Provisional Application for United States Patent

TITLE: REFRIGERATING METHOD AND APPARATUS

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BRIEF DESCRIPTION OF THE DRAWINGS

[0001] 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.

[0002] FIG. 1B is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction.

[0003] FIG. 1C is a cross-sectional view of the embodiment shown in FIG. 1A when viewed along the negative X-direction.

[0004] 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.

[0005] FIGS. 3A-J schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition.

[0006] FIG. 4 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. 3A-J.

[0007] FIG. 5 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

[0008] 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.

[0009] 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.

[00010] 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.

[00011] 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.

[00012] In FIG. 1, exemplary embodiment 720 moves with constant velocity magnitude and direction relative to a working material. 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.

[00013] 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.

[00014] 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.

[00015] 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.

[00016] 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.

[00017] 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.

[00018] 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.

[00019] 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.

[00020] 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.

[00021] 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.

[00022] 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.

[00023] 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.

[00024] 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.

[00025] 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.

[00026] 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.

[00027] 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.

[00028] 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.

[00029] 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 expansion along the radial direction in highly simplified, idealized models, for example.

[00030] 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.

[00031] 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.

[00032] 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.

[00033] 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.

[00034] 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.

[00035] 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.

[00036] 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.

[00037] 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.

[00038] 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.

[00039] In FIG. 1, exemplary embodiment 790 moves with constant velocity magnitude and direction relative to a working material. 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.

[00040] 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.

[00041] 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 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.

[00042] In other embodiments, the compression between stations 802 and 807 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.

[00043] 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.

[00044] 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.

[00045] 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.

[00046] 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.

[00047] 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.

[00048] 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.

[00049] 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.

[00050] 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.

[00051] 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.

[00052] 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 low 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.

[00053] 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.

[00054] 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.

[00055] 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.

[00056] 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.

[00057] 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.

[00058] 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.

[00059] 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.

[00060] 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.

[00061] 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 expansion 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.

[00062] 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.

[00063] 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.

[00064] 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.

[00065] FIGS. 3A-J schematically show cross-sectional views of embodiments of the invention at different points in time during an exemplary nominal operating condition.

[00066] 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.

[00067] 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.

[00068] 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.

[00069] 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 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 nine such work exchange apparatuses. In other embodiments, rotating apparatus 864 can comprise a plurality of such work exchange apparatuses. In FIG. 3G and FIG. 3H, 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.

[00070] 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.

[00071] 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.

[00072] 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. 3A-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.

[00073] 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.

[00074] In the embodiment shown in FIGS. 3A-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.

[00075] In the embodiment shown in FIGS. 3A-J, the crankshaft 885 does not rotate rotating in an inertial frame during nominal operations. In other embodiments, or other methods of operation, or other operating conditions, crankshaft 885 can rotate in an inertial frame. 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.

[00076] 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.

[00077] 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.

[00078] As shown in FIG. 3A, FIG. 3B, and FIG. 3C, 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. 3B. 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.

[00079] Between the configurations shown in FIG. 3C and FIG. 3D, 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. 3D. 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. 3D. 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.

[00080] As shown in FIG. 3E, FIG. 3F, and FIG. 3G, 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.

[00081] Between the configurations shown in FIG. 3G and FIG. 3H, 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.

[00082] As shown in FIG. 3I, and FIG. 3J, 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. 3I.

[00083] Between the configurations shown in FIG. 3J and FIG. 3A, 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. 3A.

[00084] As shown in FIGS. 3A-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.

[00085] As shown in FIGS. 3A-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.

[00086] 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. 3E and FIG. 3F.

[00087] As shown in FIGS. 3F-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.

[00088] 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. 3A-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.

[00089] 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 FIG. 3A-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.

[00090] 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.

[00091] 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.

[00092] 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.

[00093] 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. 5. 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 FIG. 3A-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. 3A, 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. 3A-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.

[00094] 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. 3A-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.

[00095] 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.

[00096] 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.

[00097] FIG. 4 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. 3A-J.

[00098] 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.

[00099] 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.

[000100] 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.

[000101] 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. 3A-J.

[000102] FIG. 5 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.

[000103] 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. 3A-J for the purposes of the thermodynamic cycle shown in FIG. 5. The principles of one such exemplary adaptation are discussed in the context of FIGS. 3A-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.

[000104] 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.

[000105] 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.

[000106] 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. 3A-J for the purposes of the thermodynamic cycle shown in FIG. 5.

[000107] 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

[000108] 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. 4, FIGS. 3A-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.

[000109] 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. 5, 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.

[000110] 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.

[000111] 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.

[000112] There are numerous ways in which such body forces per unit mass can be generated.

[000113] 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. 3A-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.

[000114] 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.

[000115] 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.

[000116] 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.

[000117] 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. 3A-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. 3A-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.

[000118] Unless specified or clear from context, the term “or” is equivalent to “and/or” throughout this paper.

[000119] 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.