. The change in the thermodynamic properties of the working material within the first chamber as perceived by the opposite side of the first chamber, e.g. the side facing the valves to the first chamber, such as first chamber 882, is described by dashed line 984. Following the completion of the compression of the working material in the first chamber, the spatial variation of the thermodynamic properties of the working material throughout the first chamber is described by line 986. Station 978 describes the thermodynamic properties of the working material within the first chamber as perceived by piston 883, i.e. at the location of piston 883 at this point in the thermodynamic cycle. Station 977 describes the thermodynamic properties of the working material within the first chamber as perceived by the opposing side of the first chamber, e.g. the side facing the valves to the first chamber, such as first chamber 882, at this point in the thermodynamic cycle.

[000267] Following the completion of the compression of the working material in the first chamber, the working material can be expelled out of the first chamber and pulled or drawn into a second chamber. In this simplified example, there is no body force per unit mass acting on the working material in the second chamber. The thermodynamic properties of the working material at the location of the valves, i.e. at station 977, provides a boundary condition for the thermodynamic properties of the working material within the second chamber. The thermodynamic properties of the working material within the entirety of the second chamber are therefore described by the thermodynamic properties at station 977 at this stage in the thermodynamic cycle. The valves between the second chamber and the first chamber are closed following the expulsion of the working material from the first chamber. The working material in the second chamber can subsequently be expanded 987 adiabatically and isentropically this simplified model. Note that a portion of line 987 between stations 977 and 980 is coincident with line 986 between stations 977 and 978. Following the adiabatic expansion 987, the thermodynamic state of the working material is described by station 980. Following the adiabatic expansion 987, the working material can be expelled from the second chamber through a valve into a second reservoir. In some embodiments, the second reservoir and the first reservoir are identical, or one and the same. Within the second reservoir, the working material can be heated isobarically 988 and return to station 973, thus completing the thermodynamic cycle. Throughout this thermodynamic cycle the working material absorbs heat from the environment, and does a net amount of work on the environment.

[000268] At least a portion of the mechanical work done on the working material in the first chamber can be provided by the mechanical work done by the working material during the expansion of the working material in the second chamber. For example, the rotating apparatus 864 or the crankshaft 885 can be employed to deliver mechanical power to the first work exchange apparatus 873 in an embodiment adapted from the embodiment shown in FIGS. 7A-J for the purposes of the thermodynamic cycle shown in FIG. 11.

[000269] In other embodiments, other types of body force generating apparatuses can be employed to modify the component of the body force per unit mass acting on objects or elements within a working material, as explained below. In general, a first work exchange apparatus can be configured to establish a spatial temperature gradient within the working material. A second work exchange apparatus can be employed to modify the local pressure and temperature of the working material, resulting the generation of acoustic waves, pressure waves, or shock waves within the working material. When these waves travel through the spatial gradient in the temperature, the local or global specific entropy of a working material can be reduced. For instance, the waves can travel through the temperature gradient in a direction such that thermal energy is transferred from a region of low temperature to a region of high temperature within the working material. Note that the first and second work exchange apparatus can be identical, i.e. at least a portion of the first work exchange apparatus can be employed to perform the operation, function, or task of the second work exchange apparatus

[000270] For example, a first work exchange apparatus can comprise a body force generating apparatus which can apply a body force per unit mass to objects within a working material, and thus generate a spatial temperature gradient within a working material. A second work exchange apparatus can be employed to allow the working material at the large temperature side of the temperature gradient within the working material to do work on the work exchange apparatus. In the process of doing work on the second work exchange apparatus, the local working material at the large temperature side of the temperature gradient expands, which is associated with an instantaneous reduction in pressure, temperature, and density of the working material at the large temperature side of the temperature gradient. The local and instantaneous reduction in pressure and density results in pressure waves, or expansion waves, or acoustic waves, or phonons travelling from the large temperature side of the temperature gradient through the temperature gradient to the low temperature side of the temperature gradient at the speed of sound. This expansion wave is associated with a cooling or a reduction in temperature of the working material, as well as a reduction in pressure and a reduction in density throughout the temperature gradient and on the low temperature side of the temperature gradient. Thus, the working material on the low temperature side of the temperature gradient, as well as the working material within the temperature gradient, experiences a reduction in temperature. Effectively, a portion of the energy consumed by the working material at the large temperature side of the temperature gradient while doing work on the second work exchange apparatus is replenished by, or provided by, the portion of the working material at the low temperature side of the temperature gradient and the working material within the temperature gradient. In this process, thermal energy is transferred from the region of low temperature in the working material to a region of large temperature in the working material. This process can lead to a reduction in the specific entropy of the working material. The scenario described in this example is also exemplified by FIG. 8, FIGS. 7A-J, the first expansion 725 and the second expansion 727 in FIG. 1A, as well as the second expansion 797 in FIG. 2. Since the instantaneous temperature change at the large temperature side of the temperature gradient is also associated with a pressure change, the temperature change is transmitted through the spatial temperature gradient via a pressure wave at the speed of sound. In some embodiments, this allows the transfer of thermal energy through a spatial temperature gradient at much larger rates than thermal conduction, for example.

[000271] In another example, a first work exchange apparatus can comprise a body force generating apparatus which can apply a body force per unit mass to objects within a working material, and thus generate a spatial temperature gradient within a working material. A second work exchange apparatus can be employed to do work on the working material at the low temperature side of the temperature gradient within the working material. In the process of work being done on the working material, the local working material at the low temperature side of the temperature gradient is compressed, which is associated with an instantaneous increase in pressure, temperature, and density of the working material at the low temperature side of the temperature gradient. The local and instantaneous increase in pressure and density results in pressure waves, compression waves, or acoustic waves, or phonons travelling from the low temperature side of the temperature gradient through the temperature gradient to the high temperature side of the temperature gradient at the speed of sound. This compression wave is associated with a heating or an increase in temperature of the working material, as well as an increase in pressure and an increase in density throughout the temperature gradient and on the large temperature side of the temperature gradient. Thus, the working material on the large temperature side of the temperature gradient, as well as the working material within the temperature gradient, experiences an increase in temperature. Effectively, a portion of the energy delivered to the working material at the low temperature side of the temperature gradient in the process of work being done by the second work exchange apparatus on the working material is delivered to the portion of the working material at the large temperature side of the temperature gradient and the working material within the temperature gradient. In this process, thermal energy is transferred from the region of low temperature in the working material to a region of large temperature in the working material. This process can lead to a reduction in the specific entropy of the working material. The scenario described in this example is also exemplified by FIG. 11, and the first contraction 724 and the second contraction 726 in FIG. 1A. Since the instantaneous temperature change at the low temperature side of the temperature gradient is also associated with a pressure change, the temperature change is transmitted through the spatial temperature gradient via a pressure wave at the speed of sound. In some embodiments, this allows the transfer of thermal energy through a spatial temperature gradient at much larger rates than thermal conduction, for example.

[000272] A work exchange apparatus can be configured to do work on a working material, or allow a working material to do work on a work exchange apparatus. A work exchange apparatus can comprise another BFGA, or the same BFGA that is being used to induce a spatial temperature gradient within a working material. A work exchange apparatus can also comprise a converging duct, a converging diverging duct, or a diverging duct. A work exchange apparatus can also comprise an axial or centrifugal compressor. A work exchange apparatus can also comprise a propeller or a thrust generating apparatus. . A work exchange apparatus can also comprise a reciprocating piston.

[000273] Note that the specific entropy of a working material can also be increased when the thermodynamic cycle, and the associated thermodynamic apparatuses, are operated in reverse. In this manner mechanical work can be converted into thermal energy. Such embodiments of the invention can be employed in heating applications, for example.

[000274] There are numerous ways in which such body forces per unit mass can be generated.

[000275] One type of such a body force per unit mass is the gravitational acceleration acting on a thermal medium. To that end a first chamber can be subjected to a gravitational field, resulting in a gravitational body force per unit mass acting on the elements of a working material in the first chamber. A piston can be employed to compress the working material in the first chamber in the direction of the gravitational acceleration, e.g. “from above”, or to expand the working material in the first chamber in the direction of the gravitational acceleration, e.g. “from below”. In this manner the working material in the first chamber can be compressed or expanded in a manner in which the specific entropy of the working material is reduced, as described herein. A second chamber can also be located in the gravitational field. A piston can be employed to compress or expand the working material in a direction perpendicular to the direction of the gravitational body force per unit mass acting on the working material in the second chamber. In other words, in an adapted embodiment of the embodiment shown in FIGS. 7A-J, the long axis of the first chamber 880 can be parallel to the local acceleration due to gravity, and the piston 883 can move in a direction parallel to the acceleration due to gravity. In this adapted embodiment, the second work exchange apparatus 895 can be rotated by ninety degrees about an axis in the XZ-plane, e.g. about an axis out of the page. In this manner the long axis of the second chamber 903 is oriented perpendicularly to the acceleration due to gravity, and the piston 907 can move in a direction perpendicular to the acceleration due to gravity. In this manner the working material in the second chamber can be compressed or expanded in substantially isentropically and adiabatically, as described herein.

[000276] A body force can also arise from the existence of a potential field gradient. One such example is the force which arises from the gradient of an electric potential. For example, the elements of a thermal medium can be configured to be electrically charged. In the context of a thermal medium, the term “elements” refers to the constituent parts of the thermal medium, such as sub-molecular particles, molecules, or a distinct or specified collection of molecules, for example. In the case of a gas, the molecules could be positively or negatively ionized, for instance. The thermal medium may also comprise a collection of mobile electrons. Note that this collection may be contained in a solid, such as a conductor, or it may be described as a gas. By applying an electric field within a reservoir, body forces per unit mass can be generated on the electrically charged elements of the thermal medium inside the reservoir.

[000277] For other embodiments it may be impossible or inconvenient to use, procure, or create a thermal medium with mobile electrical charges. In this case, elements of the thermal medium may be polarized by applying an electric field, or these elements may already have an intrinsic polarization, as in the case of polar molecules, such as dihydrogen monoxide. When placed in an electric field gradient, these polarized elements can experience a body force. Note that the magnitude of said force depends on the orientation of the polarization axis relative to the electric field, amongst other parameters. Thus an electric field can be configured to generate body forces per unit mass on the polar elements in the thermal medium in a reservoir, as well as polarize elements in the thermal medium, if necessary. The electric field can be applied in a myriad of ways known in the art.

[000278] Magnetism can also be employed to generate body forces. The thermal medium may comprise diamagnetic, paramagnetic, or ferromagnetic elements. When magnetized, the individual elements in the thermal medium may form magnetic dipoles, or these elements may already have an intrinsic magnetic dipole, such as an electron. When these magnetic dipoles are placed in a magnetic field with a non-zero curl or gradient, they can experience a body force. Note that the magnitude of the body force is a function of the orientation of the magnetic dipole relative to the local magnetic field, amongst other parameters. Thus an external magnetic field can be configured to generate body forces per unit mass on the magnetized elements in the thermal medium in a reservoir, as well as magnetize the elements in the thermal medium, if necessary. The magnetic field can be generated by permanent magnets, ferromagnets, other at least instantaneously magnetized elements, or by an electrical current flowing through an electromagnet, amongst other methods known in the art.

[000279] The body forces per unit mass may also arise from inertial effects. For instance, a reservoir may be subject to an acceleration in an inertial frame. This results an acceleration of the thermal medium relative to the reservoir. When accelerating a reservoir at a constant rate of acceleration in an inertial frame in a direction vertically upwards towards the top of the page in FIG. **1**, the thermal medium inside the reservoir will experience an acceleration relative to the reservoir, where the acceleration is directed vertically downwards towards the bottom of the page. Inertial forces can be generated by linear acceleration, i.e. motion of the reservoir along a straight line in the inertial frame. Inertial forces can also be generated by angular acceleration, i.e. motion of the reservoir along a curved path. In general, inertial forces can be generated by any accelerating motion in an inertial frame. The embodiments shown in FIG. 2 and FIGS. 7A-J employ radial acceleration of a reservoir or a chamber. Note that the centripetal acceleration varies linearly with radius in this embodiment. If a substantially uniform body force per unit mass of thermal medium is desired, the depicted apparatus can be located at a larger radius, where the radial dimension of the chamber is only a fraction of said radius. For instance, the radius can be increased by placing the horizontal axis of rotation further upwards towards the top of the page in FIGS. 7A-J. In some embodiments, the direction vector of the axis of rotation can lie anywhere in a plane perpendicular to the plane of the page and intersecting the plane of the page horizontally. Other embodiments can have different locations and orientations of the axis of rotation, as well as different rotational velocities. These parameters can also vary in time. Embodiments employing other types of forces or combinations thereof are within the spirit and scope of the invention.

[000280] Unless specified or clear from context, the term “or” is equivalent to “and/or” throughout this paper.

[000281] The embodiments and methods described in this paper are only meant to exemplify and illustrate the principles of the invention. This invention can be carried out in several different ways and is not limited to the examples, embodiments, arrangements, configurations, or methods of operation described in this paper or depicted in the drawings. This also applies to cases where just one embodiments is described or depicted. Those skilled in the art will be able to devise numerous alternative examples, embodiments, arrangements, configurations, or methods of operation, that, while not shown or described herein, embody the principles of the invention and thus are within its spirit and scope.

ASPECTS OF THE INVENTION

[000282] The invention is further defined by the following aspects.

[000283] Aspect 1. A fluid interaction apparatus, wherein the fluid interaction apparatus comprises: a working material; a work exchange apparatus, wherein the work exchange apparatus comprises an active surface against which the working material can do work, or with which the work exchange apparatus can do work on the working material; a body force generating apparatus, wherein the direction of the body force applied to the working material by the body force generating apparatus comprises a non-zero component in the positive or negative direction of the external or outward surface normal of the active surface of the work exchange apparatus.

[000284] Aspect 2. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises a converging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed against or upstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a non-zero component in the positive or same direction of the active external surface normal

[000285] Aspect 3. The fluid interaction apparatus of aspect 2, wherein the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a substantial component in the radially inward direction of the duct, perpendicular to the local free stream flow during level cruise

[000286] Aspect 4. The fluid interaction apparatus of aspect 2, wherein the body force is configured to reduce the perceived pressure on the exterior active surface of the duct, such that thermal energy can be extracted from the working material and converted into useful mechanical or electrical work at a later time or space, such as in a subsequent and downstream work exchange apparatus, such as a conventional diverging duct.

[000287] Aspect 5. The fluid interaction apparatus of aspect 2, wherein the duct can be circular, elliptical, polygonal, rectangular, or square

[000288] Aspect 6. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises a converging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed against or upstream of the streamwise flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a non-zero component in the negative or opposite direction of the active external surface normal

[000289] Aspect 7. The fluid interaction apparatus of aspect 6, wherein the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a substantial component in the radially outward direction of the duct, perpendicular to the local free stream flow during level cruise

[000290] Aspect 8. The fluid interaction apparatus of aspect 6, wherein the body force is configured to increase the perceived pressure on the exterior active surface of the duct, such that thermal energy can be delivered to, or applied on, the working material and by the application of mechanical work onto the working material by the active surface of the duct.

[000291] Aspect 9. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises a diverging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed streamwise, or downstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a non-zero component in the negative or opposite direction of the active external surface normal

[000292] Aspect 10. The fluid interaction apparatus of aspect 9, wherein the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a substantial component in the radially outward direction of the duct, perpendicular to the local free stream flow during level cruise

[000293] Aspect 11. The fluid interaction apparatus of aspect 9, wherein the body force is configured to increase the perceived pressure on the exterior active surface of the duct, such that thermal energy can be extracted from the working material and converted into useful mechanical work, such as thrust or electricity.

[000294] Aspect 12. The fluid interaction apparatus of aspect 9, wherein the duct can be circular, elliptical, polygonal, rectangular, or square

[000295] Aspect 13. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises a diverging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed streamwise, or downstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a non-zero component in the positive or same direction of the active external surface normal

[000296] Aspect 14. The fluid interaction apparatus of aspect 6, wherein the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a substantial component in the radially inward direction of the duct, perpendicular to the local free stream flow during level cruise

[000297] Aspect 15. The fluid interaction apparatus of aspect 13, wherein the body force is configured to reduce the perceived pressure on the exterior active surface of the duct, such that thermal energy can be delivered to, or applied on, the working material and by the application of mechanical work onto the working material by the active surface of the duct.

[000298] Aspect 16. The fluid interaction apparatus of aspect 1, wherein the working fluid is compressible, such as air, nitrogen, helium

[000299] Aspect 17. The fluid interaction apparatus of aspect 1, wherein the local free stream fluid flow is supersonic or faster than compression or expansion waves within the fluid

[000300] Aspect 18. The fluid interaction apparatus of aspect 1, wherein the local free stream fluid flow is subsonic.

[000301] Aspect 19. The fluid interaction apparatus of aspect 1, wherein the working fluid is substantially incompressible, such as water.

[000302] Aspect 20. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises turbomachinery, such as an axial or centrifugal compressor, where the active surface can comprise the propeller or rotor blades.

[000303] Aspect 21. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises propeller blades, or rotor discs, or turbomachinery of any kind, where the active surface can comprise the propeller or rotor blades.

[000304] Aspect 22. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises reciprocating pistons, and where the active surface is the wetted surface of the piston head which is in contact with the working fluid within any adjacent chambers

[000305] Aspect 23. The fluid interaction apparatus of aspect 1, wherein the work exchange apparatus comprises a separately arranged, specially configured additional body force generating apparatus configured to do work on the fluid or allow the fluid to do work against it.

[000306] Aspect 24. The fluid interaction apparatus of aspect 1, wherein the component of the body force is substantially perpendicular to the local free stream flow which interacts with the fluid interaction apparatus, such as a duct or otherwise conventional jet engine.

[000307] Aspect 25. The fluid interaction apparatus of aspect 1, wherein the body force per unit mass generating apparatus gravitational in nature.

[000308] Aspect 26. The fluid interaction apparatus of aspect 1, wherein the body force per unit mass generating apparatus inertial in nature.

[000309] Aspect 27. The fluid interaction apparatus of aspect 26, wherein the body force per unit mass generating apparatus is configured to rotate a volume or bulk of a working fluid in order to provide a perceived inertial body force per mass to the molecules in the working fluid.

[000310] Aspect 28. The fluid interaction apparatus of aspect 26, wherein the body force per unit mass generating apparatus is configured to accelerate in inertial space a volume or bulk of a working fluid in order to provide a perceived inertial body force per mass to the molecules in the working fluid.

[000311] Aspect 29. The fluid interaction apparatus of aspect 1, wherein the body force per unit mass generating apparatus electrical in nature.

[000312] Aspect 30. The fluid interaction apparatus of aspect 29, wherein the body force per unit mass generating apparatus comprises an electrical field generating apparatus, and wherein the working material comprises mobile electrical charges

[000313] Aspect 31. The fluid interaction apparatus of aspect 29, wherein the body force per unit mass generating apparatus comprises an electrical field generating apparatus, and wherein the working material comprises molecules or objects which carry a permanent or induced electrical polarization

[000314] Aspect 32. The fluid interaction apparatus of aspect 1, wherein the body force per unit mass generating apparatus magnetic in nature.

[000315] Aspect 33. The fluid interaction apparatus of aspect 32, wherein the body force per unit mass generating apparatus comprises a magnetic field generating apparatus, and wherein the working material comprises molecules or objects which carry a permanent or induced magnetic dipole or multipole.

[000316] Aspect 34. The fluid interaction apparatus of aspect 1, wherein the body force per unit mass generating apparatus mechanical in nature.

[000317] Aspect 35. The fluid interaction apparatus of aspect 34, wherein the body force per unit mass generating apparatus comprises annular, but not necessarily circular, airfoils or ducts configured to induce a pressure gradient substantially perpendicularly to the flow direction in a manner similar to a conventional body force generating apparatus.

[000318] Aspect 36. The fluid interaction apparatus of any one of aspects 1-35 wherein the thrust produced by such an apparatus is employed to propel and aircraft, such as commercial airliners or transport, watercraft, such as cruise ships or container ships, or land vehicles, such as a car, truck, motorcycle, bike.

[000319] Aspect 37. A system comprising two or more apparatuses of any one of aspects 1 to 35.

[000320] Aspect 38. A system comprising two or more apparatuses of any one of aspects 1 to 35, where at least two are connected in series, with the outlet of a first fluid interaction apparatus is at the same time the inlet of a second fluid interaction apparatus.

[000321] Aspect 39. A system comprising two or more apparatuses of any one of aspects 1 to 35, where at least two are connected in series, with the outlet of a first fluid interaction apparatus is at the same time the inlet of a second fluid interaction apparatus.

[000322] Aspect 40. The system of aspect 39, wherein a converging duct can be arranged upstream of a diverging duct

[000323] Aspect 41. The system of aspect 39, wherein a converging duct can be arranged adjacent to a diverging duct

[000324] Aspect 42. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise supersonic or subsonic flow velocities

[000325] Aspect 43. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise supersonic flow velocities

[000326] Aspect 44. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise subsonic flow velocities

[000327] Aspect 45. The fluid interaction apparatus of aspect 1, wherein the apparatus also comprises a working chamber, apparatuses such as valves configured for drawing and expelling fluid from the chamber, and in which work can be done on a working material by a piston, and in which the working material can do work on the piston; wherein the work exchange apparatus comprises reciprocating pistons, where the active surface is the wetted surface of the piston head which is in contact with the working fluid within any adjacent chamber, and wherein at least a portion of the working material within the working camber can be subjected to the body force per unit mass of at least one body force generating apparatus, wherein the body force per unit mass has a non-zero component in the positive or negative surface normal of the piston, or the positive or negative instantaneous stroke direction of the piston in the chamber.

[000328] Aspect 46. The fluid interaction apparatus of aspect 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the direction of the active piston head, in the opposite direction of the inward normal of the active piston head, and wherein the active piston head can be retracted from the chamber and increase the volume of the fluid inside the chamber in order to allow the working material to do work on the piston head and cool down and experience a reduction in entropy.

[000329] Aspect 47. The fluid interaction apparatus of aspect 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the opposite direction of the active piston head, in the same direction of the inward normal of the active piston head, and wherein the active piston head can be inserted into the chamber and decrease the volume of the fluid inside the chamber in order to allow the piston to do work on the fluid and heat the fluid while also reducing the entropy of the fluid.

[000330] Aspect 48. The fluid interaction apparatus of aspect 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the direction of the active piston head, in the opposite direction of the inward normal of the active piston head, and wherein the active piston head can be inserted into the chamber and decrease the volume of the fluid inside the chamber in order to allow the piston to do work on the fluid and heat the fluid while also increasing the entropy of the fluid.

[000331] Aspect 49. The fluid interaction apparatus of aspect 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the opposite direction of the active piston head, in the same direction of the inward normal of the active piston head, and wherein the active piston head can be retracted from the chamber and increase the volume of the fluid inside the chamber in order to allow the working material to do work on the piston head and cool down and experience an increase in entropy of the fluid.

[000332] Aspect 50. The fluid interaction apparatus of aspect 45, wherein a the fluid interaction apparatus also comprises a compressor, such as a centrifugal compressor, axial compressor, or turbocharger, or supercharger, or a reciprocating piston compressor, upstream of the inlet valves of the working chamber, in order to increase the nominal operating pressure and mass flow rate through the working chamber

[000333] Aspect 51. The fluid interaction apparatus of aspect 45, wherein a the fluid interaction apparatus also comprises an expander, such as a centrifugal turbine, axial turbine, or a reciprocating piston engine, downstream of the outlet valves of the working chamber, in order to recuperate or recover any excess work performed by the piston in the working chamber

[000334] Aspect 52.A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of aspects 1 to 35, providing and employing a body force generating apparatus to artificially facilitate a reduced pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local upstream direction, and contributing to a net thrust and a cooling of the working material as a result

[000335] Aspect 53.A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of aspects 1 to 35, providing and employing a body force generating apparatus to artificially facilitate an increased pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local downstream direction, and contributing to a net thrust and a cooling of the working material as a result

[000336] Aspect 54.A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of aspects 1 to 35, providing and employing a body force generating apparatus to artificially facilitate an increase in pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local upstream direction, and contributing to a drag force and a heating of the working material as a result

[000337] Aspect 55.A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of aspects 1 to 35, providing and employing a body force generating apparatus to artificially facilitate an reduced pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local downstream direction, and contributing to a drag force and a heating of the working material as a result

CLAIMS

What is claimed is:

1 A fluid interaction apparatus, wherein the fluid interaction apparatus comprises:

a working material;

a work exchange apparatus, wherein the work exchange apparatus comprises an active surface against which the working material can do work, or with which the work exchange apparatus can do work on the working material;

a body force generating apparatus, wherein the direction of the body force applied to the working material by the body force generating apparatus comprises a non-zero component in the positive or negative direction of the external or outward surface normal of the active surface of the work exchange apparatus.

2. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises:

a converging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed against or upstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a non-zero component in the positive or same direction of the active external surface normal

3. The fluid interaction apparatus of claim 2, wherein the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a substantial component in the radially inward direction of the duct, perpendicular to the local free stream flow during level cruise

4. The fluid interaction apparatus of claim 2, wherein the body force is configured to reduce the perceived pressure on the exterior active surface of the duct, such that thermal energy can be extracted from the working material and converted into

useful mechanical or electrical work at a later time or space, such as in a subsequent and downstream work exchange apparatus, such as a conventional diverging duct.

5. The fluid interaction apparatus of claim 2, wherein the duct can be circular, elliptical, polygonal, rectangular, or square

6. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises a converging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed against or upstream of the streamwise flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a non-zero component in the negative or opposite direction of the active external surface normal

7. The fluid interaction apparatus of claim 6, wherein the component of the body force acting on at least a portion of the volume of fluid entering the converging duct has a substantial component in the radially outward direction of the duct, perpendicular to the local free stream flow during level cruise

8. The fluid interaction apparatus of claim 6, wherein the body force is configured to increase the perceived pressure on the exterior active surface of the duct, such that thermal energy can be delivered to, or applied on, the working material and by the application of mechanical work onto the working material by the active surface of the duct.

9. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises a diverging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed streamwise, or downstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a non-zero component in the negative or opposite direction of the active external surface normal

10. The fluid interaction apparatus of claim 9, wherein the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a substantial component in the radially outward direction of the duct, perpendicular to the local free stream flow during level cruise

11. The fluid interaction apparatus of claim 9, wherein the body force is configured to increase the perceived pressure on the exterior active surface of the duct, such that thermal energy can be extracted from the working material and converted into useful mechanical work, such as thrust or electricity.

12. The fluid interaction apparatus of claim 9, wherein the duct can be circular, elliptical, polygonal, rectangular, or square

13. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises a diverging duct, and wherein the active surface is the interior wetted surface of the duct, and wherein the active external surface normal has a non-zero component directed streamwise, or downstream of the free stream flow direction, and where the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a non-zero component in the positive or same direction of the active external surface normal

14. The fluid interaction apparatus of claim 6, wherein the component of the body force acting on at least a portion of the volume of fluid entering the diverging duct has a substantial component in the radially intward direction of the duct, perpendicular to the local free stream flow during level cruise

15. The fluid interaction apparatus of claim 13, wherein the body force is configured to reduce the perceived pressure on the exterior active surface of the duct, such that thermal energy can be delivered to, or applied on, the working material and by the application of mechanical work onto the working material by the active surface of the duct.

16. The fluid interaction apparatus of claim 1, wherein the working fluid is compressible, such as air, nitrogen, helium

17. The fluid interaction apparatus of claim 1, wherein the local free stream fluid flow is supersonic or faster than compression or expansion waves within the fluid

18. The fluid interaction apparatus of claim 1, wherein the local free stream fluid flow is subsonic.

19. The fluid interaction apparatus of claim 1, wherein the working fluid is substantially incompressible, such as water.

20. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises turbomachinery, such as an axial or centrifugal compressor, where the active surface can comprise the propeller or rotor blades.

21. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises propeller blades, or rotor discs, or turbomachinery of any kind, where the active surface can comprise the propeller or rotor blades.

22. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises reciprocating pistons, and where the active surface is the wetted surface of the piston head which is in contact with the working fluid within any adjacent chambers

23. The fluid interaction apparatus of claim 1, wherein the work exchange apparatus comprises a separately arranged, specially configured additional body force generating apparatus configured to do work on the fluid or allow the fluid to do work against it.

24. The fluid interaction apparatus of claim 1, wherein the component of the body force is substantially perpendicular to the local free stream flow which interacts with the fluid interaction apparatus, such as a duct or otherwise conventional jet engine.

25. The fluid interaction apparatus of claim 1, wherein the body force per unit mass generating apparatus gravitational in nature.

26. The fluid interaction apparatus of claim 1, wherein the body force per unit mass generating apparatus inertial in nature.

27. The fluid interaction apparatus of claim 26, wherein the body force per unit mass generating apparatus is configured to rotate a volume or bulk of a working fluid in order to provide a perceived inertial body force per mass to the molecules in the working fluid.

28. The fluid interaction apparatus of claim 26, wherein the body force per unit mass generating apparatus is configured to accelerate in inertial space a volume or bulk of a working fluid in order to provide a perceived inertial body force per mass to the molecules in the working fluid.

29. The fluid interaction apparatus of claim 1, wherein the body force per unit mass generating apparatus electrical in nature.

30. The fluid interaction apparatus of claim 29, wherein the body force per unit mass generating apparatus comprises an electrical field generating apparatus, and wherein the working material comprises mobile electrical charges

31. The fluid interaction apparatus of claim 29, wherein the body force per unit mass generating apparatus comprises an electrical field generating apparatus, and wherein the working material comprises molecules or objects which carry a permanent or induced electrical polarization

32. The fluid interaction apparatus of claim 1, wherein the body force per unit mass generating apparatus magnetic in nature.

33. The fluid interaction apparatus of claim 32, wherein the body force per unit mass generating apparatus comprises a magnetic field generating apparatus, and wherein the working material comprises molecules or objects which carry a permanent or induced magnetic dipole or multipole.

34. The fluid interaction apparatus of claim 1, wherein the body force per unit mass generating apparatus mechanical in nature.

35. The fluid interaction apparatus of claim 34, wherein the body force per unit mass generating apparatus comprises annular, but not necessarily circular, airfoils or ducts configured to induce a pressure gradient substantially perpendicularly to the flow direction in a manner similar to a conventional body force generating apparatus.

36. The fluid interaction apparatus of any one of claims 1-35 wherein the thrust produced by such an apparatus is employed to propel and aircraft, such as commercial airliners or transport, watercraft, such as cruise ships or container ships, or land vehicles, such as a car, truck, motorcycle, bike.

37. A system comprising two or more apparatuses of any one of claim.

38. A system comprising two or more apparatuses of any one of claim, where at least two are connected in series, with the outlet of a first fluid interaction apparatus is at the same time the inlet of a second fluid interaction apparatus.

39. A system comprising two or more apparatuses of any one of claim, where at least two are connected in series, with the outlet of a first fluid interaction apparatus is at the same time the inlet of a second fluid interaction apparatus.

40. The system of claim 39, wherein a converging duct can be arranged upstream of a diverging duct

41. The system of claim 39, wherein a converging duct can be arranged adjacent to a diverging duct

42. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise supersonic or subsonic flow velocities

43. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise supersonic flow velocities

44. A system comprising at least two systems of claim 41, wherein the fluid flow between any two such systems can comprise subsonic flow velocities

45. The fluid interaction apparatus of claim 1, wherein the apparatus also comprises a

working chamber,

apparatuses such as valves configured for drawing and expelling fluid from the chamber,

wherein work can be done on a working material in the chamber by a piston, and in wherein the working material within the chamber can do work on the piston;

wherein the work exchange apparatus comprises reciprocating pistons, where the active surface is the wetted surface of the piston head which is in contact with the working fluid within any adjacent chamber, and

wherein at least a portion of the working material within the working camber can be subjected to the body force per unit mass of at least one body force generating apparatus, wherein the body force per unit mass has a non-zero component in the positive or negative surface normal of the piston, or the positive or negative instantaneous stroke direction of the piston in the chamber.

46. The fluid interaction apparatus of claim 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the direction of the active piston head, in the opposite direction of the inward normal of the active piston head, and wherein the active piston head can be retracted from the chamber and increase the volume of the fluid inside the chamber in order to allow the working material to do work on the piston head and cool down and experience a reduction in entropy.

47. The fluid interaction apparatus of claim 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the opposite direction of the active piston head, in the same direction of the inward normal of the active piston head, and wherein the active piston head can be inserted into the

chamber and decrease the volume of the fluid inside the chamber in order to allow the piston to do work on the fluid and heat the fluid while also reducing the entropy of the fluid.

48. The fluid interaction apparatus of claim 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the direction of the active piston head, in the opposite direction of the inward normal of the active piston head, and wherein the active piston head can be inserted into the chamber and decrease the volume of the fluid inside the chamber in order to allow the piston to do work on the fluid and heat the fluid while also increasing the entropy of the fluid.

49. The fluid interaction apparatus of claim 45, in which the component of the body force per unit mass acting on the working fluid has a non-zero component in the opposite direction of the active piston head, in the same direction of the inward normal of the active piston head, and wherein the active piston head can be retracted from the chamber and increase the volume of the fluid inside the chamber in order to allow the working material to do work on the piston head and cool down and experience an increase in entropy of the fluid.

50. The fluid interaction apparatus of claim 45, wherein a the fluid interaction apparatus also comprises a compressor, such as a centrifugal compressor, axial compressor, or turbocharger, or supercharger, or a reciprocating piston compressor, upstream of the inlet valves of the working chamber, in order to increase the nominal operating pressure and mass flow rate through the working chamber

51. The fluid interaction apparatus of claim 45, wherein a the fluid interaction apparatus also comprises an expander, such as a centrifugal turbine, axial turbine, or a reciprocating piston engine, downstream of the outlet valves of the working chamber, in order to recuperate or recover any excess work performed by the piston in the working chamber

52. A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of claim, providing and employing a body force generating apparatus to artificially facilitate a reduced pressure on an active surface

of a fluid interaction apparatus with an outward surface normal with non-zero component in the local upstream direction, and contributing to a net thrust and a cooling of the working material as a result

53. A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of claim, providing and employing a body force generating apparatus to artificially facilitate an increased pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local downstream direction, and contributing to a net thrust and a cooling of the working material as a result

54. A method of interacting with a fluid, the method comprising: providing at least one fluid interaction apparatus of any one of claim, providing and employing a body force generating apparatus to artificially facilitate an increase in pressure on an active surface of a fluid interaction apparatus with an outward surface normal with non-zero component in the local upstream direction, and contributing to a drag force and a heating of the working material as a result

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DECLARATION (37 CFR 1.63) FOR UTILITY OR DESIGN APPLICATION USING AN APPLICATION DATA SHEET (37 CFR 1.76)

Title of Invention	

As the below named inventor, I hereby declare that:

This declaration is directed to:

☐ The attached application, or

☐ United States application or PCT international application number ________________________

filed on ________________________________.

The above-identified application was made or authorized to be made by me.

I believe that I am the original inventor or an original joint inventor of a claimed invention in the application.

I hereby acknowledge that any willful false statement made in this declaration is punishable under 18 U.S.C. 1001 by fine or imprisonment of not more than five (5) years, or both.

WARNING:

Petitioner/applicant is cautioned to avoid submitting personal information in documents filed in a patent application that may contribute to identity theft. Personal information such as social security numbers, bank account numbers, or credit card numbers (other than a check or credit card authorization form PTO-2038 submitted for payment purposes) is never required by the USPTO to support a petition or an application. If this type of personal information is included in documents submitted to the USPTO, petitioners/applicants should consider redacting such personal information from the documents before submitting them to the USPTO. Petitioner/applicant is advised that the record of a patent application is available to the public after publication of the application (unless a non-publication request in compliance with 37 CFR 1.213(a) is made in the application) or issuance of a patent. Furthermore, the record from an abandoned application may also be available to the public if the application is referenced in a published application or an issued patent (see 37 CFR 1.14). Checks and credit card authorization forms PTO-2038 submitted for payment purposes are not retained in the application file and therefore are not publicly available.

LEGAL NAME OF INVENTOR

Inventor: ____ Date (Optional) :______________________

Signature: ____

Note: An application data sheet (PTO/SB/14 or equivalent), including naming the entire inventive entity, must accompany this form or must have been previously filed. Use an additional PTO/AIA/01 form for each additional inventor.

Privacy Act Statement

The **Privacy Act of 1974 (P.L. 93-579)** requires that you be given certain information in connection with your submission of the attached form related to a patent application or patent. Accordingly, pursuant to the requirements of the Act, please be advised that: (1) the general authority for the collection of this information is 35 U.S.C. 2(b)(2); (2) furnishing of the information solicited is voluntary; and (3) the principal purpose for which the information is used by the U.S. Patent and Trademark Office is to process and/or examine your submission related to a patent application or patent. If you do not furnish the requested information, the U.S. Patent and Trademark Office may not be able to process and/or examine your submission, which may result in termination of proceedings or abandonment of the application or expiration of the patent.

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7. A record from this system of records may be disclosed, as a routine use, to the Administrator, General Services, or his/her designee, during an inspection of records conducted by GSA as part of that agency's responsibility to recommend improvements in records management practices and programs, under authority of 44 U.S.C. 2904 and 2906. Such disclosure shall be made in accordance with the GSA regulations governing inspection of records for this purpose, and any other relevant (*i.e.*, GSA or Commerce) directive. Such disclosure shall not be used to make determinations about individuals.
8. A record from this system of records may be disclosed, as a routine use, to the public after either publication of the application pursuant to 35 U.S.C. 122(b) or issuance of a patent pursuant to 35 U.S.C. 151. Further, a record may be disclosed, subject to the limitations of 37 CFR 1.14, as a routine use, to the public if the record was filed in an application which became abandoned or in which the proceedings were terminated and which application is referenced by either a published application, an application open to public inspection or an issued patent.
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