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(54) **MICRO-SCALE ENGINES, COMPONENTS, AND METHODS FOR GENERATING POWER**

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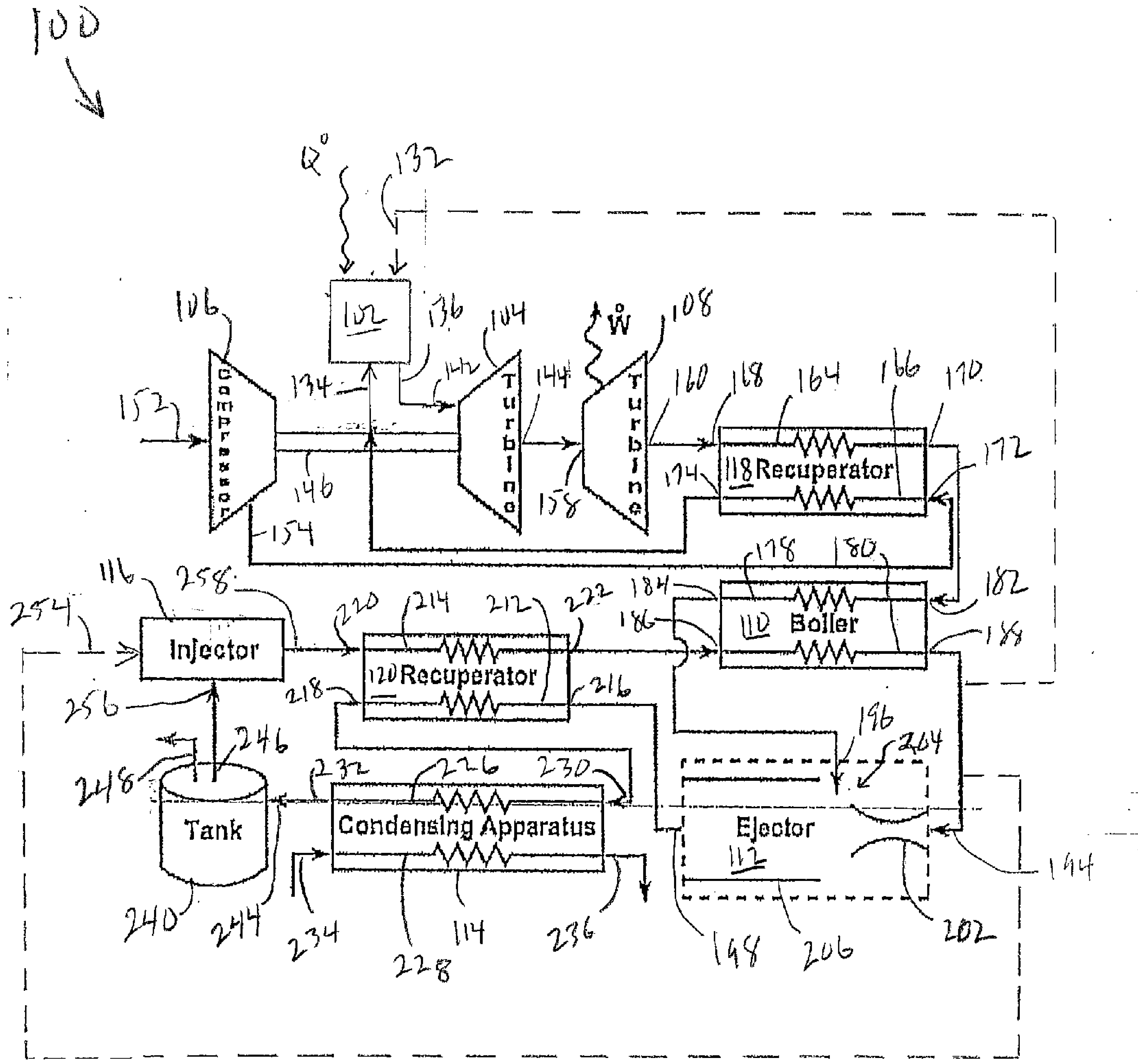
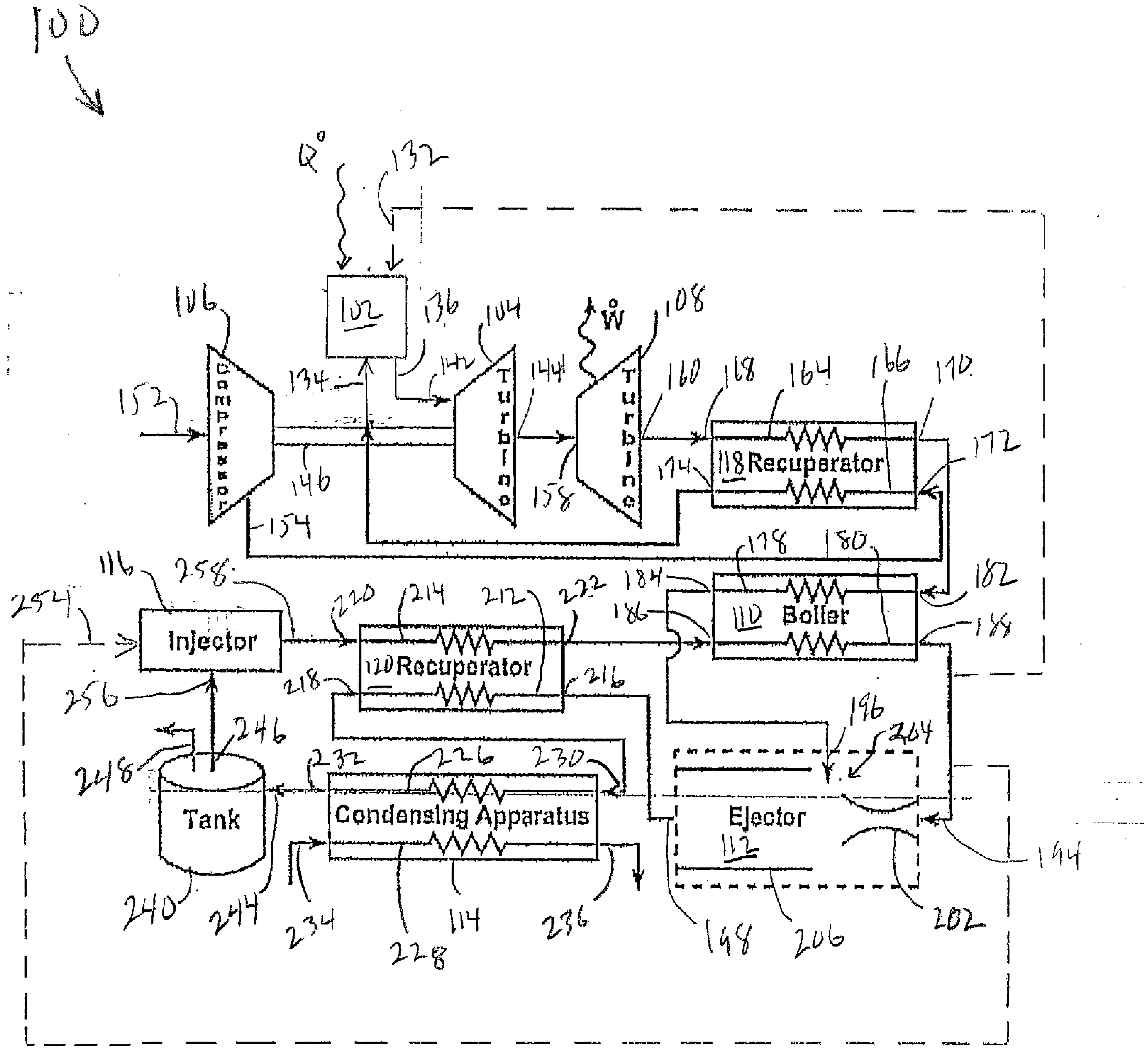
(52) **U.S. Cl.** **60/651**; 60/670; 60/654; 165/104.19

(57) **ABSTRACT**

Heat engines suitable for large-scale or micro-scale fabrication supply power from a power turbine. The power turbine is driven in part by an ejector in which a working fluid is utilized as a motive flow. Fuel utilized for combustion may also be utilized as a phase-changing working fluid and as the motive flow driving the ejector. Heat exchangers particularly suitable for micro-scale implementation are also disclosed.

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158
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118 Recuperator
172
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180
184
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Injector
220
214
212
222
186
110 Boiler
188
120 Recuperator
218
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Tank
Condensing Apparatus
Ejector
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Fig. 1

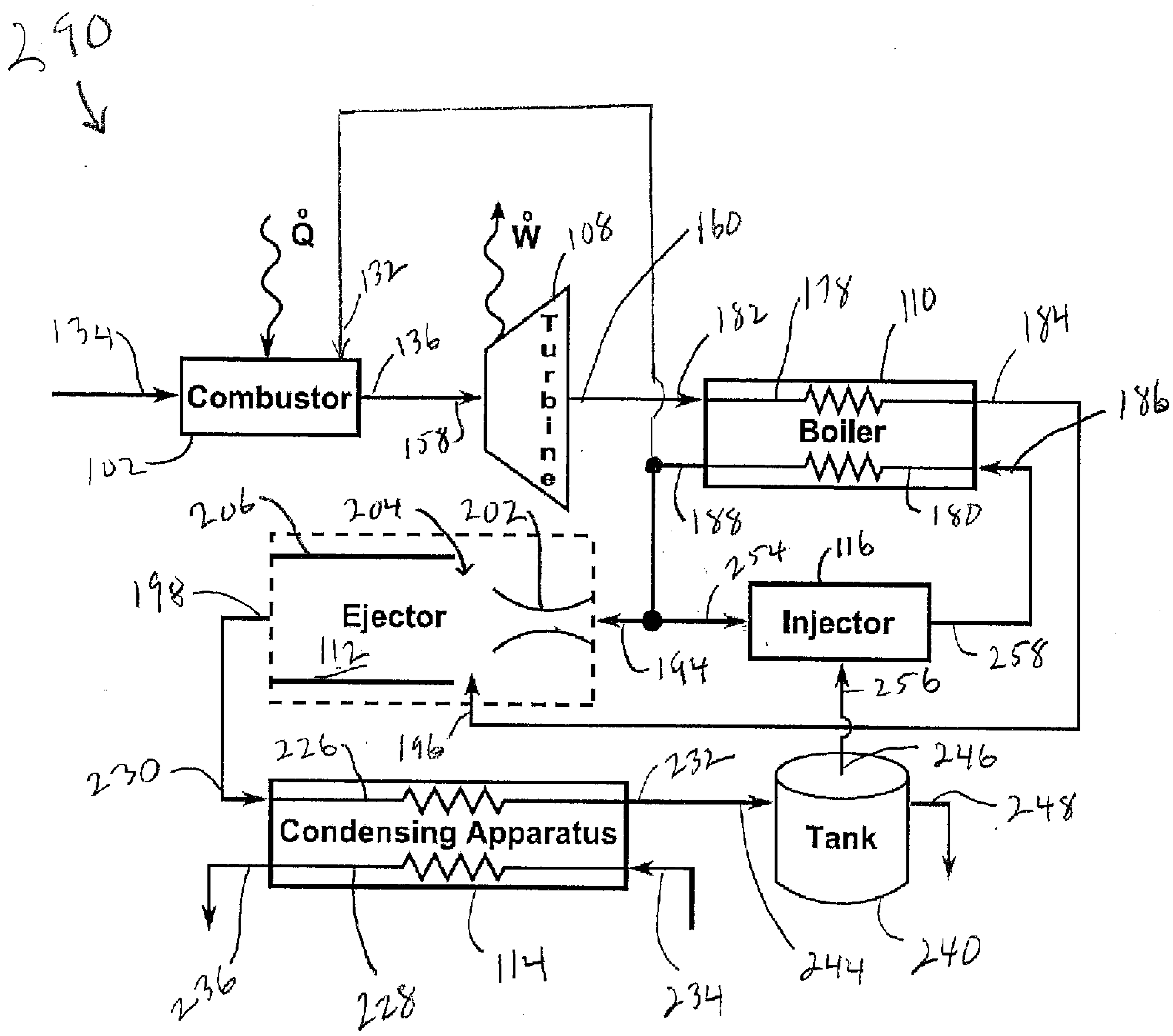
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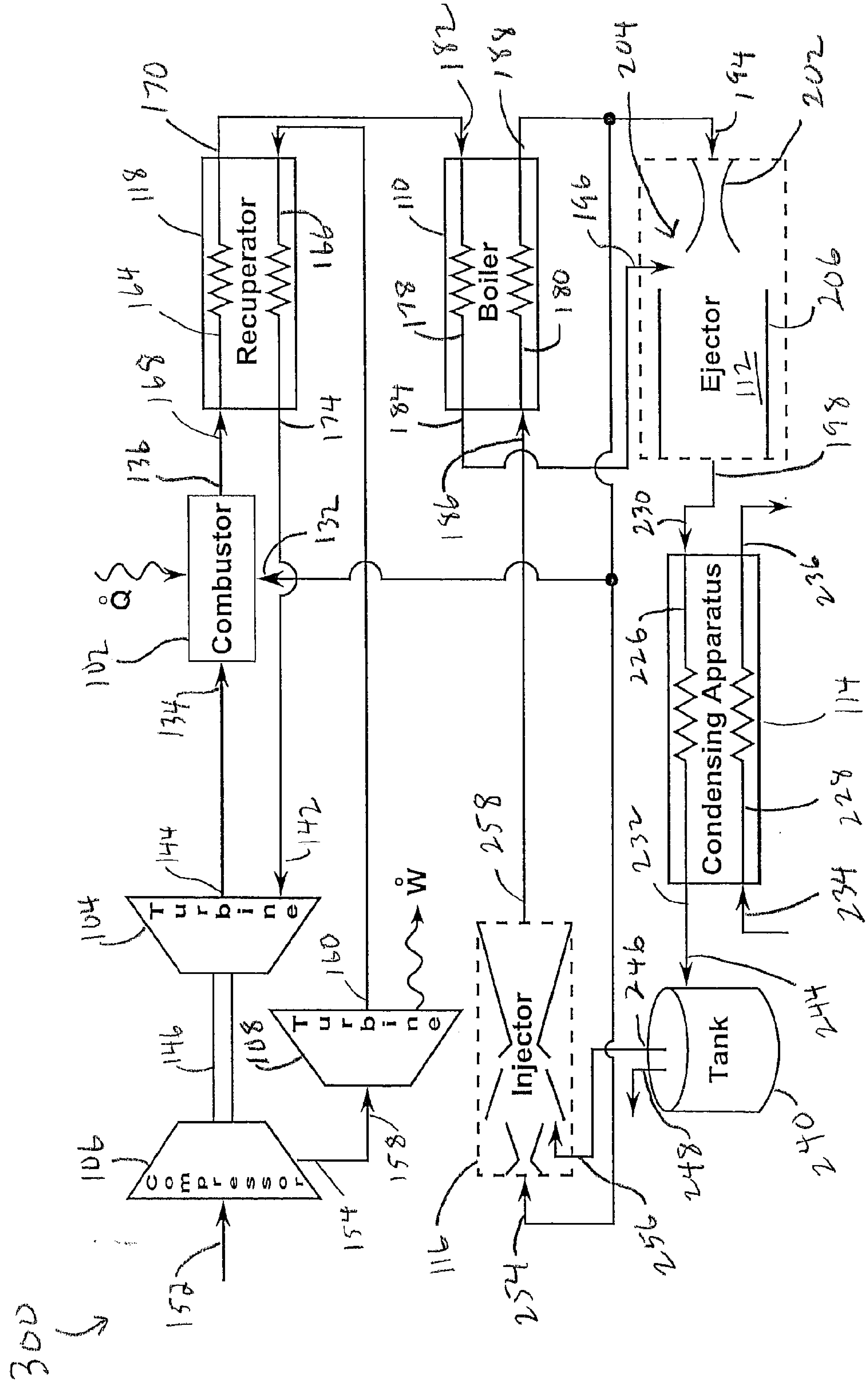
Fig. 2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Turbine
160
W̊
116
Injector
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Boiler
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Ejector
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Tank
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248

Fig. 3

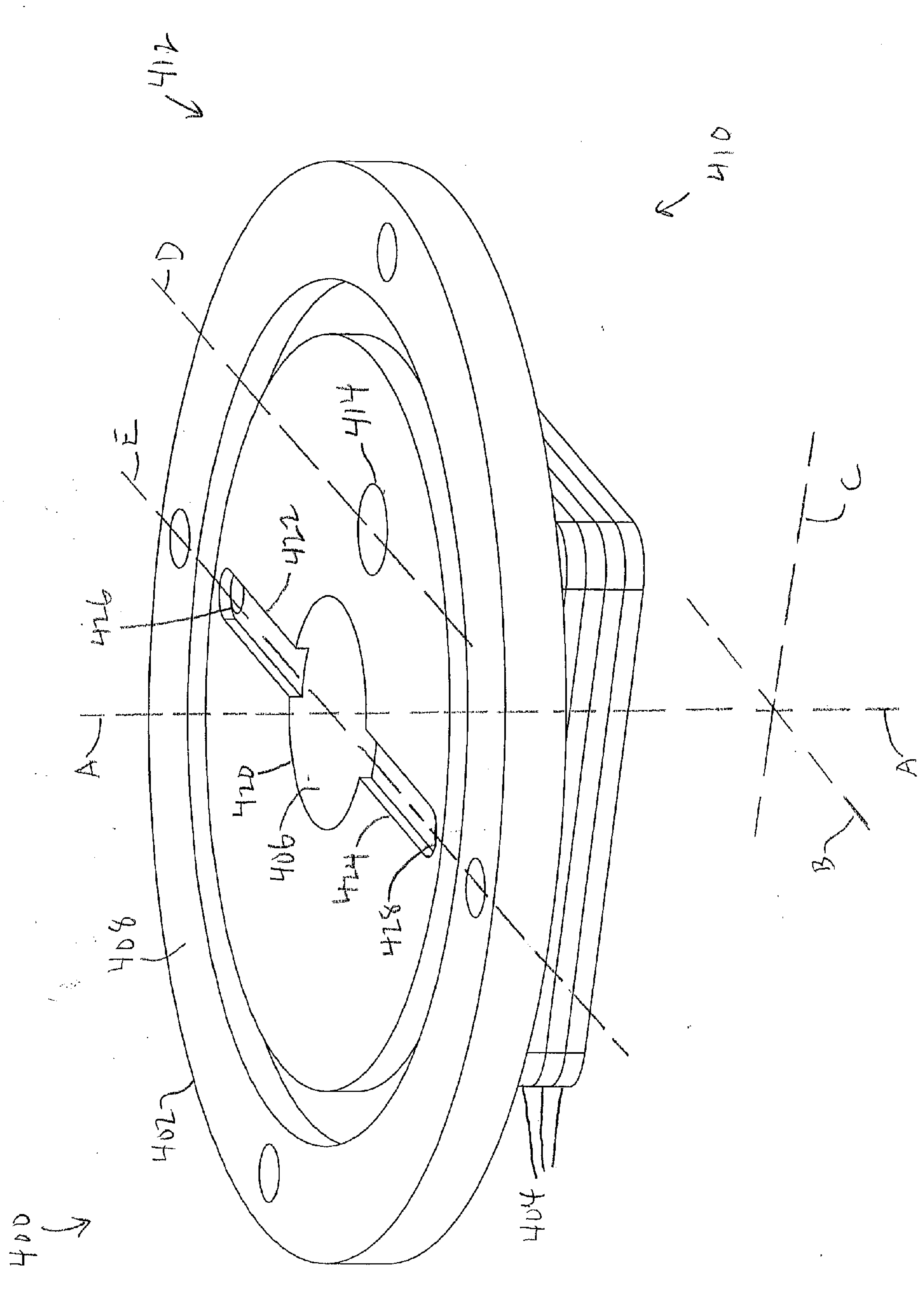

Fig. 4

Fig. 5

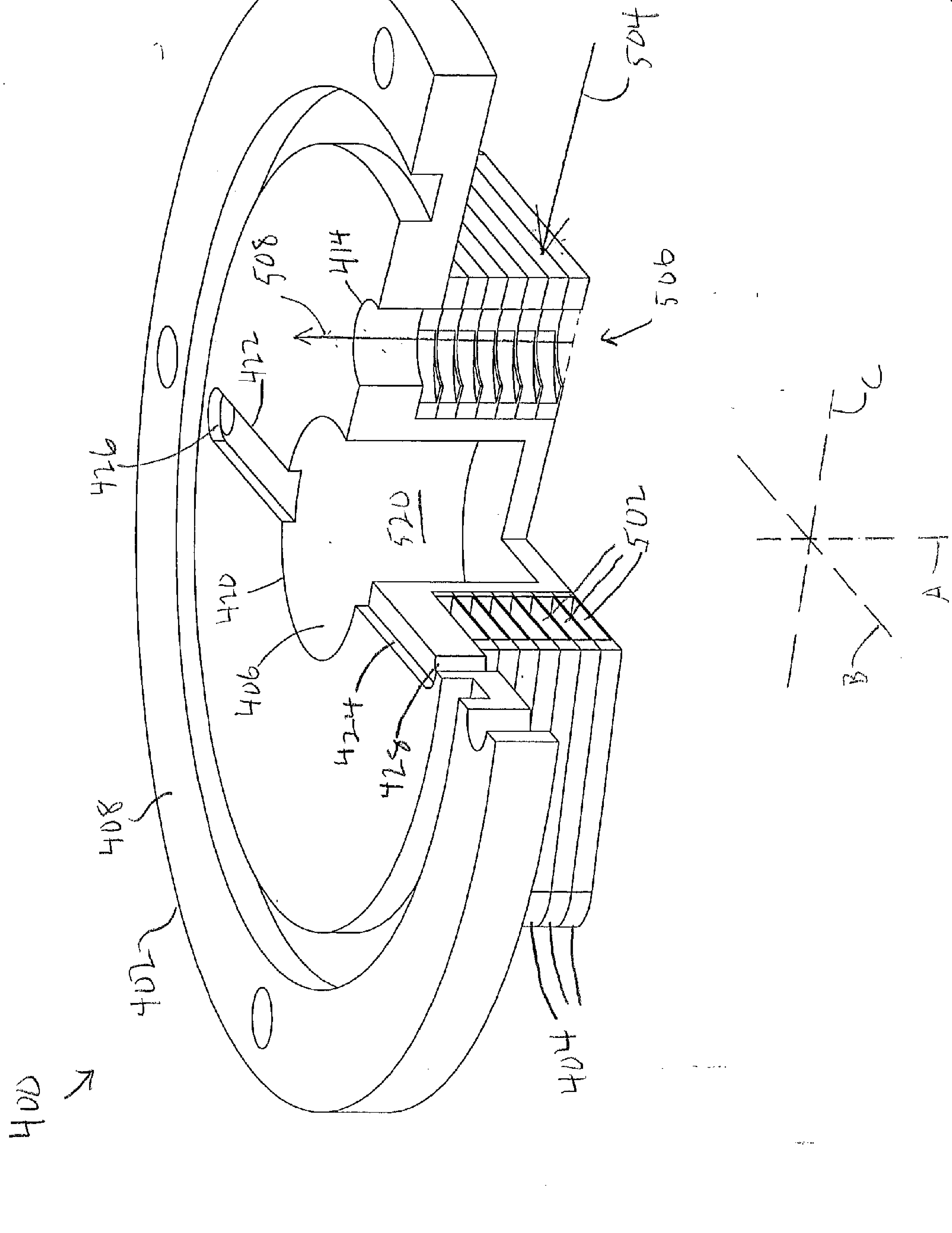
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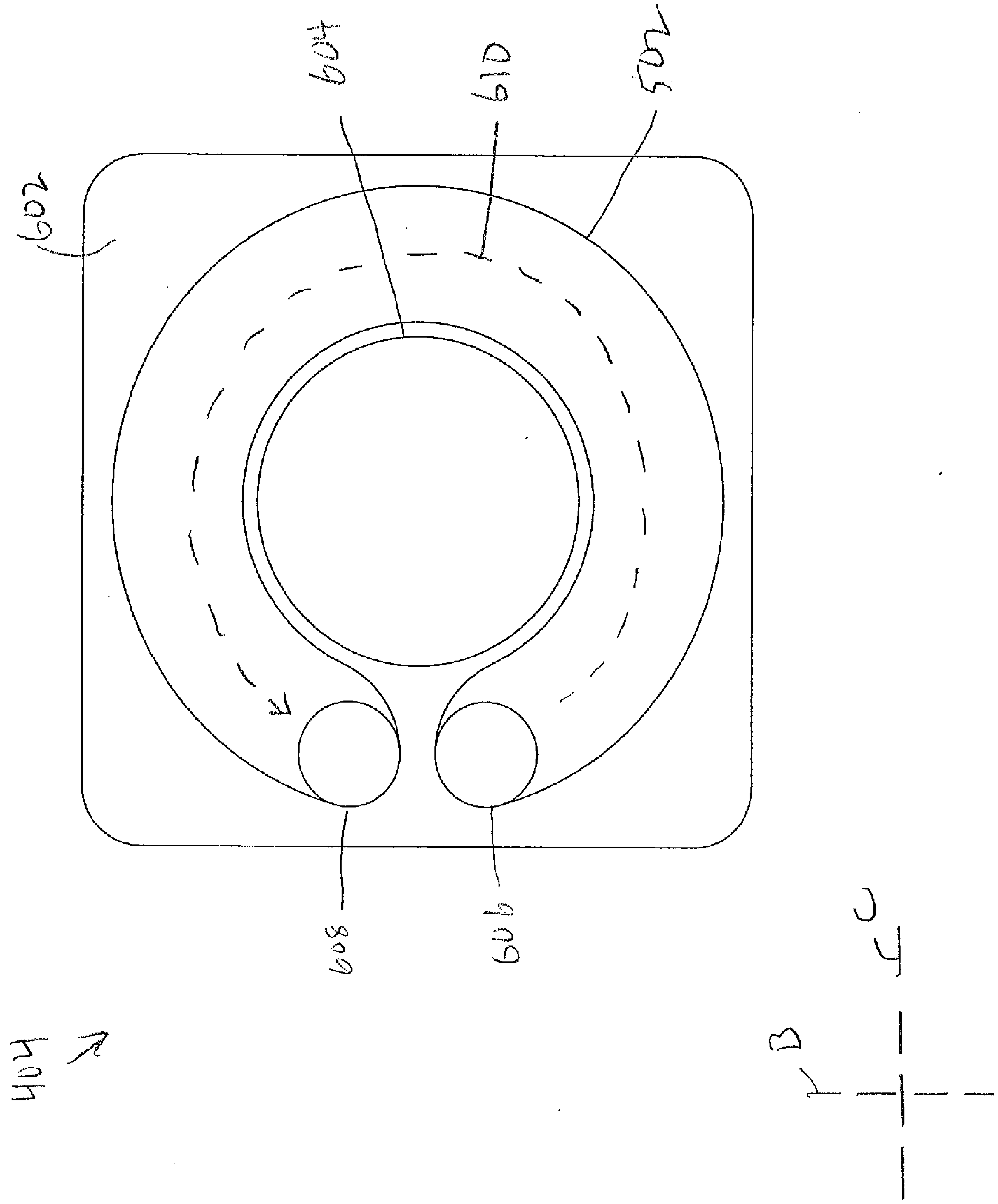
Fig. 6



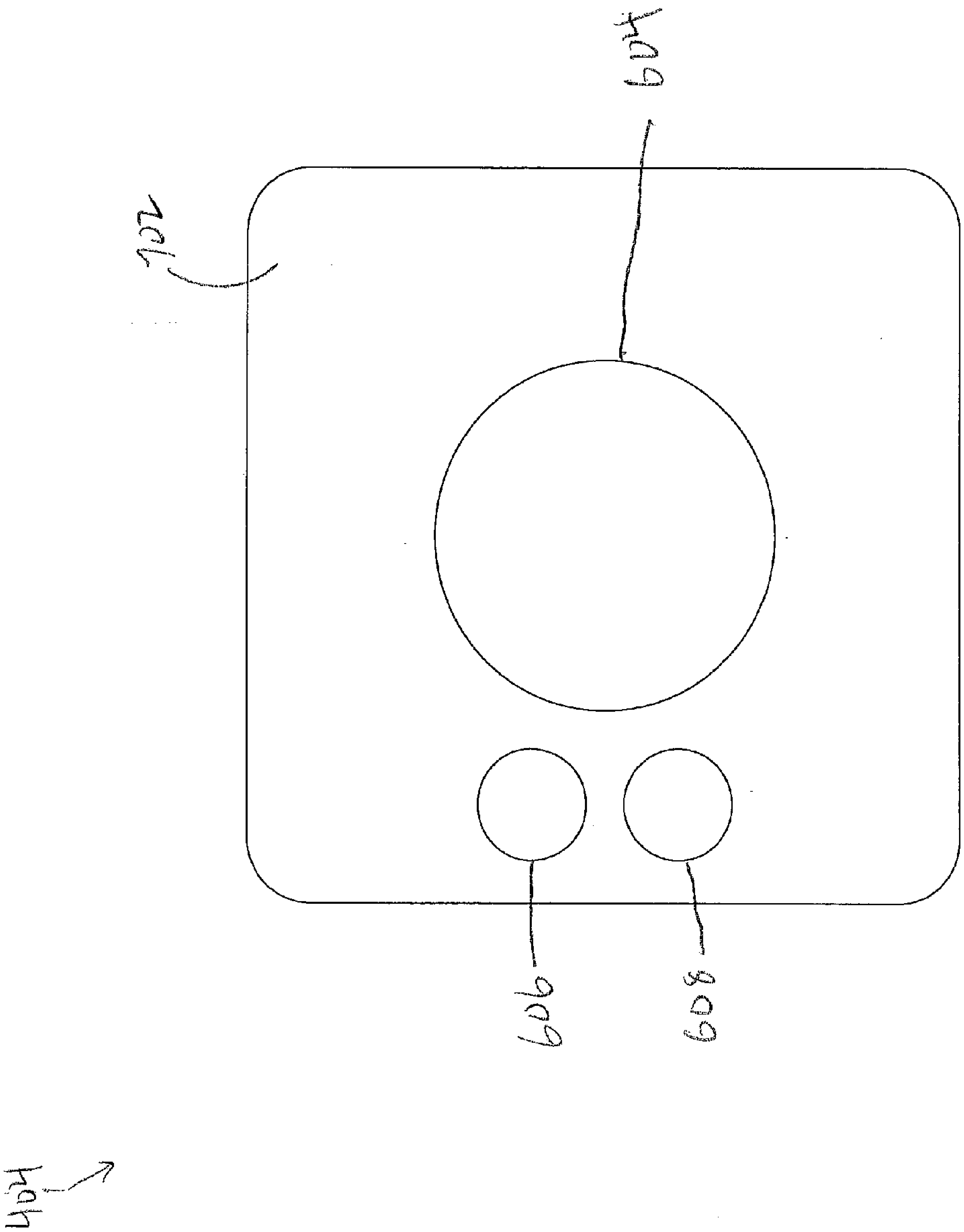


Fig. 7

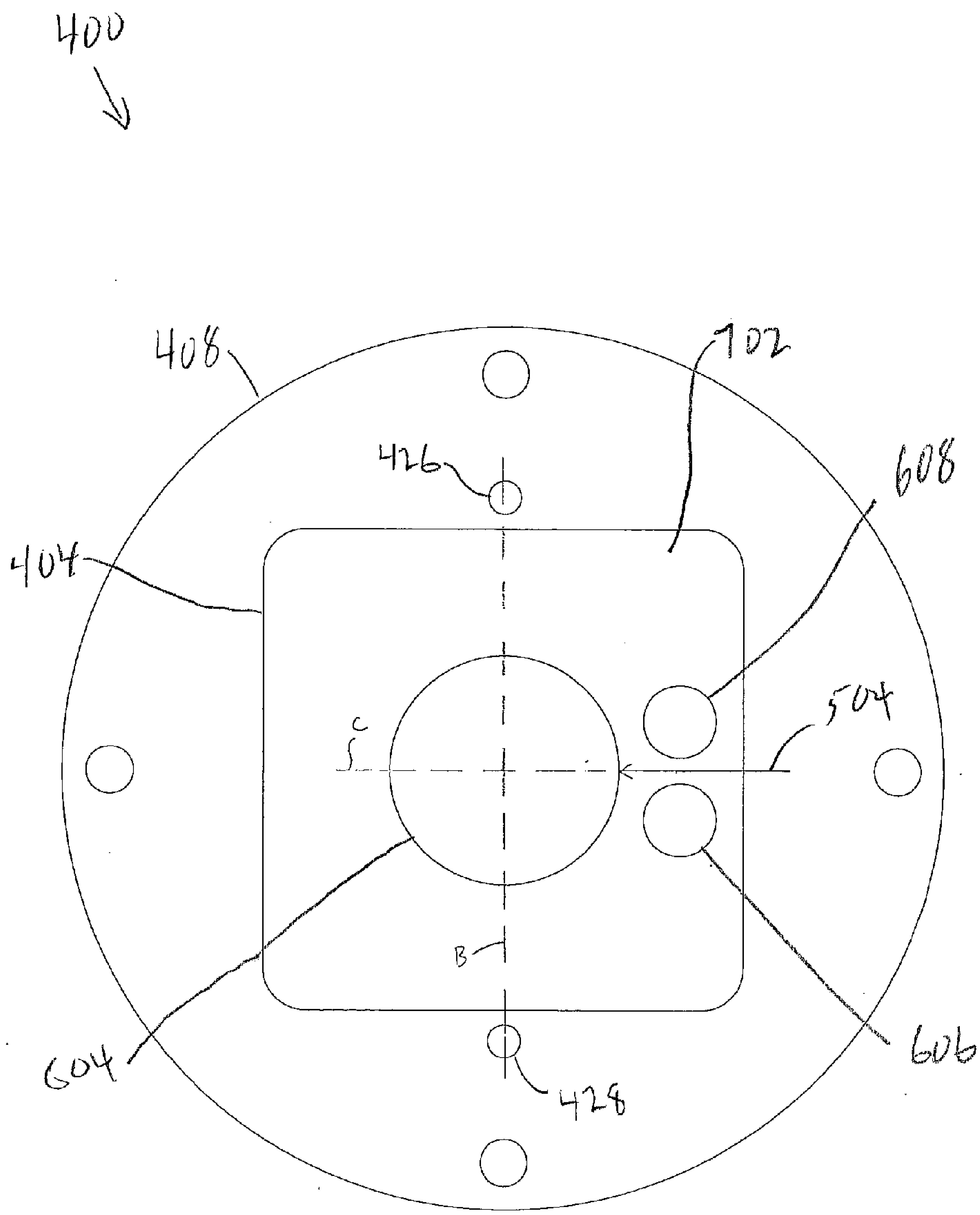


Fig. 8

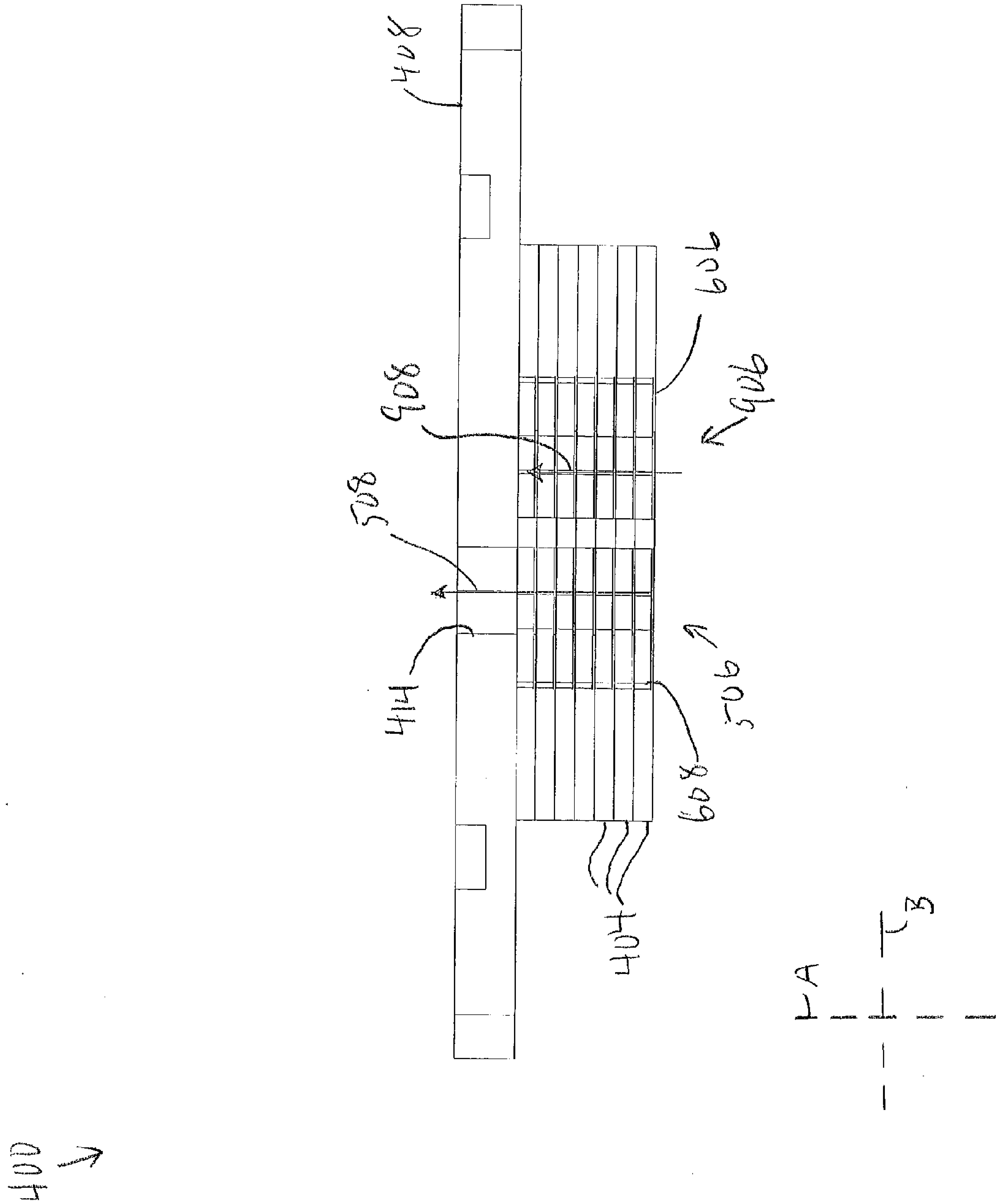


Fig. 9

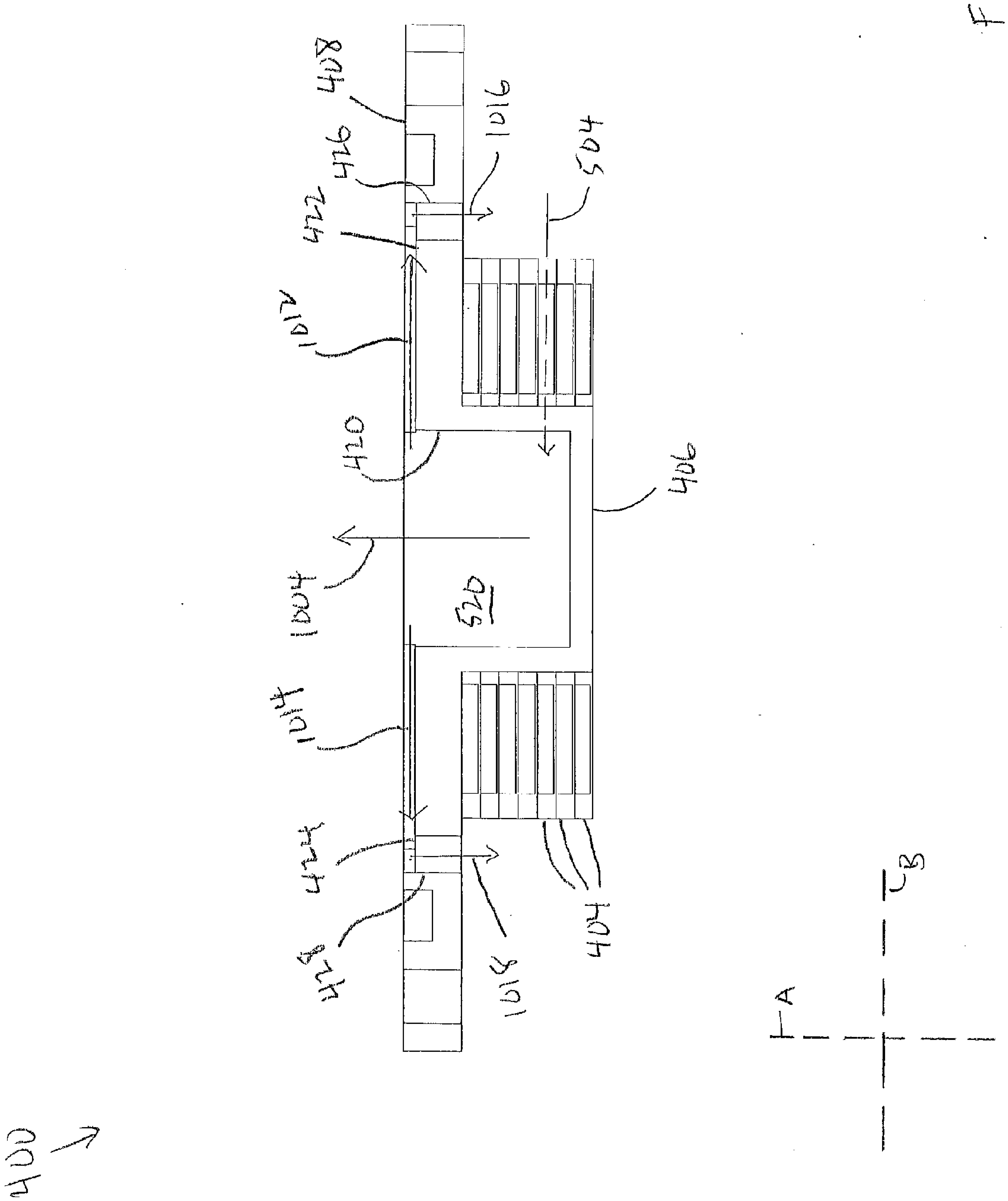

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Fig. 10

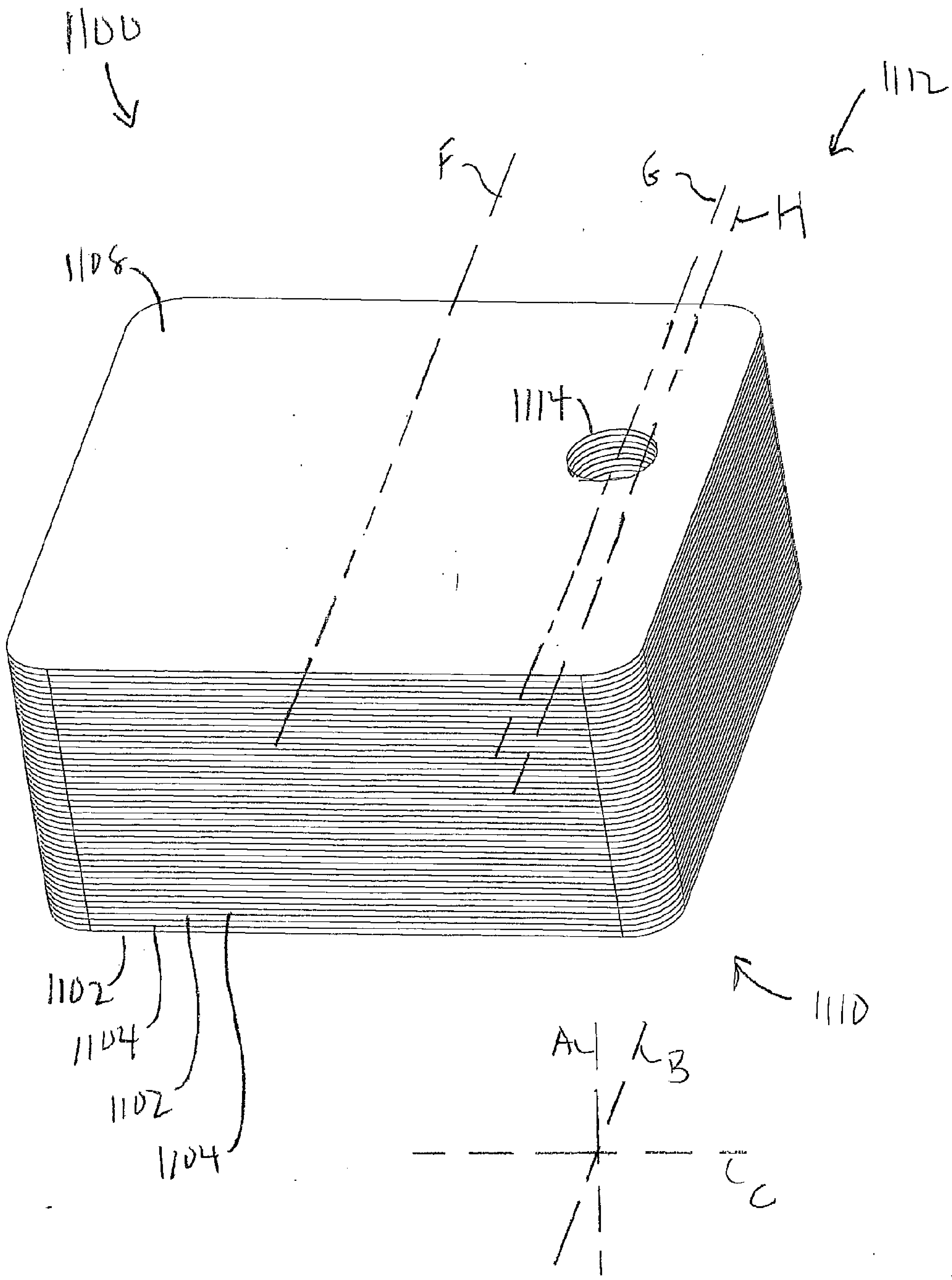

Fig. 11

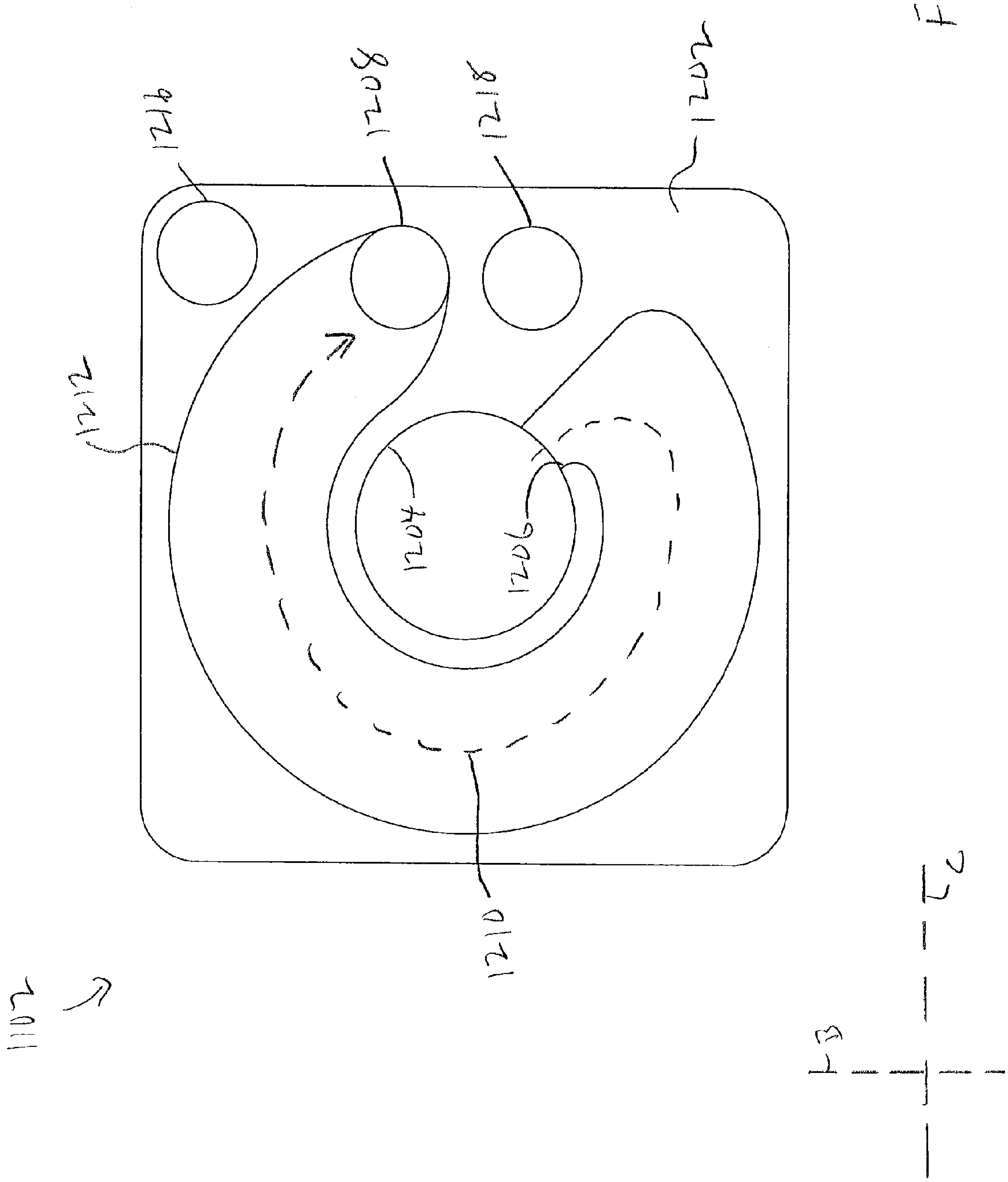

Fig. 12

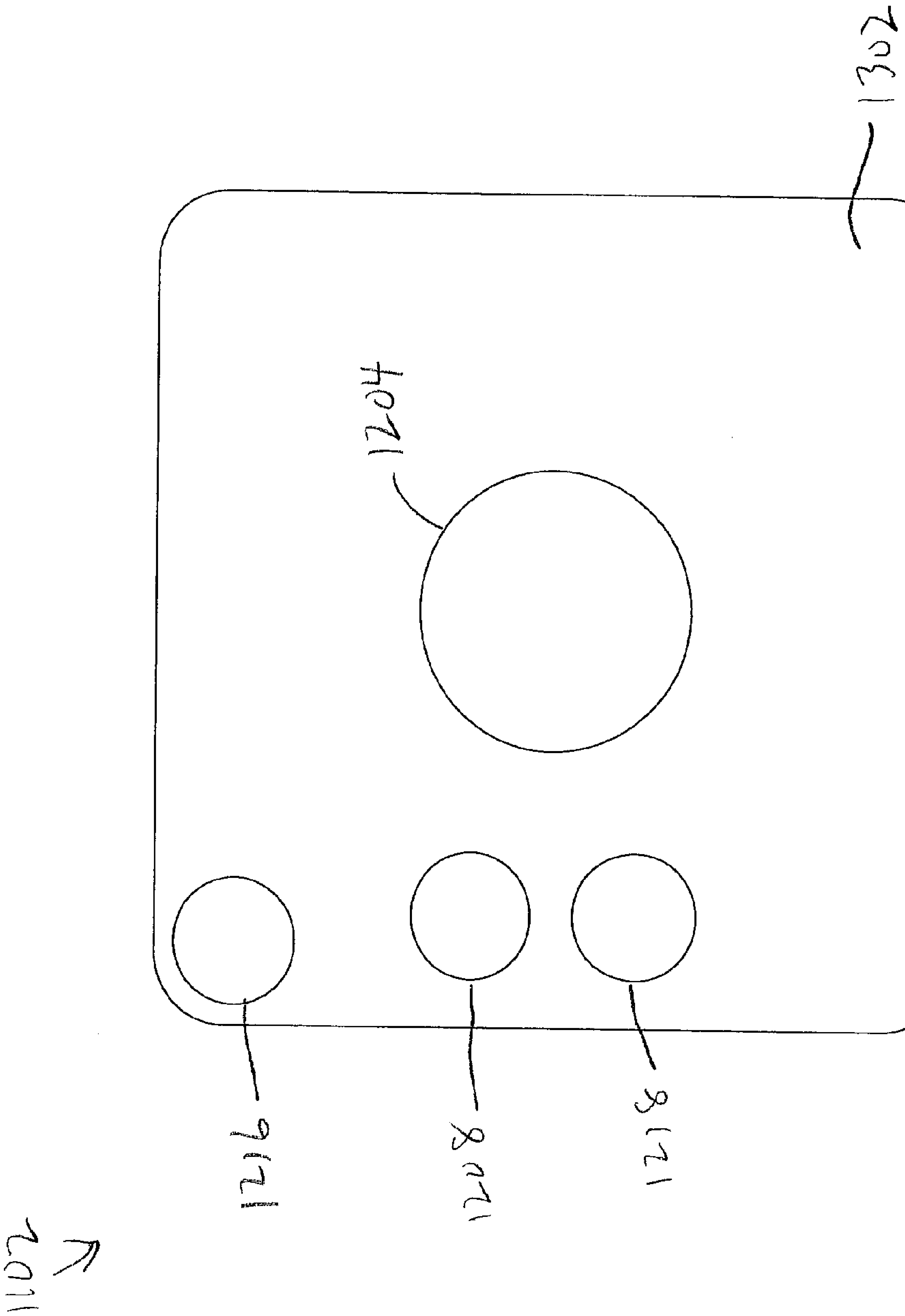

Fig. 13

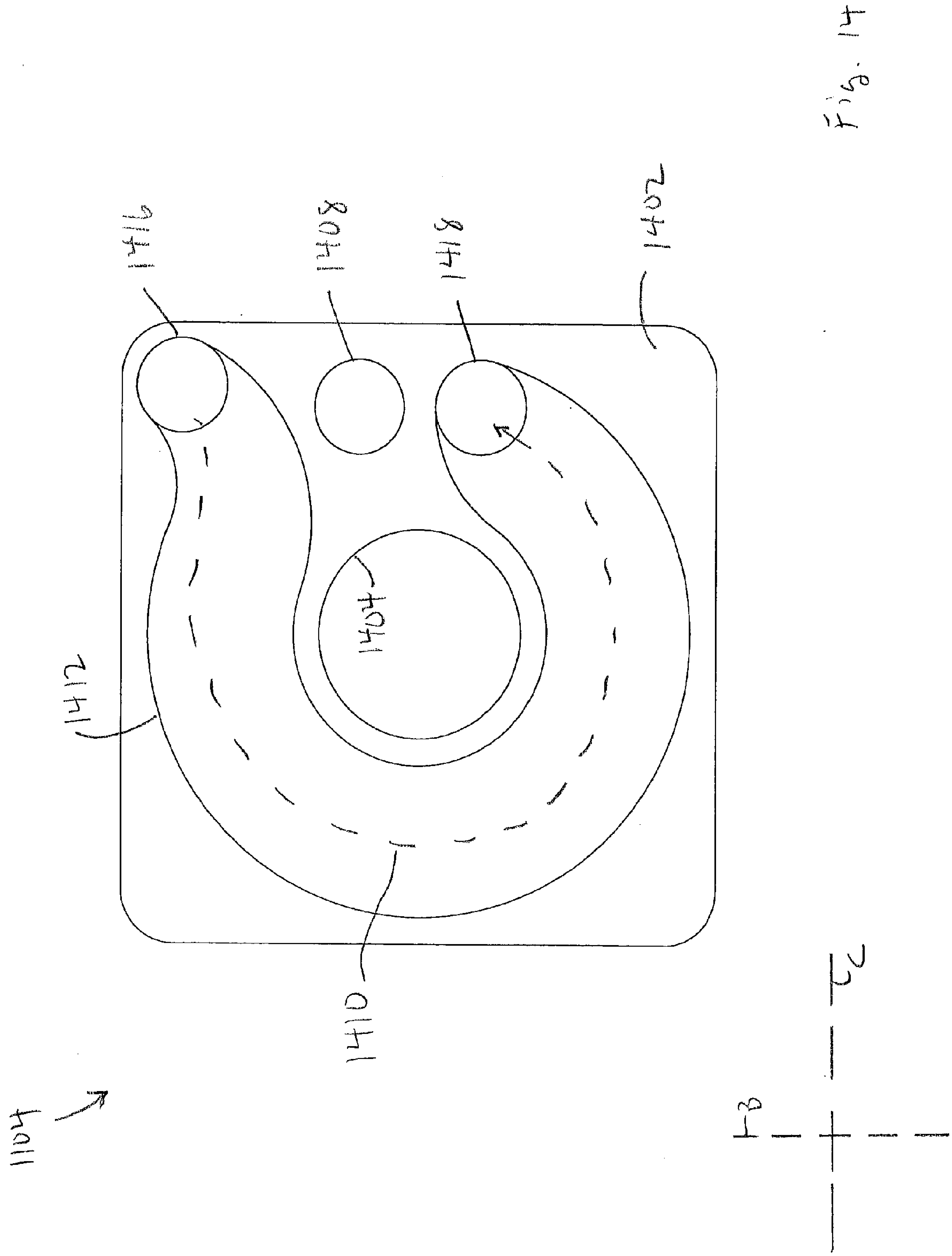
Fig. 14
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Fig. 15

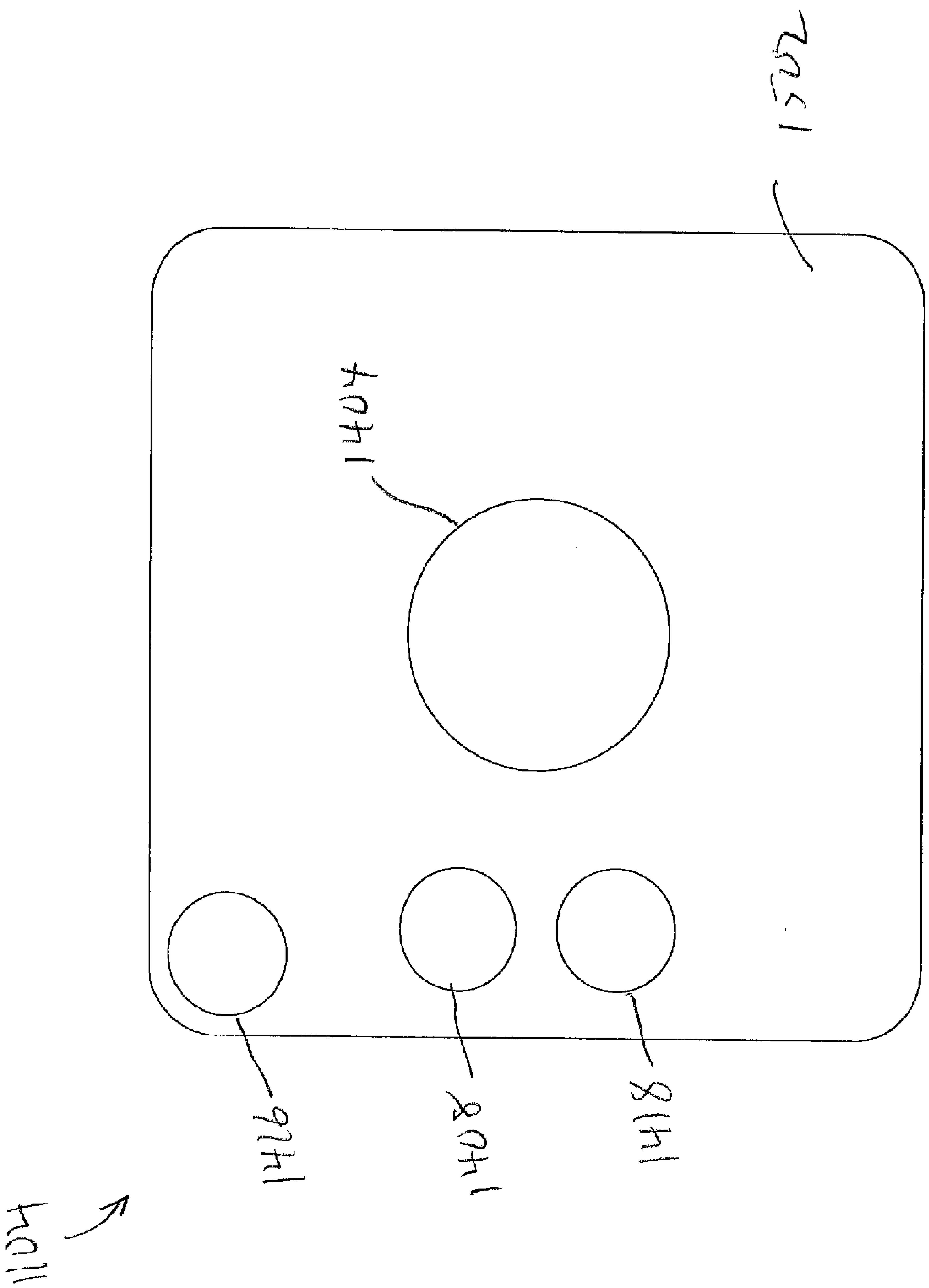


Fig. 16

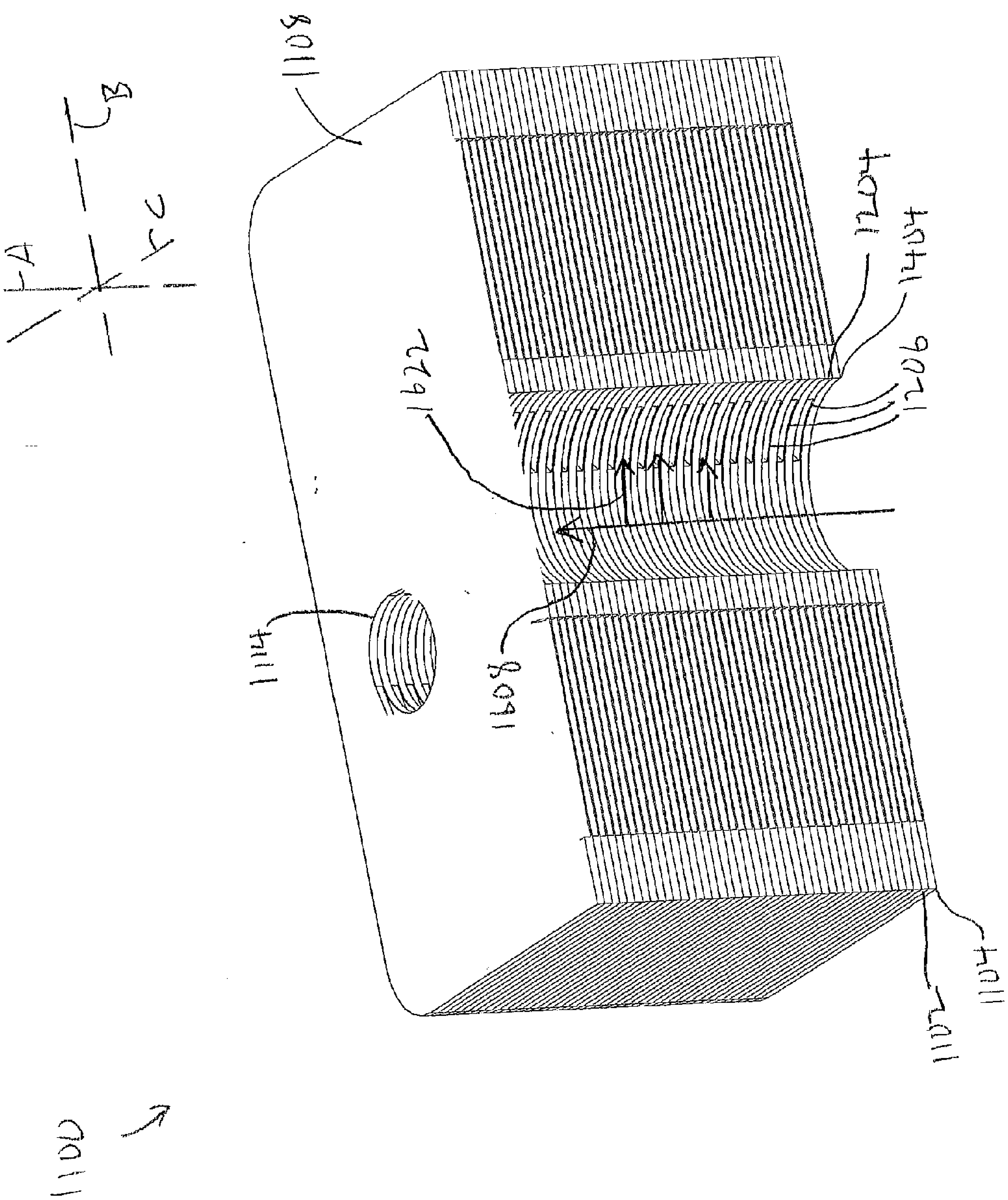


Fig. 17

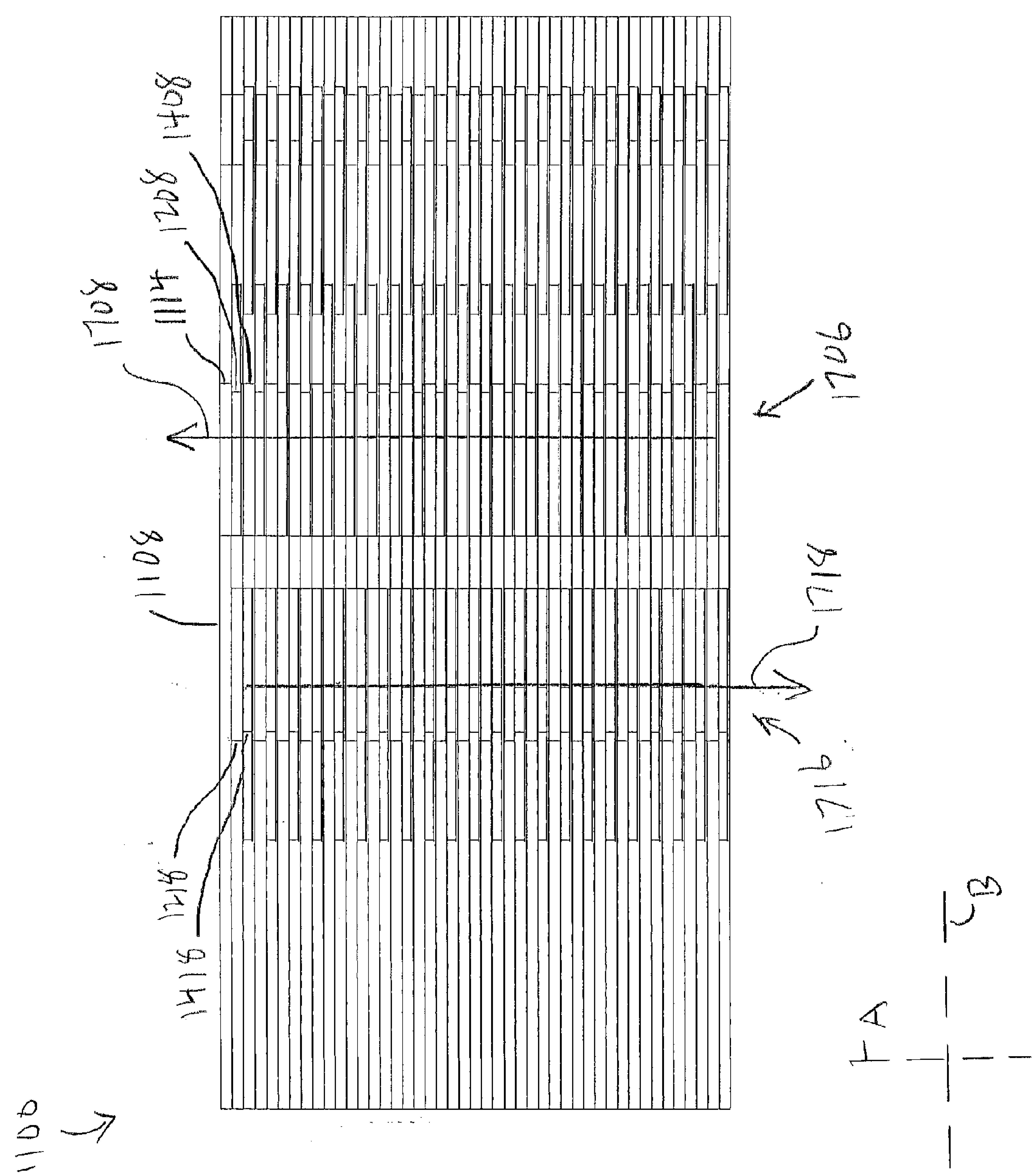
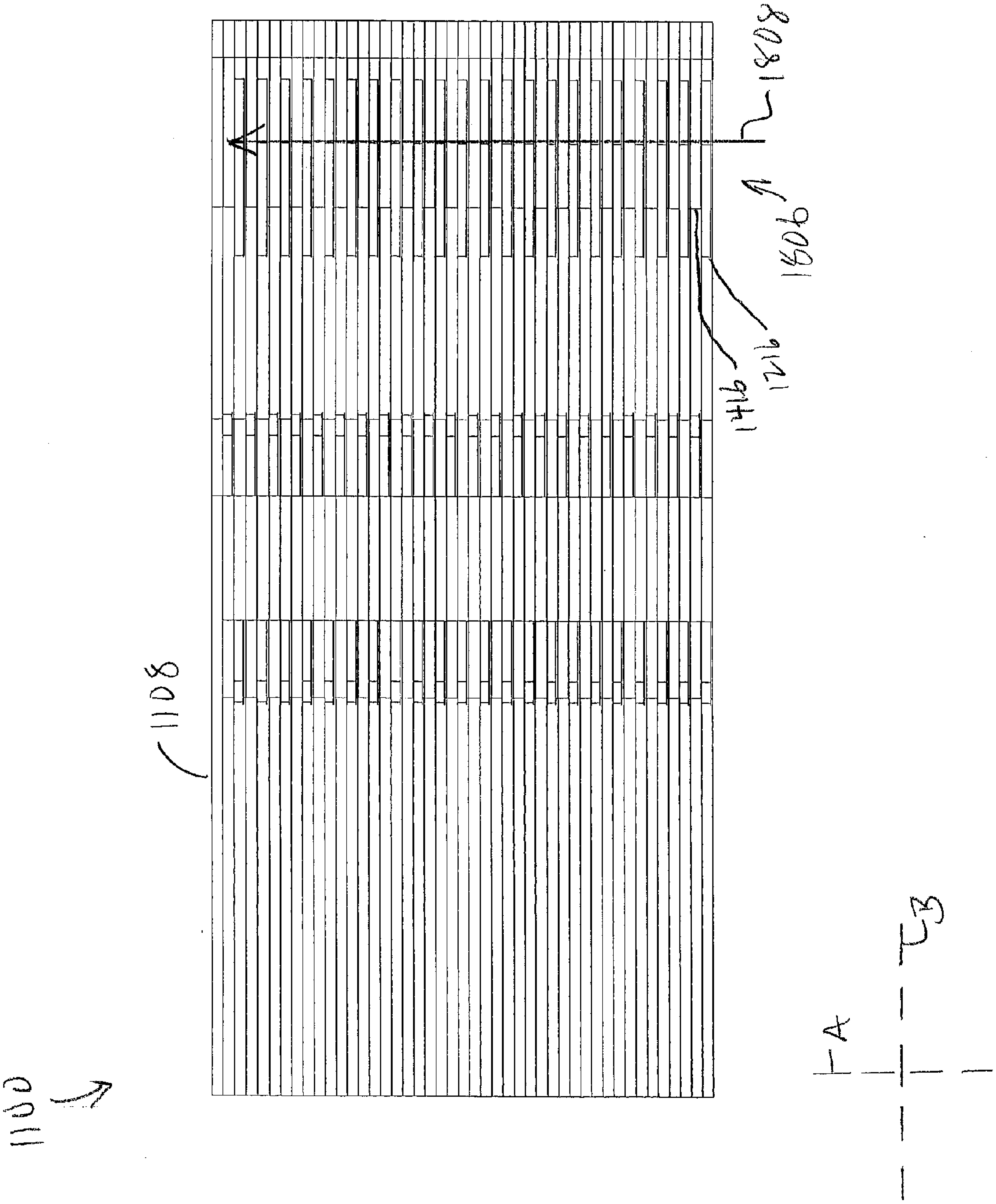


Fig. 18



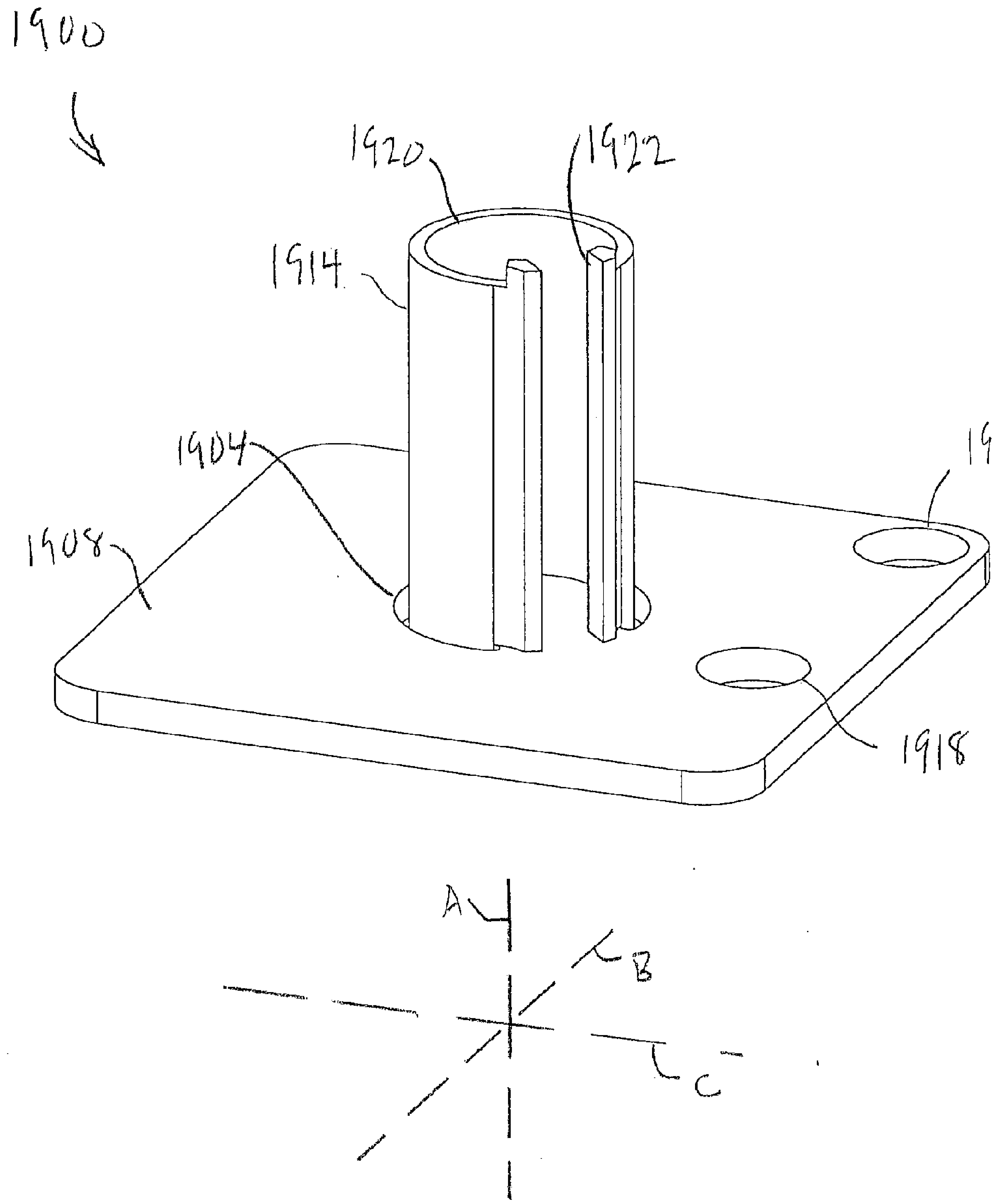


Fig. 19

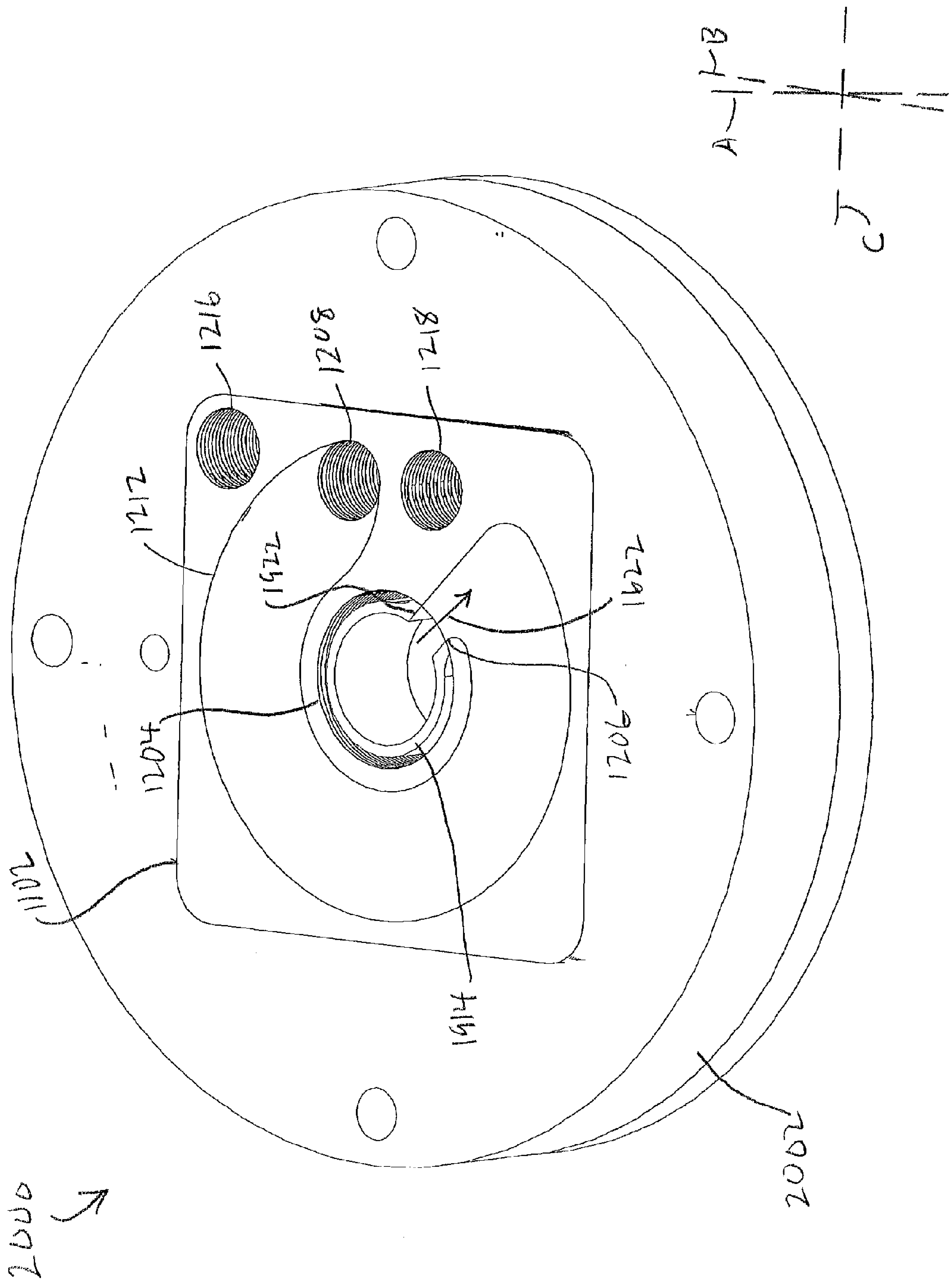

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Fig. 20

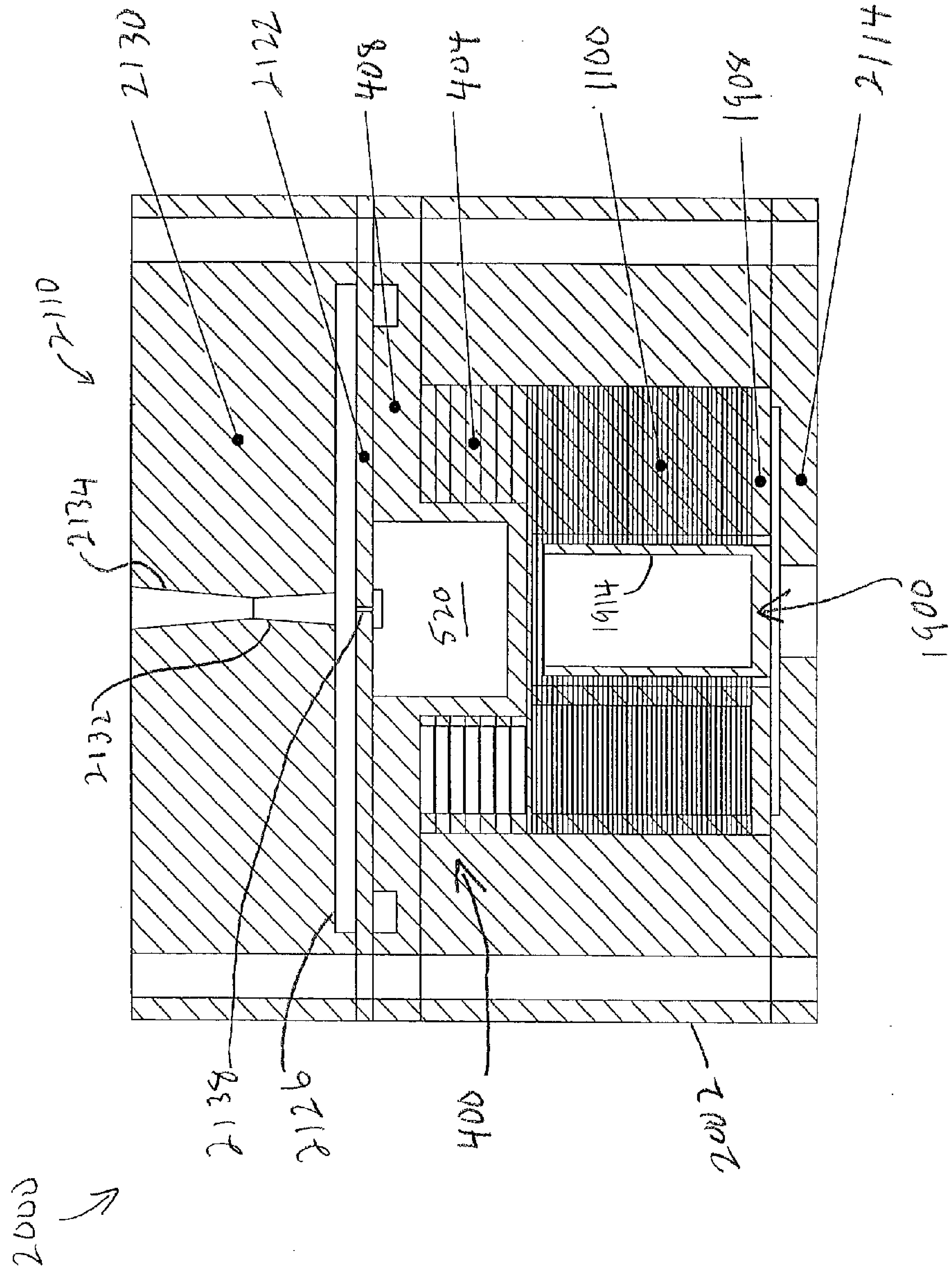
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Fig. 21

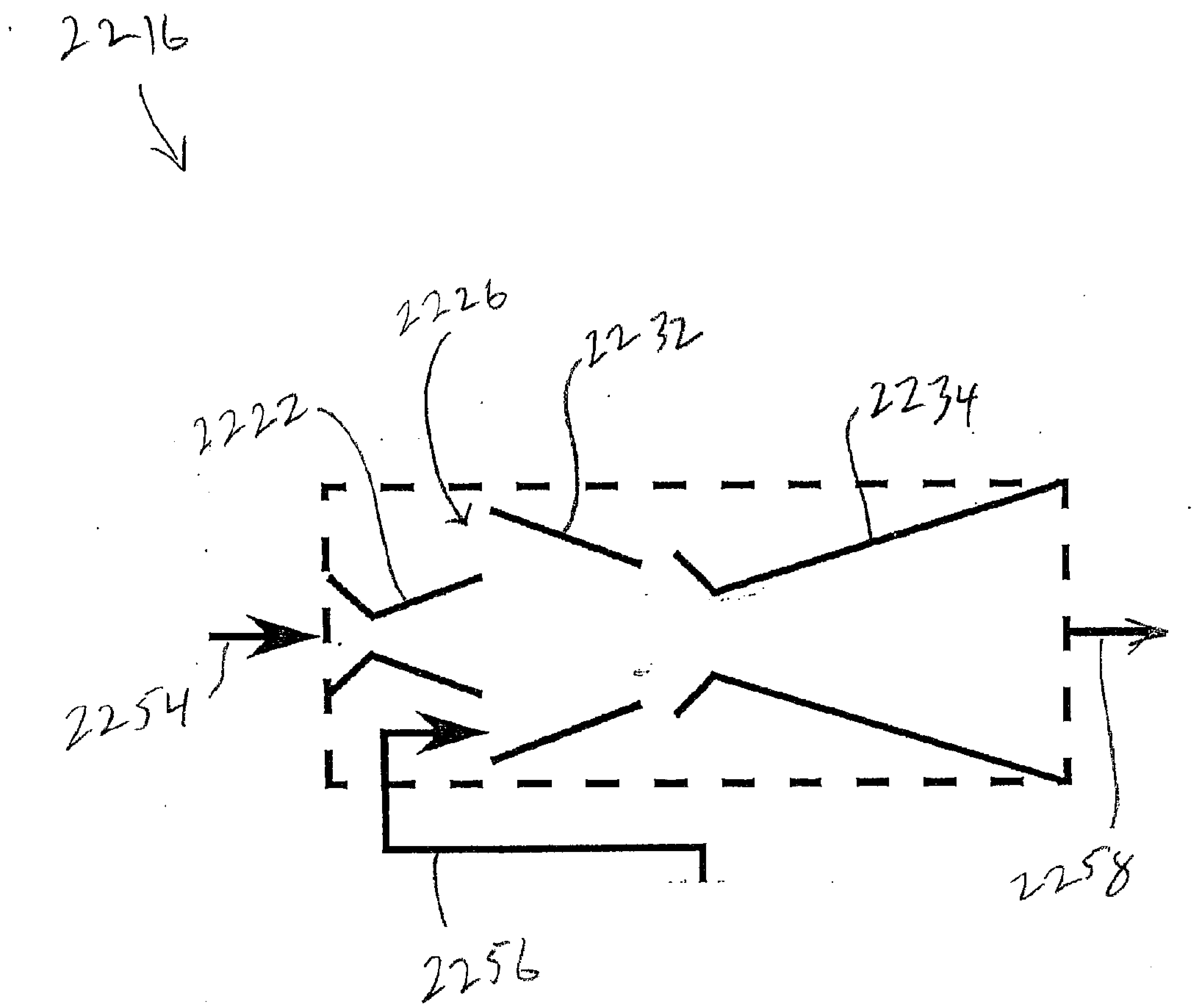

Fig. 22

MICRO-SCALE ENGINES, COMPONENTS, AND METHODS FOR GENERATING POWER

RELATED APPLICATION

[0001] This application claims the benefit of U.S. Provisional Patent Application Ser. No. 61/335,087, filed Dec. 31, 2009, titled "NOVEL THERMODYNAMIC CYCLES, ENGINES IMPLEMENTING SAME, METHODS FOR FABRICATING ENGINES, AND METHODS FOR GENERATING POWER," which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[0002] The present invention relates generally to thermodynamic cycles and engines or power plants implementing such thermodynamic cycles, including microfabricated engines or power plants.

BACKGROUND

[0003] Over the last ten years there has been an active effort to develop hydrocarbon-fueled power generation and propulsion systems on the scale of centimeters or smaller (small-scale, or micro-scale). Potential applications for micro-scale hydrocarbon-fueled power plants include those currently utilizing electrochemical batteries (e.g., lithium, lithium ion, nickel metal hydride, etc.) as energy sources. Thus, micro-scale hydrocarbon-fueled power plants are being investigated as alternatives to batteries, and more generally as energy sources for powering various kinds of micro-scale devices and systems (e.g., portable electronic devices, sensors, actuators, small vehicles and satellites, etc.). Generally, high power density portable systems have the potential for enabling new technologies as well as improving run times for existing systems requiring electrical power. High power density devices may enable designers to package the power plant and fuel needed to meet system requirements with minimal volume. While energy can be stored in many ways (chemical, mechanical, potential, nuclear), chemical energy densities far exceed any other modality (except for nuclear). Consequently, the heat engine continues to be considered a desirable method for transferring chemical energy potential into work. A typical heat engine includes a source of heat energy, a gas turbine for producing the work output, and one or more heat exchangers.

[0004] The power output of a gas turbine engine scales with length squared, and the volume scales with length cubed. Therefore, the power density scales with the inverse of length, resulting in increasing power densities as device size decreases. However, the realization of micro-scale engines is currently limited by existing microfabrication technology. Microfabrication may be based on many of the materials and techniques (e.g., vacuum deposition and crystal growth, etching techniques, micromachining, etc.) utilized in fields relating to MEMS (micro-electro-mechanical systems), microelectronics and microfluidics. To reduce the complexity and cost of microfabrication, there is a need for engine designs that minimize the number of moving parts. Moreover, the thermodynamic cycles implemented by conventional large-scale engines and power plants are not necessarily optimal when implemented at the micro-scale.

[0005] In view of the foregoing, there is an ongoing need for improved thermodynamic cycles as may be implemented for providing sources of power. This need exists generally for engines (or power plants) at any scale. This need exists in particular for micro-scale (e.g., microfabricated) engines. There is also a need for improved micro-scale engine designs and associated components.

[0006] There is also a need for micro-scale heat exchangers that can be implemented in a practical and effective manner. Known micro-scale heat exchanger configurations cannot be implemented without a major compromise to performance or manufacturing complexity. In the fluid passages of a heat exchanger, there exists an optimum length-to-diameter (or hydraulic diameter) ratio (or aspect ratio) that determines optimal performance. This length-to-diameter ratio is scale-independent and based solely on flow parameters and material properties, except at length scales at which viscous losses inhibit performance and require adjustment of flow parameters or length scale to decrease viscous losses. As the characteristic length scale of a heat exchanger decreases, the length-to-diameter ratio required for optimal performance may require flow passage lengths that are unable to be packaged conveniently into compact or micro-scale devices. Thus there is a need for heat exchanger configurations that are better suited for micro-scale implementations.

SUMMARY

[0007] To address the foregoing problems, in whole or in part, and/or other problems that may have been observed by persons skilled in the art, the present disclosure provides methods, processes, systems, apparatus, instruments, and/or devices, as described by way of example in implementations set forth below.

[0008] According to one implementation, a heat engine includes a combustor, a power turbine, a boiler, an ejector, a condenser, and an injector. The combustor includes a fuel inlet, an air inlet and an exhaust outlet. The power turbine communicates with the exhaust outlet, wherein the power turbine is driven to rotate by exhaust gas from the combustor. The boiler includes a high-temperature boiler circuit in thermal contact with a low-temperature boiler circuit for transferring heat thereto. The high-temperature boiler circuit communicates with the power turbine for receiving exhaust gas therefrom. The ejector includes a first ejector inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, a second ejector inlet communicating with the high-temperature boiler circuit for receiving exhaust gas therefrom, and an ejector outlet. The ejector is configured for entraining the exhaust gas from the second ejector inlet in the flow of vaporized working fluid from the first ejector inlet, and increasing a pressure drop across the power turbine. The condenser includes a high-temperature condenser circuit in thermal contact with a low-temperature condenser circuit for transferring heat thereto. The high-temperature condenser circuit communicates with the ejector outlet. The low-temperature condenser circuit is configured for flowing a cold fluid through the condenser. The injector includes an injector liquid inlet communicating with the high-temperature condenser circuit for receiving condensed working fluid therefrom, and an injector outlet communicating with the low-temperature boiler circuit. The injector is configured for flowing liquid-phase working fluid to the boiler.

[0009] According to another implementation, the heat engine includes a turbocharger and a compressor. The turbocharger is rotatable about a spool and communicates with the exhaust outlet, wherein the turbocharger is driven to rotate by exhaust gas from the combustor. The power turbine includes a turbine inlet communicating with the turbocharger and is driven to rotate by exhaust gas from the turbocharger. The compressor is rotatable about the spool wherein the compressor is driven to rotate by the turbocharger. The compressor includes a compressor inlet for aspirating ambient air, and a compressor outlet communicating with the air inlet wherein the compressor feeds compressed air to the combustor.

[0010] According to another implementation, the heat engine includes a recuperator. The recuperator includes a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto. The high-temperature recuperator circuit is interposed between the power turbine and the high-temperature boiler circuit, and the low-temperature recuperator circuit is disposed in upstream fluid communication with the air inlet, wherein the recuperator is configured for pre-heating air fed to the combustor.

[0011] According to another implementation, the heat engine includes a recuperator. The recuperator includes a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto. The high-temperature recuperator circuit is interposed between the ejector outlet and the high-temperature condenser circuit, and the low-temperature recuperator circuit is interposed between the injector outlet and the low-temperature boiler circuit, wherein the recuperator is configured for pre-heating the working fluid fed to the boiler.

[0012] According to another implementation, a heat engine includes a combustor, a turbocharger, a compressor, a power turbine, a recuperator, a boiler, an ejector, a condenser, and an injector. The combustor includes a fuel inlet, an air inlet and an exhaust outlet. The turbocharger is rotatable about a spool and communicates with the air inlet wherein the turbocharger feeds air to the combustor. The compressor is rotatable about the spool wherein the compressor is driven to rotate by the turbocharger. The compressor includes a compressor inlet for aspirating ambient air. The power turbine is rotatable about a turbine axis and comprises a turbine inlet communicating with the compressor wherein the power turbine is driven to rotate by compressed air from the compressor. The recuperator includes a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto. The high-temperature recuperator circuit communicates with the exhaust outlet. The low-temperature recuperator circuit is interposed between the power turbine and the turbocharger, wherein the turbocharger is driven to rotate by heated air from the recuperator. The boiler includes a high-temperature boiler circuit in thermal contact with a low-temperature boiler circuit for transferring heat thereto. The high-temperature boiler circuit communicates with the high-temperature recuperator circuit for receiving exhaust gas therefrom. The ejector includes a first ejector inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, a second ejector inlet communicating with the high-temperature boiler circuit for receiving exhaust gas therefrom, and an ejector outlet. The ejector is configured for entraining the exhaust gas from the second ejector inlet in the flow of vaporized working fluid from the first ejector inlet and increasing a pressure drop across the power turbine. The condenser includes a high-temperature condenser circuit in thermal contact with a low-temperature condenser circuit for transferring heat thereto. The high-temperature condenser circuit communicates with the ejector outlet. The low-temperature condenser circuit is configured for flowing a cold fluid through the condenser. The injector includes an injector liquid inlet communicating with the high-temperature condenser circuit for receiving condensed working fluid therefrom, and an injector outlet communicating with the low-temperature boiler circuit. The injector is configured for flowing liquid-phase working fluid to the boiler.

[0013] According to another implementation, the recuperator communicating with the turbocharger is a first recuperator, and the heat engine further includes a second recuperator. The second recuperator comprises a high-temperature second recuperator circuit in thermal contact with a low-temperature second recuperator circuit for transferring heat thereto. The high-temperature second recuperator circuit is interposed between the ejector outlet and the high-temperature condenser circuit, and the low-temperature second recuperator circuit interposed between the injector outlet and the low-temperature boiler circuit, wherein the second recuperator is configured for pre-heating the working fluid fed to the boiler.

[0014] According to another implementation, a method is provided for generating power. An exhaust gas including combustion products is flowed from a power turbine to a boiler. A working fluid is vaporized by flowing the working fluid through the boiler while flowing the exhaust gas through the boiler, wherein heat is transferred from the exhaust gas to the working fluid. The vaporized working fluid is flowed through an ejector. The exhaust gas is entrained in the vaporized working fluid as the vaporized working fluid flows through the ejector by flowing the exhaust gas from the boiler into the ejector. Entrainment of the exhaust gas creates suction downstream of the power turbine. The working fluid discharged from the ejector is condensed and returned to the boiler for vaporization by the exhaust gas flowing through the boiler. The power turbine is driven to rotate by flowing the exhaust gas to the turbine from a combustor disposed upstream of the power turbine, and by creating the suction in the exhaust gas downstream of the power turbine.

[0015] According to another implementation, a turbocharger is interposed between the combustor and the power turbine and a compressor is rotatable on a common spool with the turbocharger. The turbocharger and the compressor are driven to rotate by flowing the exhaust gas from the combustor to the turbocharger, wherein the power turbine is driven by exhaust gas discharged from the turbocharger. Compressed air from the compressor is fed to the combustor for combustion with a fuel.

[0016] According to another implementation, a method is provided for generating power. An exhaust gas including combustion products is flowed from a combustor to a recuperator. While flowing the exhaust gas through the recuperator, air discharged from a power turbine is flowed through the recuperator wherein heat is transferred from the exhaust gas to the air. The exhaust gas is flowed from the recuperator to a boiler. A working fluid is vaporized by flowing the working fluid through the boiler while flowing the exhaust gas through the boiler, wherein heat is transferred from the exhaust gas to the working fluid. The vaporized working fluid is flowed through an ejector. The exhaust gas is entrained in the vaporized working fluid as the vaporized working fluid flows through the ejector by flowing the exhaust gas from the boiler into the ejector, wherein entrainment of the exhaust gas creates suction downstream of the power turbine. The working fluid discharged from the ejector is condensed and returned to the boiler for vaporization by the exhaust gas flowing through the boiler. A turbocharger and a compressor are driven to rotate by flowing the heated air from the recuperator to the turbocharger, wherein the compressor rotates on a common spool with the turbocharger. The power turbine is driven to rotate by flowing compressed air from the compressor to the power turbine.

[0017] In any of the implementations disclosed herein, the working fluid may be a hydrocarbon fuel. In some implementations, vaporized working fluid is flowed from the boiler to the combustor to supply the combustor with fuel for combustion with air.

[0018] According to another implementation, a heat exchanger includes a plurality of hot fluid plates stacked in series along a longitudinal direction, and a cold fluid circuit. Each hot fluid plate has a thickness in the longitudinal direction and a planar area in a transverse plane orthogonal to the longitudinal direction. Each hot fluid plate includes a central hole, a hot fluid inlet hole and a hot fluid outlet hole formed through the thickness. The hot fluid inlet hole and the hot fluid outlet hole are located at respective radial distances from the central hole. Each hot fluid plate further includes a transverse channel running in the transverse plane from the hot fluid inlet hole, around the central hole and to the hot fluid outlet hole. The cold fluid circuit runs from a cold fluid inlet to a cold fluid outlet in thermal contact with the transverse channels. The central holes are aligned with each other along the longitudinal direction. The hot fluid inlet holes are aligned with each other along the longitudinal direction, forming a hot fluid inlet plenum. The hot fluid outlet holes are aligned with each other along the longitudinal direction, forming a hot fluid outlet plenum. The transverse channels establish a plurality of transverse flow paths from the hot fluid inlet plenum to the hot fluid outlet plenum.

[0019] In some implementations, the hot fluid plates each have a thickness on the order of micrometers.

[0020] According to another implementation, a heat exchanger includes a plurality of hot fluid plates and a plurality of cold fluid plates. Each hot fluid plate has a thickness in a longitudinal direction and a planar area in a transverse plane orthogonal to the longitudinal direction. Each hot fluid plate includes a central hole, a hot fluid outlet hole, a cold fluid inlet hole and a cold fluid outlet hole formed through the thickness. The hot fluid outlet hole, the cold fluid inlet hole and the cold fluid outlet hole are located at respective radial distances from the central hole. Each hot fluid plate further includes a hot fluid transverse channel running in the transverse plane from the central hole and radially outward therefrom, around the central hole and to the hot fluid outlet hole. Each cold fluid plate has a thickness in the longitudinal direction and a planar area in the transverse plane. Each cold fluid plate includes a central hole, a hot fluid outlet hole, a cold fluid inlet hole and a cold fluid outlet hole formed through the thickness. Each cold fluid plate further includes a cold fluid transverse channel running in the transverse plane from the cold fluid inlet hole, around the central hole and to the cold fluid outlet hole. The hot fluid plates and the cold fluid plates are stacked along the longitudinal direction in alternating series with each other such that each hot fluid plate is adjacent to at least one of the cold fluid plates and each hot fluid transverse channel is in thermal contact with at least one of the cold fluid transverse channels. The central holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a hot fluid inlet plenum. The hot fluid outlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a hot fluid outlet plenum. The cold fluid inlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a cold fluid inlet plenum. The cold fluid outlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a cold fluid outlet plenum. The hot fluid transverse channels establish a plurality of transverse flow paths from the hot fluid inlet plenum to the hot fluid outlet plenum. The cold fluid transverse channels establish a plurality of transverse flow paths from the cold fluid inlet plenum to the cold fluid outlet plenum.

[0021] In some implementations, the hot fluid plates and the cold fluid plates each have a thickness on the order of micrometers.

[0022] Other devices, apparatus, systems, methods, features and advantages of the invention will be or will become apparent to one with skill in the art upon examination of the following figures and detailed description. It is intended that all such additional systems, methods, features and advantages be included within this description, be within the scope of the invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0023] The invention can be better understood by referring to the following figures. The components in the figures are not necessarily to scale, emphasis instead being placed upon illustrating the principles of the invention. In the figures, like reference numerals designate corresponding parts throughout the different views.

[0024] FIG. **1** is a schematic diagram of an example of a heat engine according to an implementation disclosed herein.

[0025] FIG. **2** is a schematic diagram of an example of heat engine according to another implementation.

[0026] FIG. **3** is a schematic diagram of an example of heat engine according to another implementation.

[0027] FIG. **4** is a perspective view of an example of a micro-scale boiler according to an implementation disclosed herein.

[0028] FIG. **5** is another perspective view of the boiler illustrated in FIG. **4**, with a pie-shaped section cut-away.

[0029] FIG. **6** is a plan view of an example of a top side of a boiler plate that may be provided in the boiler illustrated in FIG. **4**.

[0030] FIG. **7** is a plan view of a bottom side of the boiler plate illustrated in FIG. **6**.

[0031] FIG. **8** is a plan view of an exhaust gas inlet side of the boiler illustrated in FIG. **4**.

[0032] FIG. **9** is a cross-sectional elevation view of the boiler, where the cross-section is taken along line D in FIG. **4**.

[0033] FIG. **10** is another cross-sectional elevation view of the boiler, where the cross-section is taken along line E in FIG. **4**.

[0034] FIG. **11** is a perspective view of an example of a micro-scale recuperator according to an implementation disclosed herein.

[0035] FIG. **12** is a plan view of an example of a top side of a hot plate that may be provided in the recuperator illustrated in FIG. **11**.

[0036] FIG. **13** is a plan view of a bottom side of the hot plate illustrated in FIG. **12**.

[0037] FIG. **14** is a plan view of an example of one a top side of a cold plate that may be provided in the recuperator illustrated in FIG. **11**.

[0038] FIG. **15** is a plan view of a bottom side of the cold plate illustrated in FIG. **14**.

[0039] FIG. **16** is a cross-sectional perspective view of the recuperator, where the cross-section is taken along line F in FIG. **11**.

[0040] FIG. **17** is a cross-sectional elevation view of the recuperator, where the cross-section is taken along line G in FIG. **11**.

[0041] FIG. **18** is a cross-sectional elevation view of the recuperator, where the cross-section is taken along line H in FIG. **11**.

[0042] FIG. **19** is a perspective view of an example of a micro-scale combustor according to an implementation disclosed herein.

[0043] FIG. **20** is a cross-sectional perspective view of a portion of an example of a micro-scale heat engine according to an implementation disclosed herein, in which the combustor illustrated in FIG. **19** and the recuperator illustrated in FIGS. **11-18** have been assembled or fabricated together.

[0044] FIG. **21** is a cross-sectional elevation view of a portion of an example of a micro-scale heat engine according to an implementation disclosed herein, in which the combustor illustrated in FIG. **19**, the recuperator illustrated in FIGS. **11-18**, the boiler illustrated in FIGS. **4-10**, and an ejector, have been assembled or fabricated together.

[0045] FIG. **22** is a schematic view of an example of an injector that may be utilized in any of the heat engines described herein.

DETAILED DESCRIPTION

[0046] As used herein, the term "micro-scale" generally applies to engines in which at least some of the structural features of the operative components (e.g., turbine, pump or compressor, heat exchanger, etc.) have dimensions on the order of microns (micrometers). One or more overall dimensions (e.g., total length, width, height, diameter, thickness, etc.) of the operative components, however, may be on the order of millimeters or centimeters. Such engines may be referred to as micro-scale engines or microengines. A microengine may be utilized as a power supply for a wide variety of small devices, including for example small vehicles and portable electronic devices.

[0047] As used herein, the term "macro-scale" or "large-scale" generally applies to engines larger than microengines, including engines of an industrial scale such as may be implemented as a power plant for powering large devices, vehicles, etc., supplying power to a building, supplying power to a power grid that distributes power over a geographical area, etc.

[0048] As used herein, the term "fluid" encompasses a liquid (liquid-phase material), a gas (gas-phase material or vapor), a supercritical fluid, or a mixture of two or more of the foregoing, unless a particular fluid is specifically indicated as being a liquid, gas (or vapor), or supercritical fluid. Depending on the context, a liquid may also be referred to as a condensate. A liquid may or may not contain a gas component (e.g., vapor or bubbles). A gas may or may not contain a liquid component. A supercritical fluid may, at least temporarily, fall below its critical point (with respect to temperature and/or pressure) such that the supercritical fluid at least partially includes a liquid-phase or gas-phase component.

[0049] FIGS. **1-3** are schematic diagrams of heat engines according to various implementations taught herein. In some implementations, the heat engine is turbocharged while in other implementations is naturally aspirated. In some implementations, the heat engine is configured for recuperation of heat lost through various structures, cooling of various structures via air and working fluid flows, and recycling of exhaust gas condensables and unburned fuel. In some implementations, the working fluid is a fuel, which may also be utilized as the fuel for combustion. In various implementations, the heat engine as taught herein may be generally characterized as implementing a combination of a Brayton cycle, which may be turbocharged and/or recuperated, and a locomotive-type Rankine cycle which may also be recuperated. The heat engines may generally be applied at the macro-scale or at the micro-scale. In some implementations disclosed herein, a microengine implemented according to the present teachings may produce a power output in the range of, for example, about 1-10 W, with a thermal efficiency of about 1-10% and an electrical generator efficiency of about 40-50%. Hence, in such implementations the microengine has an energy density comparable to or better than a typical lithium-chemistry battery.

[0050] In FIGS. **1-3**, the diagrams include several arrows that schematically depict various fluid lines and indicate the direction of fluid flow through those lines. The structure of any given fluid line depends in part on the configuration and size (macro-scale or micro-scale) of the heat engine and how it is fabricated. Thus, as examples, a given fluid line may be a conduit (e.g., a tube connected between two distinct operative components, a passage or channel formed in a block or layer of material such as by etching, etc.) of some length, or the fluid line may be a relatively short bore or opening formed through a wall or layer of material, which may simply be the boundary between two operative components.

[0051] FIG. **1** is a schematic diagram of an example of a heat engine **100** according to an implementation disclosed herein. The heat engine **100** in this example may be characterized as implementing a turbocharged locomotive-type cycle. The heat engine **100** includes a combustor **102**, a turbocharger (or secondary turbine) **104** in fluid communication with the combustor **102**, a compressor **106** in mechanical communication with the turbocharger **104**, and a power turbine **108** (or power off-take turbine) in fluid communication with the turbocharger **104**. The turbocharger **104**, power turbine **108** and compressor **106** are the only moving (rotating) components of the heat engine **100**. The heat engine **100** further includes a boiler **110** in fluid communication with the power turbine **108**, a (gas) ejector **112** in fluid communication with the boiler **110**, a condenser **114** in fluid communication with the ejector **112**, and a (liquid) injector **116** in fluid communication with the condenser **114**. In the present implementation, the heat engine **100** may further include one or more recuperators **118**, **120** as described below. In micro-scale applications, the use of a recuperator provides advantages while still allowing the heat engine **100** to maintain an acceptable power density, according to the cube-square law. Power output is proportional to intake area, and device weight is proportional to device volume, so as device size is scaled down linearly, the power density increases inversely with rotor diameter or any other selected characteristic length.

[0052] The combustor **102** may be of any type suitable for initiating and maintaining a fuel-air combustion reaction and outputting the resulting exhaust gases containing the combustion products. The combustor **102** includes a fuel inlet **132**, an air inlet **134** and an exhaust outlet **136**. Also shown is an input of heat energy Q to the combustor **102** utilized for ignition such as, for example, a spark plug or glow plug, a resistive wire, filament, needle, plate, electrode, etc. The combustor **102** generally includes a combustion chamber having a volume appropriate for the size of the heat engine **100** (i.e., macro-scale or micro-scale). In some implementations, a catalyst may be provided in the combustion chamber to promote the combustion reaction. Non-limiting examples of catalysts include noble metals such as, for example, platinum and palladium. The catalyst may be supported by any suitable substrate such, for example, a nickel foam.

[0053] The turbocharger **104** includes a turbine structure rotatable about a turbine axis, a housing (not shown) enclosing the turbine structure, a turbocharger inlet **142** and a turbocharger outlet **144**. In the present example, the turbine axis is schematically depicted as a shaft or spool **146** but may alternatively be configured as a disk. The turbine structure may include a rotor of any suitable design that is connected to (or integrated with) the spool **146** and supports turbine vanes or blades. The housing may include or serve as a stator and may or may not include stationary vanes. Generally, the turbine and housing cooperatively define fluid flow paths through the turbine structure from the turbocharger inlet **142** to the turbocharger outlet **144**. The implementations described herein are not limited to any particular design of the turbocharger **104**. Various designs of gas turbines at both the macro-scale and micro-scale level are known to persons skilled in the art. In the present implementation, the exhaust outlet **136** of the combustor **102** communicates with the turbocharger inlet **142** over an exhaust gas line. Accordingly, the turbocharger **104** is driven to rotate by the flow of hot exhaust gas produced by the combustor **102**.

[0054] The compressor **106** includes a compressor structure rotatable about a compressor axis, a housing (not shown) enclosing the compressor structure, a compressor inlet **152** and a compressor outlet **154**. In the present example, the compressor axis is collinear with the turbine axis, i.e., the schematically depicted spool **146** is common to both the turbocharger **104** and the compressor **106**. Accordingly, the compressor **106** in this example is driven to rotate by the torque transferred from the rotating turbocharger **104** via the spool **146**. The compressor structure may include a rotor of any suitable design that is connected to (or integrated with) the spool **146** and supporting compressor vanes or fan-type blades. For example, the spool **146** may be provided in the form of a compressor rotor and a turbocharger rotor interconnected by a bearing-supported shaft or hub, or the spool **146** may be a bearing supported disk-type structure of which one side serves as the compressor rotor and the opposite side serves as the turbocharger rotor. In some implementations, the compressor **106** may have an axial-flow or rotary vane type of design. The housing may include or serve as a stator and may or may not include stationary vanes. Depending on design, an integral housing may be structured to enclose both the compressor **106** and the turbocharger **104**. Generally, the compressor **106** and housing cooperatively define fluid flow paths through the compressor structure from the compressor inlet **152** to the compressor outlet **154**. The implementations described herein are not limited to any particular design of the compressor **106**. Various designs of gas compressors at both the macro-scale and micro-scale level are known to persons skilled in the art. The compressor inlet **152** is configured to receive (aspirate) air from the ambient environment in which the heat engine **100** operates. The compressor outlet **154** is in fluid communication with the air inlet **134** to feed compressed air to the combustor **102**, either directly or after pre-heating as described below.

[0055] The power turbine **108** includes a turbine structure rotatable about a power turbine axis, a housing (not shown) enclosing the turbine structure, a power turbine inlet **158** and a power turbine outlet **160**. The power turbine axis may be a shaft, spool, disk or other rotating element (not shown). The power turbine axis may or may not be in-line with the turbocharger axis. In the present implementation, the power turbine **108** is not mechanically referenced to either the turbocharger **104** or the compressor **106**. The turbine structure of the power turbine **108** may include a rotor and vanes or blades and generally may be similar to that of the turbocharger **104**. The housing may include or serve as a stator and may or may not include stationary vanes. Generally, the turbine and housing cooperatively define fluid flow paths through the turbine structure from the power turbine inlet **158** to the power turbine outlet **160**. In the present implementation, the turbocharger outlet **144** is in fluid communication with the power turbine inlet **158** over a turbocharger exhaust gas line. Accordingly, the power turbine **108** is driven to rotate by the flow of hot exhaust gas outputted from the turbocharger **104**. Also shown schematically is a work output W produced by the power turbine **108**. In a typical implementation, the work output W is torque produced by a rotating component of the power turbine **108** such as the shaft that rotates about the turbine axis. Depending on the use of the heat engine **100**, the work output W may be coupled to any device via any appropriate transmission or transducer to supply power to that device.

[0056] Additional examples of turbines, compressors, pumps and other rotatable components that may generally be suitable for use in micro-scale versions of the heat engines described herein are described in U.S. Pat. Nos. 5,932,540; 6,392,313; and 7,074,016; each of which is incorporated by reference herein in its entirety.

[0057] In the present implementation, the heat engine **100** may further include a recuperator **118**. The recuperator **118** includes a heat exchanger structure that generally includes a high-temperature recuperator circuit **164** and a low-temperature recuperator circuit **166**. In the present context, "high temperature" generally means that a hot fluid flows through the high-temperature recuperator circuit **164** and "low temperature" generally means that a cold fluid ("cold" being relative to the hot fluid) flows through the low-temperature recuperator circuit **166**, and that heat is transferred from the hot fluid to the cold fluid via the heat exchanger structure due to the temperature differential between the hot fluid and the cold fluid. The high-temperature recuperator circuit **164** runs from a hot fluid recuperator inlet **168** to a hot fluid recuperator outlet **170**, and the low-temperature recuperator circuit **166** runs from a cold fluid recuperator inlet **172** to a cold fluid recuperator outlet **174**. The circuits **164**, **166** are configured as any suitable type of passages through which fluids flow. The fluid flow path(s) running through the high-temperature recuperator circuit **164** is physically separate from the fluid flow path(s) running through the low-temperature recuperator circuit **166**. The heat exchanger structure is configured such that the high-temperature recuperator circuit **164** is in thermal contact with the low-temperature recuperator circuit **166**, whereby heat is transferred from the fluid flowing in the high-temperature recuperator circuit **164** to the fluid flowing in the low-temperature recuperator circuit **166** in the direction (s) of temperature gradients resulting from the configuration. For this purpose, the heat exchanger structure may have any suitable configuration such as, for example, tube-shell, stack of thin-walled plates, etc.

[0058] As appreciated by persons skilled in the art, the fluid passages provided by the high-temperature recuperator circuit **164** and/or the low-temperature recuperator circuit **166** may be multi-directional (e.g., serpentine, labyrinthine, helical, etc.) as desired for maximizing heat transfer. As also appreciated by persons skilled in the art, while the high-temperature recuperator circuit **164** is illustrated as being in a counterflow relation with the low-temperature recuperator circuit **166**, alternative configurations such as concurrent flow, cross-flow, combinations of different types of flow arrangements, and variations of such flow arrangements may be suitable.

[0059] In the present implementation, the hot fluid recuperator inlet **168** is in fluid communication with the power turbine outlet **160** over a power turbine exhaust gas line. The hot fluid recuperator outlet **170** is in fluid communication with the boiler **110** over a recuperator exhaust gas line. The cold fluid recuperator inlet **172** is in fluid communication with the compressor outlet **154** and thus receives the compressed air from the compressor **106**. The cold fluid recuperator outlet **174** is in fluid communication with the air inlet **134** of the combustor **102**. By this configuration, the hot exhaust gas received from the power turbine **108** flows through the high-temperature recuperator circuit **164**, while the air received from the compressor **106** flows through the low-temperature recuperator circuit **166**. While these flows occur, heat is transferred from the hot exhaust gas to the air and the resulting pre-heated air is fed to the combustor **102**.

[0060] In the present context of heat exchangers, it will be appreciated that the terms "hot" and "cold," and "high-temperature" and "low-temperature," are being used in a relative sense to distinguish between different circuits of a given heat exchanger and the flow paths associated with the different circuits, and also to indicate which circuit gives up heat and which circuit receives heat during operation. It will be noted that in the high-temperature recuperator circuit **164**, the temperature of the exhaust gas at the hot fluid recuperator inlet **168** is "high" relative to the temperature of the exhaust gas at the hot fluid recuperator outlet **170** due to the loss of heat to the low-temperature recuperator circuit **166**. In the low-temperature recuperator circuit **166**, the temperature of the air at the cold fluid recuperator outlet **174** is "high" relative to the temperature of the air at the cold fluid recuperator inlet **172** due to the deposition of heat from the high-temperature recuperator circuit **164**. These labeling conventions also apply to other heat exchangers of the heat engine **100** such as the boiler **110** and condenser **114**.

[0061] The boiler **110** includes a heat exchanger structure that generally includes a high-temperature boiler circuit **178** and a low-temperature boiler circuit **180**. The high-temperature boiler circuit **178** runs from a hot fluid boiler inlet **182** to a hot fluid boiler outlet **184**, and the low-temperature boiler circuit **180** runs from a cold fluid boiler inlet **186** to a cold fluid boiler outlet **188**. The fluid flow path(s) running through the high-temperature boiler circuit **178** is physically separate from the fluid flow path(s) running through the low-temperature boiler circuit **180**. The heat exchanger structure is configured such that the high-temperature boiler circuit **178** is in thermal contact with the low-temperature boiler circuit **180**, whereby heat is transferred from the fluid flowing in the high-temperature boiler circuit **178** to the fluid flowing in the low-temperature boiler circuit **180**. As in the case of the recuperator **118**, the heat exchanger structure of the boiler **110** may have any suitable configuration (tube-shell, stack of thin-walled plates, etc.), one or more of the fluid passages may be multi-directional, and the flow arrangement may be a counterflow or other arrangement.

[0062] The hot fluid boiler inlet **182** is in fluid communication with the hot fluid recuperator outlet **170** over the recuperator exhaust gas line. The hot fluid boiler outlet **184** is in fluid communication with the ejector **112** over a boiler exhaust gas line. The cold fluid boiler inlet **186** is in fluid communication with the injector **116** over a liquid working fluid line to receive a liquid-phase (or a mixture of liquid-phase and gas-phase) working fluid to be heated and vaporized by the boiler **110**. The cold fluid boiler outlet **188** is in fluid communication with the ejector **112** over a working fluid gas (or vapor) line. By this configuration, the hot exhaust gas received from the recuperator **118** flows through the high-temperature boiler circuit **178**, while the working fluid received from the injector **116** flows through the low-temperature boiler circuit **180**. While these flows occur, heat is transferred from the hot exhaust gas to the working fluid and the resulting pressurized and boiled (or vaporized) working fluid is fed to the ejector **112**.

[0063] The ejector **112** includes an ejector structure, a first ejector inlet **194**, a second ejector inlet **196**, and an ejector outlet **198**. The first ejector inlet **194** is in fluid communication with the high temperature boiler outlet **188** via the working fluid gas line, whereby the vaporized working fluid is flowed through the ejector structure as a motive flow. The second ejector inlet **196** is in fluid communication with the hot fluid boiler outlet **184** for feeding the exhaust gas to the ejector **112**. The ejector structure may include a nozzle **202** into which the first ejector inlet **194** leads, whereby these components operate as a gas jet. The ejector structure may also include an exhaust gas inlet plenum **204** (or smoke box) into which the second ejector inlet **196** leads. The second ejector inlet **196** may be oriented at an angle relative to the first ejector inlet **194** such that the exhaust gas flow into the ejector **112** from the second ejector inlet **196** is at an angle (in some advantageous implementations, a ninety-degree angle) to the vaporized working fluid flow from the first ejector inlet **194**. By this configuration, the motive flow of the vaporized working fluid reduces the pressure in the exhaust gas inlet plenum **204**, thereby inducing flow of the exhaust gas toward the motive flow such that the exhaust gas becomes entrained in the motive flow by viscous effects. Consequently, the operation of the ejector **112** creates suction on the outlet side of the power turbine **108** that increases the pressure drop across the power turbine **108**. In this manner, the power turbine **108** is driven in part by the fluid flow through the ejector **112**. The resulting hot ejector gas (i.e., the mixture of vaporized working fluid and exhaust gas) is ejected from the ejector outlet **198** and into a hot ejector gas outlet line. The ejector structure may include a diffuser **206** leading to the ejector outlet **198**. As appreciated by persons skilled in the art, the nozzle **202**, the diffuser **206** or both may have converging and/or diverging sections.

[0064] In the present implementation the heat engine **100** may further include another recuperator **120**, which is between the ejector **112** and the condenser **114**. The recuperator **120** includes a heat exchanger structure that generally includes a high-temperature recuperator circuit **212** and a low-temperature recuperator circuit **214**. The high-temperature recuperator circuit **212** runs from a hot fluid recuperator inlet **216** to a hot fluid recuperator outlet **218**, and the low-temperature recuperator circuit **214** runs from a cold fluid recuperator inlet **220** to a cold fluid recuperator outlet **222**. The fluid flow path(s) running through the high-temperature recuperator circuit **212** is physically separate from the fluid flow path(s) running through the low-temperature recuperator circuit **214**. The heat exchanger structure is configured such that the high-temperature recuperator circuit **212** is in thermal contact with the low-temperature recuperator circuit **214**, whereby heat is transferred from the fluid flowing in the high-temperature recuperator circuit **212** to the fluid flowing in the low-temperature recuperator circuit **214**. As in the case of the other recuperator **118**, the heat exchanger structure of this recuperator **120** may have any suitable configuration (tube-shell, stack of thin-walled plates, etc.), one or more of the fluid passages may be multi-directional, and the flow arrangement may be a counterflow or other arrangement.

[0065] The hot fluid recuperator inlet **216** is in fluid communication with the ejector outlet **198** over the hot ejector gas outlet line. The hot fluid recuperator outlet **218** is in fluid communication with the condenser **114** over a hot gas condenser inlet line. The cold fluid recuperator inlet **220** is in fluid communication with the injector **116** and thus receives working fluid from the injector **116**. The cold fluid recuperator outlet **222** is in fluid communication with the boiler **110**. By this configuration, the hot ejector gas (mixture of vaporized working fluid and exhaust gas) received from the ejector **112** flows through the high-temperature recuperator circuit **212**, while the working fluid received from the injector **116** flows through the low-temperature recuperator circuit **214**. While these flows occur, heat is transferred from the hot gas to the working fluid and the resulting pre-heated working fluid is fed to the boiler **110** to assist in vaporizing the working fluid. Moreover, the ejector gas is pre-cooled prior to being fed to the condenser **114**.

[0066] In implementations where the heat engine **100** provides both recuperators **118** and **120**, the recuperator **118** between the power turbine **108** and the boiler **110** may be referred to as the first recuperator, and the recuperator **120** between the ejector **112** and the condenser **114** may be referred to as the second recuperator.

[0067] The condenser **114** includes a heat exchanger structure that generally includes a high-temperature condenser circuit **226** and a low-temperature condenser circuit **228**. The high-temperature condenser circuit **226** runs from a hot fluid condenser inlet **230** to a hot fluid condenser outlet **232**, and the low-temperature condenser circuit **228** runs from a cold fluid condenser inlet **234** to a cold fluid condenser outlet **236**. The fluid flow path(s) running through the high-temperature condenser circuit **226** is physically separate from the fluid flow path(s) running through the low-temperature condenser circuit **228**. The heat exchanger structure is configured such that the high-temperature condenser circuit **226** is in thermal contact with the low-temperature condenser circuit **228**, whereby heat is transferred from the fluid flowing in the high-temperature condenser circuit **226** to the fluid flowing in the low-temperature condenser circuit **228**. As in the case of the other heat exchangers described above, the heat exchanger structure of the condenser **114** may have any suitable configuration (tube-shell, stack of thin-walled plates, cooling fins, etc.), one or more of the fluid passages may be multi-directional, and the flow arrangement may be a counterflow or other arrangement.

[0068] The hot fluid condenser inlet **230** is in fluid communication with the hot fluid recuperator outlet **218** over the hot gas condenser inlet line. The hot fluid condenser outlet **232** is in fluid communication with the injector **116**. The cold fluid condenser inlet **234** and the cold fluid condenser outlet **236** are in fluid communication with the ambient environment whereby ambient air flows through the low-temperature condenser circuit **228**. By this configuration, the hot ejector gas received from the recuperator **120** flows through the high-temperature condenser circuit **226** while cool air is flowed through the low-temperature condenser circuit **228**. While these flows occur, heat is transferred from the hot ejector gas to the air by an amount sufficient to condense the vaporized working fluid and any condensable components of the exhaust gas. The resulting condensate, including liquid-phase working fluid, is fed to the injector **116** for injection into the boiler **110**.

[0069] Alternatively, a heat exchanging medium other than air (e.g., water, etc.) may be flowed through the low-temperature condenser circuit **228**. The use of ambient air, however, is relatively simple to implement and ambient air serves as an effective heat exchanging medium for many implementations of the heat engine **100**.

[0070] The heat engine **100** may include a tank **240** between the condenser **114** and the injector **116**. The tank **240** includes a tank volume, a tank inlet **244** in fluid communication with the hot fluid condenser outlet **232** over a condensate line, and a tank outlet **246** in fluid communication with the injector **116** over a working fluid liquid line. The tank volume may serve as a reservoir for condensate received from the condenser **114**. The tank volume may also include a liquid-gas separation device (liquid-gas separator) interposed between the tank inlet **244** and the tank outlet **246**. The liquid-gas separation device may be of any suitable known design that functions to separate any non-condensible portion of the fluid received from the condenser from the condensed portion. In some implementations, the liquid-gas separation device may simply be a vent to atmosphere. Also shown is an outlet line **248** for removal or discharge of the non-condensible fluid from the tank **240**.

[0071] The injector **116** includes an injector structure, one or more injector liquid inlets **254**, **256**, and an injector outlet **258**. The injector **116** may have any suitable configuration for injecting liquid-phase working fluid to the boiler **110**. In some implementations, a reservoir is in fluid communication with the injector **116** to provide a supply of working fluid thereto. For example, the tank **240** may serve as the reservoir in which case the tank **240** communicates with the injector liquid inlet **256** over the working fluid liquid line. In some implementations, the injector structure is configured similar to the ejector structure, and thus may include an inlet plenum between a nozzle and a diffuser, either or both of which may include converging and diverging sections. The injector structure may further include a combining (or mixing) cone between the nozzle and the diffuser. The injector structure may be configured as a Giffard-type injector. In these latter cases, the injector may include another injector gas inlet **254** communicating with the nozzle oriented so as to flow gas at an angle to the liquid working fluid received from the tank **240**. The vaporized working fluid outputted from the boiler **110** may be utilized as the motive flow through the injector **116** in the same manner as the ejector **112**. Accordingly, the injector gas inlet **254** may be in fluid communication with the high temperature boiler outlet **188** via another working fluid gas line, whereby the vaporized working fluid is flowed through the injector structure and draws in the liquid working fluid. The injector **116** injects the liquid working fluid (or mixture of liquid working fluid and vaporized working fluid) into the boiler **110** from the injector outlet **258** (which may be done via a diffuser). In implementations providing the recuperator **120**, the working fluid is first fed to the cold fluid recuperator inlet **220** via a recuperator inlet line, is pre-heated by the recuperator **120**, and then is fed to the boiler **110** from the cold fluid recuperator outlet **222** via a boiler inlet line.

[0072] The working fluid generally may be any suitable heat transfer medium that is readily evaporated in the boiler **110** and condensable in the condenser **114**. For instance, the working fluid may be water. In some advantageous implementations, the working fluid is a hydrocarbon fuel such as, for example, ethanol, methanol, kerosene, jet fuel, or RP-8 (kerosene-based rocket fuel, military specification). At the present time, ethanol in particular has been found suitable for the heat engine **100**, particularly in micro-scale implementations. In addition to being utilized as a phase-changing working fluid and as a motive flow for the ejector **112** (and also the injector **116** in some implementations), the ethanol or other hydrocarbon fuel may be utilized as the fuel for combustion. For this purpose, in the illustrated implementation the cold fluid boiler outlet **188** is shown as also being in fluid communication with the fuel inlet **132** of the combustor **102** over a fuel supply line, whereby vaporized fuel is supplied to the combustor **102**. In this manner, the injector **116** is utilized to recycle the unburned fuel that condenses out from the exhaust gas condensibles by running the unburned fuel through the boiler **110** for vaporization and for downstream use as a motive flow, and as the fuel for combustion. Alternatively or additionally, the combustor **102** may also receive a fresh supply of fuel from a reservoir (not shown).

[0073] In some implementations, the ethanol or other hydrocarbon fuel may additionally be utilized as a gas for maintaining gas journal bearings for any of the rotating components (turbocharger **104**, power turbine **108**, or compressor **106**). As an example, bleed lines (not shown) may run from the vaporized working fluid line to gas bearing circuits (not shown) provided in one or more of the rotating components. The design and implementation of gas bearing circuits are generally known to persons skilled in the art. Some examples of gas bearings are described in above-referenced U.S. Pat. No. 6,392,313.

[0074] According to another implementation, a turbocharged locomotive-type heat engine is provided that is similar to that described above and illustrated in FIG. **1**, except that the first recuperator **118** is not provided. Instead, the hot exhaust gas discharged from the power turbine outlet **160** is fed directly to the hot fluid boiler inlet **182** via the power turbine exhaust gas line. Also, the compressed air discharged from the compressor outlet **154** is fed directly to the combustor **102**.

[0075] According to another implementation, a turbocharged locomotive-type heat engine is provided that is similar to that described above and illustrated in FIG. **1**, except that the second recuperator **120** is also not provided. Instead, the vaporized working fluid/exhaust gas mixture discharged from the ejector outlet **198** is fed directly to the hot fluid condenser inlet **230**, and the working fluid discharged from the injector outlet **258** is fed directly to the cold fluid boiler inlet **186**.

[0076] According to another implementation, a turbocharged locomotive-type heat engine is provided that is similar to that described above and illustrated in FIG. **1**, except that the first recuperator **118** is provided while the second recuperator **120** is not provided. Hence, as in the implementation just described the ejector **112** directly feeds the condenser **114** and the injector **116** directly feeds the boiler **110**.

[0077] FIG. **2** is a schematic diagram of an example of a heat engine **290** according to another implementation. The heat engine **290** in this example may be characterized as implementing a naturally aspirated locomotive-type cycle. Thus, a turbocharger and compressor such as described above and illustrated in FIG. **1** are not provided. Instead, the exhaust gas from the combustor **102** is fed directly to the power turbine **108**. The heat engine **290** in this example may otherwise be similar to that of FIG. **1**. In alternative implementations, the heat engine **290** may include a first recuperator **118** and/or second recuperator **120** placed in fluid communication with other operative components in the same manner as described above in conjunction with FIG. **1**.

[0078] FIG. **3** is a schematic diagram of an example of a heat engine **300** according to another implementation. The heat engine **300** in this example may be characterized as implementing a turbocharged locomotive-type cycle. In each of the heat engines (both turbocharged and naturally aspirated) described thus far (FIGS. **1** and **2**), the power turbine **108** is located downstream of the combustor exhaust. By contrast, in the heat engine **300** of FIG. **3**, the turbocharger **104** and power turbine **108** are located immediately upstream of the combustor air inlet **134** and immediately downstream of the recuperator air outlet (i.e., the cold fluid recuperator outlet **174**). In this implementation, the turbocharger **104** discharges air to the combustor air inlet **134** and the exhaust gas produced by the combustor **102** is flowed directly into the high-temperature recuperator circuit **164**. The cold fluid recuperator inlet **172** is in fluid communication with the power turbine outlet **160**, and the cold fluid recuperator outlet **174** is in fluid communication with the turbocharger inlet **142**. The compressor outlet **154** is in fluid communication with the power turbine inlet **158**. By this configuration, the heat transferred from the high-temperature recuperator circuit **164** to the low-temperature recuperator circuit **166** adds energy to the air flowing through the low-temperature recuperator circuit **166**, and this heated air flow drives the turbocharger **104**. In turn, the rotating turbocharger **104** establishes a flow of air into the combustor **102** and also drives the rotation of the compressor **106** via the common spool **146**. In turn, the compressed air outputted by the compressor **106** drives the power turbine **108**. The heat engine **300** in this implementation may otherwise be similar to that of FIG. **1**, and may optionally include the second recuperator **120** in the same manner as described above in conjunction with FIG. **1**.

[0079] One advantage provided by the heat engine **300** is that the power turbine **108** is not in fluid communication or direct structural contact with the turbocharger **104** or any other high-temperature components. That is, the power turbine **108** is thermally isolated from the high-temperature components and high-temperature fluid circuits. Thus, for example, in an implementation where generator magnets are housed in the same rotor as the power turbine **108** for generating electricity, the generator magnets will not experience the high temperatures experienced by the turbocharger **104** that drives the compressor **106**. Thus, higher temperatures may be achieved without a detrimental effect on the generator magnets or other heat-sensitive components. Moreover, a shaft or other mechanical means is not required for transmitting power to the generator rotor from the hot working fluid or combustion gases. The heat engine **300** may also present advantages with system packaging.

[0080] Each of the heat engines described above provides the advantage that the ejector **112** will always cause a pressure drop across the power turbine **108**, even when the turbocharger **104** or other rotating component is stopped or only slowly rotating. This ensures that the cycle will close and produce power even if the individual components have poor efficiency. Moreover, there is always a ready supply of secondary air or other type of gas for bearing pressurization and other such uses, even at zero speed. It will be noted that this advantage also applies to the heat engine **300** depicted in FIG. **3**, in which the ejector **112** drives the power turbine **108** indirectly—i.e., the ejector **112** spins the turbocharger **104**, which in turn drives the compressor **106**, which in turn drives the power turbine **108**. This advantage is particularly manifested during the startup sequence and subsequent low spool speeds. At moderate to higher spool speeds the operation of the compressor **106** will typically be dominant and the operation of the ejector **112** supplemental. Hence, even though the ejector **112** is not in direct fluidic communication with the power turbine **108** in the implementation illustrated in FIG. **3**, the ejector **112** nonetheless contributes to the driving of the power turbine **108**.

[0081] Additionally, as with a steam locomotive each heat engine described above is self starting, requiring only that ignition occur in the combustion chamber and/or that vaporization occur in the boiler **110**. The starting sequence does not require an electric motor to spin the rotors of the rotating components. Instead, in one example of a starting sequence, the boiler **110** is first heated such as by use of a resistive heating element. The resulting vapor produced by the boiler **110** then passes through the ejector **112** and motivates air flow through the combustor **102** and rotating components. By the operation of the ejector **112**, the rotating components begin to function and the combustor **102** begins to operate normally as well. Initiation of fluid flow also initiates the operation of the injector **116**.

[0082] Each of the heat engines described above features mechanical simplicity and a limited number of moving parts. Consequently, the above-described implementations are very attractive at small scales, where fabrication is always the most serious challenge. Generally, any suitable microfabrication techniques (e.g., MEMS, micromachining, etc.) may be utilized to fabricate the various components of the microengine. Various structural materials may be utilized and generally will be suitable for withstanding the pressures and temperatures associated with the operation of the microengine and compatible with microfabrication techniques. A few non-limiting examples of structural materials include metals (e.g., copper, stainless steel, silver, etc.), including transition metals such as zirconium and rhenium, silicon, oxides (e.g., silicon oxide, etc.), nitrides (e.g., silicon nitride, etc.), graphite, carbides (e.g., silicon carbide), ceramics (e.g., quartz, various glasses, etc.), etc.

[0083] FIGS. **4-10** illustrate an example of a micro-scale heat exchanger. In this specific example, the heat exchanger will be referred to as a micro-scale boiler **400** with the understanding that this heat exchanger may be utilized as any other type of heat exchanger (e.g., a recuperator, a condenser, etc.). Accordingly, the term "heat exchanger" may be substituted for the term "boiler" throughout the following description of the boiler **400**. The boiler **400** may be utilized, for example as the boiler in any of the heat engines described above and illustrated in FIGS. **1-3** (when such heat engines are implemented at the micro-scale), or with other heat engines not specifically described herein.

[0084] For reference purposes, FIGS. **4-10** provide three mutually orthogonal axes: a longitudinal axis A passing through the center of the boiler **400**, a first transverse axis B, and a second transverse axis C. The transverse axes B and C lie in a transverse plane B-C orthogonal to the longitudinal axis A. The origin of the three axes A, B and C is not intended to be fixed at any particular position of the boiler **400** in any of FIGS. **4-10**. The term "axis" is used interchangeably with the term "direction". Also for reference purposes, the longitudinal axis A is arbitrarily associated with a "height" (or "depth" or "thickness") of the boiler **400**, the first transverse axis B is arbitrarily associated with a "width" of the boiler **400**, and the second transverse axis C is arbitrarily associated with a "length" of the boiler **400**. Terms such as "radial" and "transverse" will refer to directions along the transverse plane B-C and taken relative to the longitudinal axis A.

[0085] FIG. **4** is a perspective view of the boiler **400**. FIG. **5** is another perspective view of the boiler **400**, but with a pie-shaped section cut-way in the A-B and A-C planes to reveal features along the longitudinal axis A of the boiler **400**. In the present example, the boiler structure includes a boiler body **402** and a plurality of boiler plates **404** (or heat exchanger plates, or hot fluid plates, or hot plates) stacked in series along the longitudinal axis A. Each boiler plate **404** has a thickness in the longitudinal direction A and a planar area in the transverse plane B-C. The boiler body **402** includes a cylindrical core section **406** having a depth along the longitudinal axis A and a diameter in the transverse plane B-C, and a lid or flange section **408** having a diameter in the transverse plane B-C. The diameter of the flange section **408** is greater than that of the core section **406** such that, from the perspective of FIGS. **4** and **5**, the boiler body **402** has the shape of an inverted hat. The core section **406** and the flange section **408** may be integrally formed as a one-piece structure by any suitable (micro)fabrication technique. The boiler plates **404** have the shape of a rectangle or square and thus have a length and a width. The diameter of the flange section **408** is greater than the length and width of the boiler plates **404**. The boiler **400** generally includes an exhaust gas inlet side **410** and an exhaust gas outlet side **412**, or from the perspective of FIGS. **4** and **5**, a bottom side and a top side, respectively. The terms "bottom," "top" and the like are used arbitrarily for reference purposes and not as a limitation on the orientation of the boiler **400** relative to any particular heat engine or other reference object or system. The boiler plates **404** coaxially surround the core section **406** and extend from the exhaust gas inlet side **410** to the underside of the flange section **408**.

[0086] In alternative implementations, the core section **406** and/or the flange section **408** may have a rectilinear shape or some other shape, and the boiler plates **404** may have a circular or cylindrical shape or some other shape. Accordingly, it will be understood that terms such as "length," "width," "diameter" and the like are utilized by way of example only and not as a limitation on the shape of a particular component or structural feature. Any component or structural feature may be considered in more general terms as having a characteristic dimension—i.e., a dominant dimension indicative of the size of the component or structural feature—which, depending on the shape may be appropriately termed a "length," "width," "diameter" or the like.

[0087] FIG. **6** is a plan view of an example of one of the boiler plates **404** at a top side **602** thereof. FIG. **7** is a plan view of the boiler plate **404** at a bottom side **702** thereof. Each boiler plate **404** has a central hole **604** through which the core section **406** extends. Each boiler plate **404** has an inlet hole **606** and an outlet hole **608** formed through the thickness of the boiler plate **404**. The inlet hole **606** and outlet hole **608** are located at respective radial distances from the central hole **604**. A curved transverse channel **502** (or groove, recess, depression, etc.) is formed into the thickness of the boiler plate **404** from the top side **602**, such that the transverse channel **502** is in fluid communication with the inlet hole **606** and the outlet hole **608** and runs coaxially about the central hole **604**. Accordingly, the transverse channel **502** may be characterized as being generally C-shaped or at least including a C-shaped section. When the boiler plates **404** are stacked together, the bottom side **702** of each boiler plate **404** defines the upper boundary of the transverse channel **502** of the boiler plate **404** immediately below. This arrangement is evident, for instance, in FIG. **5** which shows the transverse channels **502** stacked in series along the longitudinal axis A. Each transverse channel **502** provides a curved flow path **610** in the transverse plane B-C for exhaust gas. Thus, the flow path **610** through each transverse channel **502** may be characterized as two-dimensional, multi-directional or circumferential in that it has a flow component along the first transverse axis B and a flow component along the second transverse axis C.

[0088] In operation, exhaust gas enters the transverse channel **502** from the inlet hole **606**, passes through the transverse channel **502** along the curved flow path **610**, exits the outlet hole **608**, and flows through the outlet hole **608** of the next boiler plate **404**. The exhaust gas continues to pass through the outlet holes **608** of additional boiler plates **404**, eventually reaching an exhaust gas outlet **414** (or hot fluid hole, FIGS. **4** and **5**) formed through the flange section **408**. Each transverse channel **502** is proximate to the central hole **604** and thus is in good thermal contact with the core section **406** over a large area. Generally, the term "thermal contact" means that the transverse channels **502** are in close enough proximity to the central hole **604** for effective heat transfer to occur from a hot fluid to a cold fluid, at least by way of heat conduction through the solid material separating the transverse channels **502** from the central hole **604**. In addition, a working fluid (e.g., fuel in some implementations) flows through the core section **406** in the longitudinal direction while the exhaust gas flows through the inlet holes **606**, transverse channels **502** and outlet holes **608** of the boiler plates **404**. In this manner, heat from the exhaust gas is transferred to the working fluid in a large amount and at a large rate, thereby vaporizing the working fluid.

[0089] FIG. **8** is a plan view of the boiler **400** at the bottom side **410** (FIG. **4**). The lowermost boiler plate **404** (i.e., one of the two outermost plates of the stack) is associated with the bottom side **410**. In the present implementation, the inlet hole **606** of the lowermost boiler plate **404** may serve as the exhaust gas inlet into the boiler **400**. This exhaust gas inlet may, for example, correspond to the hot fluid boiler inlet **182** shown in FIGS. **1-3**. In the present implementation, the outlet hole **608** of the lowermost boiler plate **404** is not operational and thus may be blocked or plugged by any means, or may not be present. In some implementations, this outlet hole **608** may be blocked by a wall or other structure of a component abutting the bottom side **410** of the boiler **400**, for example a recuperator, a turbine housing, a combustor, etc.

[0090] An arrow **504** in FIGS. **5** and **8** depicts the flow of working fluid into the core section **406**. A working fluid inlet into the core section **406** is not specifically shown. This working fluid inlet may, for example, correspond to the cold fluid boiler inlet **186** shown in FIGS. **1-3**. As one non-limiting example, after the boiler plates **404** are stacked together (e.g., assembled together, or formed as layers in a microfabrication process), a bore (not shown) may be drilled in a transverse direction from the outside of the stack of boiler plates **404** to the core section **406** to serve as the working fluid inlet. This bore may be drilled or etched through the solid region between the inlet holes **606** and outlet holes **608** of the boiler plates **404**—that is, through the portion of the boiler plates **404** where the transverse channels **502** are not located. In practice, the gap between the inlet hole **606** and outlet hole **608** of each boiler plate **404** may be increased to provide a larger solid region through which the bore is formed.

[0091] Referring to FIGS. **4** and **5**, the exhaust gas outlet **414** (hot fluid hole) formed through the flange section **408** is located so as to be in fluid communication with the outlet hole **608** of the uppermost (outermost) boiler plate **404** just underneath the flange section **408**. This exhaust gas outlet **414** may, for example, correspond to the hot fluid boiler outlet **184** shown in FIGS. **1-3**.

[0092] FIG. **9** is a cross-sectional elevation view of the boiler **400**, where the cross-section is taken along line D in FIG. **5** in the A-B plane. FIG. **9** reveals the cross-section of the exhaust gas outlet **414** and the inlet holes **606** and outlet holes **608** of each boiler plate **404**. As shown in FIGS. **5** and **9**, when the boiler plates **404** are stacked together the outlet holes **608** are aligned in fluid communication with each other to form a cylindrical exhaust gas (hot fluid) outlet plenum **506**. An arrow **508** in FIGS. **5** and **9** depicts the net axial direction of the flow of exhaust gas from the outlet hole **608** of the lowermost boiler plate **404**, through the exhaust gas outlet plenum **506**, and through the exhaust gas outlet **414**. As further shown in FIG. **9**, when the boiler plates **404** are stacked together the inlet holes **606** are likewise aligned in fluid communication with each other to form a cylindrical exhaust gas (hot fluid) inlet plenum **906**. An arrow **908** in FIG. **9** depicts the net axial direction of the flow of exhaust gas from the exhaust gas inlet (e.g., the inlet hole **606** of the lowermost boiler plate **404**), through the exhaust gas inlet plenum **906**, and to the uppermost boiler plate **404** (bounded from above by the flange section **408**). The respective flow paths **908** and **508** through the exhaust gas inlet plenum **906** and the exhaust gas outlet plenum **506** are parallel to each other, both directions being oriented along the longitudinal axis A. However, exhaust gas flowing through the exhaust gas inlet plenum **906** must enter the transverse channel **502** (FIG. **6**) of at least one boiler plate **404** to reach the exhaust gas outlet plenum **506**.

[0093] Thus, in the present implementation the high-temperature boiler circuit and associated exhaust gas (hot fluid) flow path include a three-dimensional network of passages in which multiple turns may be taken. Specifically, the high-temperature boiler circuit and associated exhaust gas flow path run from the exhaust gas inlet (inlet hole **606** of the lowermost boiler plate **404**) and through the exhaust gas inlet plenum **906** along the longitudinal direction A, through one or more of the multiple curved transverse channels **502** along the transverse plane B-C, and through the exhaust gas outlet plenum **506** and the exhaust gas outlet **414** along the longitudinal direction A. There is a net flow of exhaust gas from the exhaust gas inlet (inlet hole **606** of the lowermost boiler plate **404**) to the exhaust gas outlet **414**. In a typical implementation, the net direction of the exhaust gas flow is driven by a pressure differential across the high-temperature boiler circuit, but in other implementations may be additionally or alternatively due to pumping.

[0094] Referring to FIGS. **5**, the core section **406** of the body **402** of the boiler **400** defines a boiler chamber **520** (or cold fluid plenum) in which liquid working fluid is vaporized. The boiler chamber **520** opens at a central working fluid (cold fluid) outlet **420** at the top of the flange section **408**. This working fluid outlet **420** may, for example, correspond to the cold fluid boiler outlet **188** shown in FIGS. **1-3**. In some implementations, the working fluid outlet **420** may be aligned with and adjacent to (or otherwise in fluid communication with) the nozzle of an ejector, or with any other destination desired for the vaporized working fluid. Other passages or outlets may be provided for conducting the vaporized working fluid to other components of a heat engine. For example, as shown in FIGS. **4** and **5**, one or more radial channels **422**, **424** are formed in the flange section **408** and respectively extend outward from the central working fluid outlet **420** to one or more corresponding outer working fluid (cold fluid) outlets **426**, **428**. In practice, the two outer working fluid outlets **426**, **428** may be placed in fluid communication with a combustor, or with one or more other components of a heat engine.

[0095] FIG. **10** is a cross-sectional elevation view of the boiler **400**, where the cross-section is taken along line E in FIG. **4** in the A-B plane. FIG. **10** reveals the cross-section of the central working fluid outlet **420**, the radial channels **422**, **424** and the outer working fluid outlets **426**, **428**. The arrow **504** in FIG. **10** again depicts the flow of working fluid to be vaporized through an inlet bore (not shown) formed through the boiler plates **404**. Another arrow **1004** depicts the flow of working fluid through the boiler chamber **520** and out from the central working fluid outlet **420**. Other arrows **1012**, **1014** depict the flow of vaporized working fluid from the boiler chamber **520** through the radial channels **422**, **424** and to the outer working fluid outlets **426**, **428**. Other arrows **1016**, **1018** depict the flow of vaporized working fluid through the outer working fluid outlets **426**, **428**. These arrows collectively describe the flow paths for working fluid through the low-temperature boiler circuit. By this configuration, working fluid flowing through the boiler chamber **520** along the longitudinal axis A is vaporized due to heat transfer from the exhaust gas flowing through the high-temperature boiler circuit (i.e., the exhaust gas inlet plenum **906**, transverse channels **502** and exhaust gas outlet plenum **506** provided by the stack of boiler plates **404**).

[0096] In one non-limiting example, the overall height of the boiler **400** along the longitudinal axis A (e.g., from the bottom side **410** to the top side **412** ranges from 5 to 10 mm, and the maximum characteristic dimension of the boiler **400** in the transverse plane B-C (e.g., the diameter of the flange section **408**) ranges from 20 to 40 mm. The thickness (in the longitudinal direction) of each boiler plate **404** is generally on the order of micrometers (i.e., ranges from 1 to 999 μm, or 0.001 to 0.999 mm) In one non-limiting example, the thickness of each boiler plate **404** may range from 0.1 to 0.8 mm.

[0097] In the implementation described above, the net axial flow of working fluid through the boiler chamber **520** is illustrated as being in the same direction as the net axial flow of exhaust gas through the exhaust gas inlet plenum **908** and outlet plenum **508**, with the exhaust gas outlet **414** and the working fluid outlet **420** being on the same side of the boiler **400**. It will be appreciated that the net flow of the working fluid through the boiler **400** may alternatively be counter to the net flow of exhaust gas through the boiler **400**. This alternative may be realized, for example, by reversing the roles of the above-referenced "inlet" and "outlet" of either the high-temperature or low-temperature boiler circuit, such as by reversing the direction of fluid flow through either the high-temperature or low-temperature boiler circuit. Thus, in FIGS. **5**, **9** and **10**, the direction of either the flow paths **508**, **908** or the flow paths **504**, **1004** may be reversed.

[0098] It will also be appreciated that the terms "exhaust gas" and "working fluid" are used in the present context by way of example only. More generally, the boiler **400** is configured for flowing a "hot fluid" through the high-temperature boiler circuit and a "cold fluid" through the low-temperature boiler circuit. The hot fluid may be any fluid that is flowed through the boiler **400** at a temperature and pressure (relative to the temperature and pressure of a cold fluid that is simultaneously flowed through the boiler **400**) sufficient for vaporizing or evaporating the cold fluid by heat transferring mechanisms enabled by the boiler structure. Accordingly, exhaust gas is one example of a hot fluid and working fluid is one example of a cold fluid.

[0099] FIGS. **11-18** illustrate another example of a micro-scale heat exchanger. In this specific example, the heat exchanger will be referred to as a micro-scale recuperator **1100** with the understanding that this heat exchanger may be utilized as any other type of heat exchanger (e.g., a boiler, a condenser, etc.). Accordingly, the term "heat exchanger" may be substituted for the term "recuperator" throughout the following description of the recuperator **1100**. The recuperator **1100** may be utilized, for example, as a recuperator in any of the heat engines described above and illustrated in FIGS. **1-3** (when such heat engines are implemented at the micro-scale), or with other heat engines not specifically described herein. For reference purposes, the system of three mutually orthogonal axes A, B and C will again be utilized.

[0100] FIG. **11** is a perspective view of the recuperator **1100**. In the present example, the recuperator structure includes a plurality of recuperator plates stacked in series along the longitudinal axis A. The recuperator plates have the shape of a rectangle or square and thus have a width along the first transverse axis B and a length along the second transverse axis C. Alternatively, the recuperator plates may be circular or cylindrical. In the present example, stack of recuperator plates is an alternating series of recuperator hot plates **1102** (hot fluid plates) and recuperator cold plates **1104** (cold fluid plates). That is, each hot plate **1102** is interposed between two cold plates **1104** and each cold plate **1104** is interposed between two hot plates **1102**. In a case where a hot plate **1102** is the uppermost or lowermost recuperator plate of the stack (i.e., an outermost plate), that hot plate **1102** is positioned immediately adjacent to (above or below) just one cold plate **1104**. Likewise, in a case where a cold plate **1104** is the uppermost or lowermost recuperator plate of the stack, that cold plate **1104** is positioned immediately adjacent to (above or below) just one hot plate **1102**. The recuperator **1100** generally includes a bottom side **1110** and a top side **1112**. The lowermost recuperator plate is associated with the bottom side **1110** and the uppermost recuperator plate is associated with the top side **1112**. The terms "bottom," "top," "lower" and "upper" are used arbitrarily for reference purposes and not as a limitation on the orientation of the recuperator **1100** relative to any particular heat engine or other reference object or system. Each hot plate **1102** and each cold plate **1104** has a thickness in the longitudinal direction A and a planar area in the transverse plane B-C.

[0101] In the present example, the uppermost plate is a lid or cover **1108** that includes a hot fluid outlet **1114**. The hot fluid outlet **1114** is part of the high-temperature recuperator circuit and may, for example, correspond to the hot fluid recuperator outlet **170** or **218** shown in FIGS. **1-3**.

[0102] The hot plates **1102** (and certain holes of the intervening cold plates **1104**) collectively form a high-temperature recuperator circuit through the recuperator **1100**. The cold plates **1104** (and certain holes of the intervening hot plates **1102**) collectively form a low-temperature recuperator circuit through the recuperator **1100**. Each hot plate **1102** provides a flow path for flowing a hot fluid, and each cold plate **1104** provides a flow path for flowing a cold fluid. The hot fluid may be any fluid that is flowed through the recuperator **1100** at a temperature and pressure (relative to the temperature and pressure of a cold fluid that is simultaneously flowed through the recuperator **1100**) effective for transferring heat to the cold fluid by an amount and rate suitable for the heat exchanging function intended for the recuperator **1100** in an associated heat engine. Thus, for example, the hot fluid may be exhaust gas from a combustor or turbine or steam from a boiler, while the cold fluid may be air, fuel, or another type of working fluid. In a typical implementation, the structure of the hot plates **1102** (e.g., position of holes relative to transverse channels, described below) is different from the structure of the cold plates **1104**.

[0103] FIG. **12** is a plan view of an example of one of the hot plates **1102** at a top side **1202** thereof. FIG. **13** is a plan view of the hot plate **1102** at a bottom side **1302** thereof. Each hot plate **1102** has a central hole **1204**, a hot fluid inlet hole **1206** communicating with the central hole **1204**, a hot fluid outlet hole **1208**, a cold fluid inlet hole **1216**, and a cold fluid outlet hole **1218**. The central hole **1204** may surround or form a part of a passage for hot fluid, or may surround or form a part of a hot fluid source (e.g., a combustor). The central hole **1204**, hot fluid outlet hole **1208**, cold fluid inlet hole **1216** and cold fluid outlet hole **1218** are formed through the thickness of the hot plate **1102**. The hot fluid outlet hole **1208**, cold fluid inlet hole **1216** and cold fluid outlet hole **1218** are located at respective radial distances from the central hole **1204**. In the present implementation, the hot fluid outlet hole **1208** may be positioned axially between the cold fluid inlet hole **1216** and cold fluid outlet hole **1218** along the first transverse axis B.

[0104] Each hot plate **1102** also includes a curved transverse channel **1212** (or groove, recess, depression, etc.) formed into the thickness of the hot plate **1102** from the top side such that the transverse channel **1212** is in fluid communication with the hot fluid inlet hole **1206** and the hot fluid outlet hole **1208** and runs coaxially about the central hole **1204**. Accordingly, the transverse channel **1212** may be characterized as being generally C-shaped or at least including a C-shaped section. When the hot plates **1102** and cold plates **1104** are stacked together in alternating series, the bottom side of a cold plate **1104** defines the upper boundary of the transverse channel **1212** and hot fluid inlet hole **1206** of the underlying hot plate **1102**. The hot fluid inlet hole **1206** is oriented generally orthogonal to the central hole **1204** and provides an inlet for hot fluid from the central hole **1204** into the transverse channel **1212**. Each transverse channel **1212** provides a curved flow path **1210** in the transverse plane B-C for hot fluid. Thus, the flow path **1210** through each transverse channel **1212** may be characterized as two-dimensional, multi-directional or circumferential in that it has a flow component along the first transverse axis B and a flow component along the second transverse axis C. The flow path **1210** may also be characterized as being generally spiral-shaped in that the hot fluid enters the transverse channel **1212** from the central hole **1204** via the hot fluid inlet hole **1206**, runs radially outward and then follows a curved path to the hot fluid outlet hole **1208** located at a radial distance from the central hole **1204**.

[0105] In operation, the hot fluid exiting the hot fluid outlet hole **1208** flows passes through a hot fluid outlet hole **1408** (FIGS. **14** and **15**) of an adjacent cold plate **1104** and then through the hot fluid outlet hole **1208** of the next succeeding hot plate **1102**. The hot fluid continues to pass through additional hot fluid outlet holes **1208**, **1408** of alternating hot plates **1102** and cold plates **1104**, eventually reaching the hot fluid outlet **1114** of the lid **1108** (FIG. **11**). Each transverse channel **1212** is proximate to the transverse channels **1412** (FIG. **14**) through which cold fluid flows in the cold plate(s) **1104** positioned immediately above and/or below each hot plate **1102**. Consequently, the hot fluid flowing through each transverse channel **1212** is in good thermal contact with the cold fluid flowing through the transverse channels **1412** of each adjacent cold plate **1104**. That is, each transverse channel **1212** is in close proximity to each adjacent transverse channels **1412** whereby effective heat transfer occurs from the hot fluid to the cold fluid via heat conduction through the solid material separating the transverse channel **1212** from the adjacent transverse channels **1412**. The cold fluid inlet hole **1216** of the hot plate **1102** conducts cold fluid through the thickness of the hot plate **1102** from the cold plate **1104** located immediately adjacent to the hot plate **1102** on one side thereof to the cold plate **1104** located immediately adjacent to the hot plate **1102** on the other side thereof. Likewise, the cold fluid outlet hole **1218** conducts cold fluid through the thickness of the hot plate **1102** from one cold plate **1104** to the opposite cold plate **1104**.

[0106] FIG. **14** is a plan view of an example of one of the cold plates **1104** at a top side **1402** thereof. FIG. **15** is a plan view of the cold plate **1104** at a bottom side **1502** thereof. Each cold plate **1104** has a central hole **1404** through which hot fluid flows (as in the case of each hot plate **1102**), a hot fluid outlet hole **1408**, a cold fluid inlet hole **1416**, and a cold fluid outlet hole **1418**. The central hole **1404**, hot fluid outlet hole **1408**, cold fluid inlet hole **1416** and cold fluid outlet hole **1418** are formed through the thickness of the cold plate **1104**. The hot fluid outlet hole **1408**, cold fluid inlet hole **1416** and cold fluid outlet hole **1418** are located at respective radial distances from the central hole **1404**. When the hot plates **1102** and cold plates **1104** are stacked together to form the recuperator **1100**, the central holes **1404**, hot fluid outlet holes **1408**, cold fluid inlet holes **1416** and cold fluid outlet holes **1418** of the cold plates **1104** are respectively axially aligned with the central holes **1204**, hot fluid outlet holes **1208**, cold fluid inlet holes **1216** and cold fluid outlet holes **1218** of the hot plates **1102**. A curved transverse channel **1412** (or groove, recess, depression, etc.) is formed into the thickness of the cold plate **1104** from the top side **1402** such that the transverse channel **1412** is in fluid communication with the cold fluid inlet hole **1416** and the cold fluid outlet hole **1418** and runs coaxially about the central hole **1404**. Accordingly, the transverse channel **1412** may be characterized as being generally C-shaped or at least including a C-shaped section. When the hot plates **1102** and cold plates **1104** are stacked together in alternating series, the bottom side **1302** (FIG. **13**) of a hot plate **1102** defines the upper boundary of the transverse channel **1412** of the underlying cold plate **1104**. As in the case of the hot plates **1102**, each transverse channel **1412** of the cold plates **1104** provides a curved (two-dimensional, multi-directional or circumferential) flow path **1410** in the transverse plane B-C for cold fluid, with a flow component along the first transverse axis B and a flow component along the second transverse axis C.

[0107] In operation, cold fluid enters the transverse channel **1412** from the cold fluid inlet hole **1416** and follows the curved flow path **1410** through the transverse channel **1412** to the cold fluid outlet hole **1418**. Cold fluid exiting the cold fluid outlet hole **1418** passes through the cold fluid outlet hole **1218** (FIGS. **12** and **13**) of an adjacent hot plate **1102** and then through the cold fluid outlet hole **1418** of the next succeeding cold plate **1104**. The cold fluid continues to pass through additional cold fluid outlet holes **1218**, **1418** of alternating hot plates **1102** and cold plates **1104**, eventually reaching the cold fluid outlet **1120** of the lid **1108** (FIG. **11**). As cold fluid flows through the transverse channel **1412** of a given cold plate **1104** it picks up heat from the hot fluid flowing through the transverse channel(s) **1212** of the adjacent hot plate(s) **1102** (i.e., located above and/or below the cold plate **1104**). The central hole **1404** of the cold plate **1104** conducts hot fluid through the thickness of the cold plate **1104** from the hot plate **1102** located immediately adjacent to the cold plate **1104** on one side thereof to the hot plate **1102** located immediately adjacent to the cold plate **1104** on the other side thereof. Likewise, the hot fluid outlet hole **1408** conducts hot fluid through the thickness of the cold plate **1104** from one hot plate **1102** to the opposite hot plate **1102**.

[0108] FIG. **16** is a cross-sectional perspective view of the recuperator **1100**, where the cross-section is taken along line F in FIG. **11** in the A-B plane. FIG. **16** reveals the cross-section of the central holes **1204**, **1404** of the hot plates **1102** and cold plates **1104**. When the hot plates **1102** and cold plates **1104** are stacked together in alternating series, the central holes **1204**, **1404** are aligned in fluid communication with each other to form a cylindrical hot fluid inlet plenum **1606**. An arrow **1608** in FIG. **16** depicts the net axial direction of the flow of hot fluid through the hot fluid inlet plenum **1606**. The central hole **1204** or **1404** of the lowermost hot plate **1102** or cold plate **1104** may serve as a hot fluid inlet into the recuperator **1100**. This hot fluid inlet may, for example, correspond to the hot fluid recuperator inlet **168** or **216** shown in FIG. **1**. Also shown in FIG. **16** are the individual hot fluid inlet holes **1206** into the respective transverse channels **1212** of the hot plates **1102**, which are oriented transversely to the hot fluid inlet plenum **1606**. Hot fluid flowing through the hot fluid inlet plenum **1606** may enter any one of the hot fluid inlet holes **1206** along a transverse flow path **1622** and then flow along a curved path as described above in conjunction with FIG. **12**.

[0109] FIG. **17** is a cross-sectional elevation view of the recuperator **1100**, where the cross-section is taken along line G in FIG. **11** in the A-B plane. FIG. **17** reveals the cross-section of the hot fluid outlet holes **1208**, **1408** of the hot plates **1102** and cold plates **1104**. When the hot plates **1102** and cold plates **1104** are stacked together in alternating series, the hot fluid outlet holes **1208**, **1408** are aligned in fluid communication with each other to form a cylindrical hot fluid outlet plenum **1706**. An arrow **1708** in FIG. **17** depicts the net axial direction of the flow of hot fluid through the hot fluid outlet plenum **1706**. The hot fluid outlet hole **1208** or **1408** of the uppermost hot plate **1102** or cold plate **1104** may serve as a hot fluid outlet from the recuperator **1100** or, as noted above, a lid **1108** may provide the hot fluid outlet **1114**. This hot fluid outlet **1114** may, for example, correspond to the hot fluid recuperator outlet **170** or **218** shown in FIG. **1**. The respective flow paths **1608**, **1708** through the hot fluid inlet plenum **1606** and the hot fluid outlet plenum **1706** are parallel to each other, both directions being oriented along the longitudinal axis A. However, like in the case of the boiler **400** described above and illustrated in FIGS. **4-10**, hot fluid flowing through the hot fluid inlet plenum **1606** must enter the transverse channel **1212** of at least one hot plate **1102** to reach the hot fluid outlet plenum **1706**.

[0110] Thus, in the present implementation the high-temperature recuperator circuit and associated hot fluid flow path include a three-dimensional network of passages in which multiple turns may be taken. Specifically, the high-temperature recuperator circuit and associated hot fluid flow path run from the hot fluid inlet (hot fluid inlet hole **1204** or **1404** of the lowermost hot plate **1102** or cold plate **1104**) and through the hot fluid inlet plenum **1606** along the longitudinal direction A, through one or more of the multiple curved transverse channels **1212** along the transverse plane B-C, and through the hot fluid outlet plenum **1706** and the hot fluid outlet **1114** (or, alternatively, the hot fluid outlet hole **1208** or **1408** of the uppermost hot plate **1102** or cold plate **1104** if the lid **1108** is not provided) along the longitudinal direction A. There is a net flow of hot fluid from the hot fluid inlet to the hot fluid outlet **1114** of the recuperator **1100**. In a typical implementation, the net direction of the hot fluid flow is driven by a pressure differential across the high-temperature recuperator circuit, but in other implementations may be additionally or alternatively due to pumping.

[0111] FIG. **18** is a cross-sectional elevation view of the recuperator **1100**, where the cross-section is taken along line H in FIG. **11** in the A-B plane. FIG. **18** reveals the cross-section of the cold fluid inlet holes **1216**, **1416** of the hot plates **1102** and cold plates **1104**. When the hot plates **1102** and cold plates **1104** are stacked together in alternating series, the cold fluid inlet holes **1216**, **1416** are aligned in fluid communication with each other to form a cylindrical cold fluid inlet plenum **1806**. An arrow **1808** in FIG. **18** depicts the net axial direction of the flow of cold fluid through the cold fluid inlet plenum **1806**. The cold fluid inlet hole **1216** or **1416** of the lowermost hot plate **1102** or cold plate **1104** may serve as a cold fluid inlet into the recuperator **1100**. This cold fluid inlet may, for example, correspond to the cold fluid recuperator inlet **172** or **220** shown in FIG. **1**. Alternatively, a lid (not shown) may be located under the lowermost hot plate **1102** or cold plate **1104** to provide the cold fluid inlet.

[0112] Referring back to FIG. **17**, FIG. **17** also reveals the cross-section of the cold fluid outlet holes **1218**, **1418** of the hot plates **1102** and cold plates **1104**. When the hot plates

1102 and cold plates 1104 are stacked together in alternating series, the cold fluid outlet holes 1218, 1418 are aligned in fluid communication with each other to form a cylindrical cold fluid outlet plenum 1716. An arrow 1718 in FIG. 17 depicts the net axial direction of the flow of cold fluid through the cold fluid outlet plenum 1716. The cold fluid outlet hole 1218 or 1418 of the lowermost hot plate 1102 or cold plate 1104 may serve as a cold fluid outlet from the recuperator 1100. This cold fluid outlet may, for example, correspond to the cold fluid recuperator outlet 174 or 222 shown in FIG. 1. Alternatively, a lid (not shown) may be located under the lowermost hot plate 1102 or cold plate 1104 to provide the cold fluid outlet. The respective flow paths 1808 and 1718 through the cold fluid inlet plenum 1806 and the cold fluid outlet plenum 1716 are parallel to each other, both directions being oriented along the longitudinal axis A. However, like in the case of the hot fluid flowing through the recuperator 1100, the cold fluid flowing through the cold fluid inlet plenum 1806 must enter the transverse channel 1412 of at least one cold plate 1104 to reach the cold fluid outlet plenum 1716.

[0113] Thus, like the high-temperature recuperator circuit, in the present implementation the low-temperature recuperator circuit and associated cold fluid flow path include a three-dimensional network of passages in which multiple turns may be taken. Specifically, the low-temperature recuperator circuit and associated cold fluid flow path run from the cold fluid inlet (cold fluid inlet hole 1216 or 1416 of the lowermost hot plate 1102 or cold plate 1104) and through the cold fluid inlet plenum 1806 along the longitudinal direction A, through one or more of the multiple curved transverse channels 1412 along the transverse plane B-C, and through the cold fluid outlet plenum 1716 and the cold fluid outlet along the longitudinal direction A. As noted above, the cold fluid outlet may be the cold fluid outlet hole 1218 or 1418 of the lowermost hot plate 1102 or cold plate 1104 if a lid is not provided. There is a net flow of cold fluid from the cold fluid inlet to the cold fluid outlet of the recuperator 1100. In a typical implementation, the net direction of the cold fluid flow is driven by a pressure differential across the low-temperature recuperator circuit, but in other implementations may be additionally or alternatively due to pumping.

[0114] In one non-limiting example, the overall height of the recuperator 1100 along the longitudinal axis A (e.g., from the bottom side 1110 to the top side 1112 ranges from 20 to 25 mm, and the maximum characteristic dimension (e.g., length or width) of the recuperator 1100 in the transverse plane B-C ranges from 20 to 25 mm. The thickness (in the longitudinal direction) of each hot plate 1102 and/or cold plate 1104 is generally on the order of micrometers (i.e., ranges from 1 to 999 μm, or 0.001 to 0.999 mm). In one non-limiting example, the thickness of each hot plate 1102 and/or cold plate 1104 may range from 0.05 to 0.25 mm.

[0115] In the implementation described above, the net axial flow of cold fluid through the cold fluid inlet plenum 1806 is illustrated as being in the opposite direction as the net axial flow of cold fluid through the cold fluid outlet plenum 1716, with the cold fluid inlet and the cold fluid outlet being on the same side of the recuperator 1100. It will be appreciated that the net flow of the cold fluid through the cold fluid inlet plenum 1806 may alternatively be in the same direction as the net flow of cold fluid through the cold fluid outlet plenum 1716. This alternative may be realized, for example, by appropriately relocating the cold fluid inlet and cold fluid outlet to opposite sides of the recuperator 1100 and modifying any upper or lower lids provided. Thus, in FIGS. 16-18 the direction of the cold fluid flow paths 1808, 1718 may alternatively be the same. Moreover, the direction of the cold fluid flow paths 1808, 1718 may be either the same as or opposite to the direction of the hot fluid flow paths 1608, 1708.

[0116] Heat exchangers such as described by example above (boiler 400 and recuperator 1100) are well-suited for micro-scale implementation. These heat exchangers are configured so as to allow a designer to control the dimensions of the plenums or headers and to control the length-to-diameter (or hydraulic diameter) ratio (or aspect ratio) of the transverse channels 1212, 1412. These heat exchangers thus allow the designer to package the required dimensions and length-to-diameter ratio within a given volume constraint. For example, if the heat exchanger (or its associated engine or system) is specified to have a maximum external diameter and length, the designer may control the length of the circumferential flow paths by adjustment of the dimensions of the associated plenums. Moreover, by controlling the length-to-diameter ratio and the quantity of the transverse channels 1212, 1412, the designer can allow the flow of fluid via the inlet plenums into any tier of the heat exchanger stack.

[0117] FIG. 19 is a perspective view of an example of a micro-scale combustor 1900. In the present implementation, the combustor 1900 is configured to be assembled or fabricated with the above-described recuperator 1100. The combustor 1900 may include a base 1908 and a housing 1914 extending from the base 1908 along the longitudinal axis A. Depending on the fabrication technique utilized, the housing 1914 may be supported or mounted on the base 1908 or may be integrated with the base 1908. The housing 1914 encloses an interior in which combustion occurs. An ignition device (not shown) may be positioned in the interior for initializing and maintaining a fuel-air combustion reaction. The housing 1914 may include one or more inlets for fuel and air and one or more outlets for exhaust gas. In the present implementation, the housing 1914 is a cylindrical structure that includes a closed axial end at the base 1908 and an opposite open axial end 1920 that serves as a combustor inlet for admitting fuel and air. The housing 1914 further includes an elongated opening 1922 extending along the longitudinal axis A. As illustrated, the edges of the housing 1914 defining the elongated opening 1922 may be configured such that the elongated opening 1922 has a depth in a radial direction whereby the flow of exhaust gas is directed in the transverse plate B-C. The elongated opening 1922 may serve as a hot fluid plenum between the interior of the housing 1914 and the hot fluid inlet holes 1206 of the recuperator 1100 (FIG. 16). The combustor 1900 may further include an annular gap 1904 between the base 1908 and the housing 1914 that at least partially surrounds the housing 1914. The gap 1904 may be utilized for conducting a fluid during the operation of an associated heat engine. One or more holes 1916, 1918 may be formed through the base 1908 for conducting other fluids. For example, the hole 1916 may conduct cold fluid to the recuperator 1100 and the hole 1918 may conduct (heated) cold fluid from the recuperator 1100.

[0118] FIG. 20 is a cross-sectional perspective view of a portion of an example of a micro-scale heat engine 2000 in which the combustor 1900 and the recuperator 1100 of the above examples have been assembled or fabricated together, where the cross-section is taken in the transverse plane B-C. In this example, the combustor 1900 and the recuperator 1100 are disposed in a structure 2002 of the heat engine 2000. The combustor housing **1914** is coaxially surrounded by the central holes of the hot fluid and cold fluid plates of the recuperator **1100**. In the cross-sectional view of FIG. **20**, only the central hole **1204** of one hot fluid plate **1102** is shown. The outside diameter of the combustor housing **1914** is less than the inside diameter of the central holes. The elongated opening **1922** of the combustor housing **1914** is aligned with the hot fluid inlet holes **1206** of the hot fluid plates **1102**, thereby defining a hot fluid inlet plenum through which exhaust gas produced in the interior of the combustor housing **1914** flows into the transverse channels **1212** of the hot fluid plates **1102** along transverse flow paths **1622**.

[0119] FIG. **21** is a cross-sectional elevation view of a portion of the heat engine **2000** in which the combustor **1900**, recuperator **1100**, and boiler **400** of the above examples, and an ejector **2110**, have been assembled or fabricated together. The heat engine **2000** may be configured in accordance with any of the heat engines schematically illustrated in FIGS. **1-3**, or as any other heat engine. The structure **2002** of the heat engine **2000** may include a base plate **2114** that includes one or more plenums, holes or the like for conducting fluids to and/or from various components of the heat engine **2000**. For instance, rotating components (e.g., power turbine, turbocharger, compressor, etc., not shown) may be located below the base plate **2114** and transmit or receive air or exhaust gas via passages of the base plate **2114**. In the present implementation, the ejector **2110** includes a nozzle **2122** that receives vaporized working fluid from the boiler chamber **520**, a hot fluid (exhaust gas) inlet plenum **2126** that receives exhaust gas from the boiler plates **404** via one or more passages (not shown), and a diffuser **2130** for outputting the mixture of working fluid and exhaust gas to a downstream component (e.g., a condenser, another recuperator, etc.).

[0120] In the present implementation, the diffuser **2130** includes a converging section **2132** followed by a diverging section **2134**. The nozzle **2122** includes a nozzle bore **2138** that may also include a converging section and a diverging section (not shown). In operation the vaporized working fluid flows as a jet through the centerline of the ejector **2110**, serving as the high-velocity primary flow (or motive flow) through the ejector **2110**. The exhaust gas introduced into the inlet plenum **2126** flows radially inward toward the flow of vaporized working fluid, serving as a quiescent or low-velocity flow. The motive jet of vaporized working fluid entrains the surrounding exhaust gas by viscous interaction and exchanges momentum with the exhaust gas. Mixing of the two fluids proceeds in the converging section **2132** of the diffuser **2130**, and the resulting mixed fluid flow expands in the diverging section **2134**.

[0121] FIG. **22** is a schematic view of an example of an injector **2216** that may be utilized in any of the heat engines described herein. The injector **2216** includes a motive nozzle **2222**, an inlet plenum **2226**, and a diffuser **2234**. In the present example, the injector **2216** also includes a combining (or mixing) cone **2232** interposed between the nozzle **2222** and the diffuser **2234**. As illustrated, the nozzle **2222** and/or the diffuser **2234** may include both converging and diverging sections. In some implementations, vaporized working fluid serves as the motive flow and liquid-phase working fluid serves as a nearly quiescent suction flow. The vaporized working fluid may be provided from a boiler over a fluid line **2254** and the liquid-phase working fluid may be provided from a condenser over a fluid line **2258**. In operation, the vaporized working fluid is accelerated to a high velocity by the nozzle **2222** and entrains the liquid-phase working fluid flowing into the inlet plenum **2226**. Mixing of the two fluids proceeds in the combining cone **2232**, where the vaporized working fluid may become fully condensed. The resulting high-momentum mixed fluid flow is decelerated in the diffuser **2234** to recover the dynamic head as static pressure, and is discharged into an outlet line **2258**. The mixed fluid flow may be discharged from the injector **2216** at a higher pressure than the pressure at which the vaporized working fluid is inputted to the nozzle **2222**. In some implementations, the injector **2216** supplies the mixed fluid flow to a boiler as described above.

[0122] In general, terms such as "communicate" and "in . . . communication with" (for example, a first component "communicates with" or "is in communication with" a second component) are used herein to indicate a structural, functional, mechanical, electrical, signal, optical, magnetic, electromagnetic, ionic or fluidic relationship between two or more components or elements. As such, the fact that one component is said to communicate with a second component is not intended to exclude the possibility that additional components may be present between, and/or operatively associated or engaged with, the first and second components.

[0123] For purposes of the present disclosure, it will be understood that when a layer (or film, region, substrate, component, device, or the like) is referred to as being "on" or "over" another layer, that layer may be directly or actually on (or over) the other layer or, alternatively, intervening layers (e.g., buffer layers, transition layers, interlayers, sacrificial layers, etch-stop layers, masks, electrodes, interconnects, contacts, or the like) may also be present. A layer that is "directly on" another layer means that no intervening layer is present, unless otherwise indicated. It will also be understood that when a layer is referred to as being "on" (or "over") another layer, that layer may cover the entire surface of the other layer or only a portion of the other layer. It will be further understood that terms such as "formed on" or "disposed on" are not intended to introduce any limitations relating to particular methods of material transport, deposition, fabrication, surface treatment, or physical, chemical, or ionic bonding or interaction. The term "interposed" is interpreted in a similar manner.

[0124] It will be understood that various aspects or details of the invention may be changed without departing from the scope of the invention. Furthermore, the foregoing description is for the purpose of illustration only, and not for the purpose of limitation—the invention being defined by the claims.

What is claimed is:

1. A heat engine, comprising:

a combustor comprising a fuel inlet, an air inlet and an exhaust outlet;

a power turbine communicating with the exhaust outlet, wherein the power turbine is driven to rotate by exhaust gas from the combustor;

a boiler comprising a high-temperature boiler circuit in thermal contact with a low-temperature boiler circuit for transferring heat thereto, the high-temperature boiler circuit communicating with the power turbine for receiving exhaust gas therefrom;

an ejector comprising a first ejector inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, a second ejector inlet communicating with the high-temperature boiler circuit for receiving exhaust gas therefrom, and an ejector outlet, wherein the ejector is configured for entraining the exhaust gas from the second ejector inlet in the flow of vaporized working fluid from the first ejector inlet and increasing a pressure drop across the power turbine;

a condenser comprising a high-temperature condenser circuit in thermal contact with a low-temperature condenser circuit for transferring heat thereto, the high-temperature condenser circuit communicating with the ejector outlet, wherein the low-temperature condenser circuit is configured for flowing a cold fluid through the condenser; and

an injector comprising an injector liquid inlet communicating with the high-temperature condenser circuit for receiving condensed working fluid therefrom, and an injector outlet communicating with the low-temperature boiler circuit, wherein the injector is configured for flowing liquid-phase working fluid to the boiler.

2. The heat engine of claim **1**, wherein the injector comprises an injector gas inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, and the injector is configured for entraining condensed working fluid from the injector liquid inlet in the flow of vaporized working fluid from the injector gas inlet.

3. The heat engine of claim **1**, comprising a tank interposed between the hot fluid condenser outlet and the injector liquid inlet, the tank comprising a liquid/gas separator wherein the tank is configured for separating uncondensed components from condensed working fluid received from the condenser and feeding the condensed working fluid to the injector.

4. The heat engine of claim **1**, wherein the low-temperature boiler circuit communicates with the fuel inlet for feeding vaporized working fluid as a fuel to the combustor,

5. The heat engine of claim **1**, comprising a recuperator comprising a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto, the high-temperature recuperator circuit interposed between the power turbine and the high-temperature boiler circuit, and the low-temperature recuperator circuit disposed in upstream fluid communication with the air inlet, wherein the recuperator is configured for pre-heating air fed to the combustor.

6. The heat engine of claim **1**, comprising a recuperator comprising a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto, the high-temperature recuperator circuit interposed between the ejector outlet and the high-temperature condenser circuit, and the low-temperature recuperator circuit interposed between the injector outlet and the low-temperature boiler circuit, wherein the recuperator is configured for pre-heating the working fluid fed to the boiler.

7. The heat engine of claim **1**, comprising:

a first recuperator comprising a high-temperature first recuperator circuit in thermal contact with a low-temperature first recuperator circuit for transferring heat thereto, the high-temperature first recuperator circuit interposed between the power turbine and the high-temperature boiler circuit, and the low-temperature recuperator circuit disposed in upstream fluid communication with the air inlet, wherein the first recuperator is configured for pre-heating the compressed air fed to the combustor; and

a second recuperator comprising a high-temperature second recuperator circuit in thermal contact with a low-temperature second recuperator circuit for transferring heat thereto, the high-temperature second recuperator circuit interposed between the ejector outlet and the high-temperature condenser circuit, and the low-temperature second recuperator circuit interposed between the injector outlet and the low-temperature boiler circuit, wherein the second recuperator is configured for pre-heating the working fluid fed to the boiler.

8. The heat engine of claim **1**, comprising:

a turbocharger rotatable about a spool and communicating with the exhaust outlet, wherein the turbocharger is driven to rotate by exhaust gas from the combustor, and the power turbine comprises a turbine inlet communicating with the turbocharger and is driven to rotate by exhaust gas from the turbocharger; and

a compressor rotatable about the spool wherein the compressor is driven to rotate by the turbocharger, the compressor comprising a compressor inlet for aspirating ambient air, and a compressor outlet communicating with the air inlet wherein the compressor feeds compressed air to the combustor.

9. A heat engine, comprising:

a combustor comprising a fuel inlet, an air inlet and an exhaust outlet;

a turbocharger rotatable about a spool and communicating with the air inlet wherein the turbocharger feeds air to the combustor;

a compressor rotatable about the spool wherein the compressor is driven to rotate by the turbocharger, the compressor comprising a compressor inlet for aspirating ambient air;

a power turbine communicating with the compressor wherein the power turbine is driven to rotate by compressed air from the compressor;

a recuperator comprising a high-temperature recuperator circuit in thermal contact with a low-temperature recuperator circuit for transferring heat thereto, the high-temperature recuperator circuit communicating with the exhaust outlet, and the low-temperature recuperator circuit interposed between the power turbine and the turbocharger, wherein the turbocharger is driven to rotate by heated air from the recuperator;

a boiler comprising a high-temperature boiler circuit in thermal contact with a low-temperature boiler circuit for transferring heat thereto, the high-temperature boiler circuit communicating with the high-temperature recuperator circuit for receiving exhaust gas therefrom;

an ejector comprising a first ejector inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, a second ejector inlet communicating with the high-temperature boiler circuit for receiving exhaust gas therefrom, and an ejector outlet, wherein the ejector is configured for entraining the exhaust gas from the second ejector inlet in the flow of vaporized working fluid from the first ejector inlet and increasing a pressure drop across the power turbine;

a condenser comprising a high-temperature condenser circuit in thermal contact with a low-temperature condenser circuit for transferring heat thereto, the high-temperature condenser circuit communicating with the ejector outlet, wherein the low-temperature condenser circuit is configured for flowing a cold fluid through the condenser; and

an injector comprising an injector liquid inlet communicating with the high-temperature condenser circuit for receiving condensed working fluid therefrom, and an injector outlet communicating with the low-temperature boiler circuit, wherein the injector is configured for flowing liquid-phase working fluid to the boiler.

10. The heat engine of claim **9**, wherein the injector comprises an injector gas inlet communicating with the low-temperature boiler circuit for receiving a flow of vaporized working fluid therefrom, and the injector is configured for entraining condensed working fluid from the injector liquid inlet in the flow of vaporized working fluid from the injector gas inlet.

11. The heat engine of claim **10**, comprising a tank interposed between the hot fluid condenser outlet and the injector liquid inlet, the tank comprising a liquid/gas separator wherein the tank is configured for separating uncondensed components from condensed working fluid received from the condenser and feeding the condensed working fluid to the injector.

12. The heat engine of claim **9**, wherein the low-temperature boiler circuit communicates with the fuel inlet for feeding vaporized working fluid as a fuel to the combustor.

13. The heat engine of claim **9**, wherein the recuperator communicating with the turbocharger is a first recuperator, and further comprising a second recuperator, the second recuperator comprising a high-temperature second recuperator circuit in thermal contact with a low-temperature second recuperator circuit for transferring heat thereto, the high-temperature second recuperator circuit interposed between the ejector outlet and the high-temperature condenser circuit, and the low-temperature second recuperator circuit interposed between the injector outlet and the low-temperature boiler circuit, wherein the second recuperator is configured for pre-heating the working fluid fed to the boiler.

14. A method for generating power, the method comprising:

flowing an exhaust gas comprising combustion products from a power turbine to a boiler;

vaporizing a working fluid by flowing the working fluid through the boiler while flowing the exhaust gas through the boiler, wherein heat is transferred from the exhaust gas to the working fluid;

flowing the vaporized working fluid through an ejector;

entraining the exhaust gas in the vaporized working fluid as the vaporized working fluid flows through the ejector by flowing the exhaust gas from the boiler into the ejector, wherein entrainment of the exhaust gas creates suction downstream of the power turbine;

condensing the working fluid discharged from the ejector and returning the condensed working fluid to the boiler for vaporization by the exhaust gas flowing through the boiler; and

driving the power turbine to rotate by flowing the exhaust gas to the turbine from a combustor disposed upstream of the power turbine, and by creating the suction in the exhaust gas downstream of the power turbine.

15. The method of claim **14**, comprising flowing the exhaust gas from the power turbine through a recuperator before flowing the exhaust gas to the boiler, and flowing air through the recuperator wherein heat is transferred from the exhaust gas to the air, and feeding the heated air to the combustor for combustion with a fuel.

16. The method of claim **14**, comprising flowing the working fluid from the ejector through a recuperator before condensing the working fluid, and flowing the condensed working fluid through the recuperator before returning the condensed working fluid to the boiler, wherein the recuperator transfers heat from the working fluid discharged from the ejector to the condensed working fluid flowing through the recuperator, and the heated condensed working fluid is flowed to the boiler for vaporization.

17. The method of claim **14**, comprising:

flowing the exhaust gas from the power turbine through a first recuperator before flowing the exhaust gas to the boiler, and flowing air through the first recuperator wherein heat is transferred from the exhaust gas to the air, and feeding the heated air to the combustor for combustion with a fuel; and

flowing the working fluid from the ejector through a second recuperator before condensing the working fluid, and flowing the condensed working fluid through the second recuperator before returning the condensed working fluid to the boiler, wherein the second recuperator transfers heat from the working fluid discharged from the ejector to the condensed working fluid flowing through the second recuperator, and the heated condensed working fluid is flowed to the boiler for vaporization.

18. The method of claim **14**, wherein a turbocharger is interposed between the combustor and the power turbine and a compressor is rotatable on a common spool with the turbocharger, and comprising driving the turbocharger and the compressor to rotate by flowing the exhaust gas from the combustor to the turbocharger, wherein the power turbine is driven by exhaust gas discharged from the turbocharger, and feeding compressed air from the compressor to the combustor for combustion with a fuel.

19. The method of claim **14**, wherein returning the condensed working fluid to the boiler comprises flowing vaporized working fluid from the boiler through an injector, entraining the condensed working fluid in the vaporized working fluid as the vaporized working fluid flows through the injector by flowing the condensed working fluid into the injector, and flowing the condensed working fluid from the injector into the boiler.

20. The method of claim **14**, wherein the working fluid is a hydrocarbon fuel.

21. The method of claim **20**, comprising flowing vaporized working fluid from the boiler to the combustor to supply the combustor with fuel for combustion with air.

22. A method for generating power, comprising:

flowing an exhaust gas comprising combustion products from a combustor to a recuperator;

while flowing the exhaust gas through the recuperator, flowing air discharged from a power turbine through the recuperator wherein heat is transferred from the exhaust gas to the air;

flowing the exhaust gas from the recuperator to a boiler;

vaporizing a working fluid by flowing the working fluid through the boiler while flowing the exhaust gas through the boiler, wherein heat is transferred from the exhaust gas to the working fluid;

flowing the vaporized working fluid through an ejector;

entraining the exhaust gas in the vaporized working fluid as the vaporized working fluid flows through the ejector by flowing the exhaust gas from the boiler into the ejector, wherein entrainment of the exhaust gas creates suction downstream of the power turbine;

condensing the working fluid discharged from the ejector and returning the condensed working fluid to the boiler for vaporization by the exhaust gas flowing through the boiler; and

driving a turbocharger and a compressor to rotate by flowing the heated air from the recuperator to the turbocharger, wherein the compressor rotates on a common spool with the turbocharger;

driving the power turbine to rotate by flowing compressed air from the compressor to the power turbine.

23. The method of claim **22**, wherein the recuperator to which exhaust gas is flowed from the combustor is a first recuperator, and comprising flowing the working fluid from the ejector through a second recuperator before condensing the working fluid, and flowing the condensed working fluid through the second recuperator before returning the condensed working fluid to the boiler, wherein the second recuperator transfers heat from the working fluid discharged from the ejector to the condensed working fluid flowing through the second recuperator, and the heated condensed working fluid is flowed to the boiler for vaporization.

24. The method of claim **22**, wherein returning the condensed working fluid to the boiler comprises flowing vaporized working fluid from the boiler through an injector, entraining the condensed working fluid in the vaporized working fluid as the vaporized working fluid flows through the injector by flowing the condensed working fluid into the injector, and flowing the condensed working fluid from the injector into the boiler.

25. The method of claim **22**, wherein the working fluid is a hydrocarbon fuel.

26. The method of claim **25**, comprising flowing vaporized working fluid from the boiler to the combustor to supply the combustor with fuel for combustion with air.

27. A heat exchanger, comprising:

a plurality of hot fluid plates stacked in series along a longitudinal direction, each hot fluid plate having a thickness in the longitudinal direction and a planar area in a transverse plane orthogonal to the longitudinal direction, and each hot fluid plate comprising a central hole, a hot fluid inlet hole and a hot fluid outlet hole formed through the thickness, the hot fluid inlet hole and the hot fluid outlet hole located at respective radial distances from the central hole, and each hot fluid plate further comprising a transverse channel running in the transverse plane from the hot fluid inlet hole, around the central hole and to the hot fluid outlet hole; and

a cold fluid circuit running from a cold fluid inlet to a cold fluid outlet in thermal contact with the transverse channels, wherein:

the central holes are aligned with each other along the longitudinal direction;

the hot fluid inlet holes are aligned with each other along the longitudinal direction, forming a hot fluid inlet plenum;

the hot fluid outlet holes are aligned with each other along the longitudinal direction, forming a hot fluid outlet plenum; and

the transverse channels establish a plurality of transverse flow paths from the hot fluid inlet plenum to the hot fluid outlet plenum.

28. The heat exchanger of claim **27**, wherein the hot fluid plates each have a thickness on the order of micrometers.

29. The heat exchanger of claim **27**, wherein the cold fluid circuit comprises a cold fluid plenum extending along the longitudinal direction and surrounded by the central holes.

30. The heat exchanger of claim **27**, comprising a lid disposed on an outermost one of the hot fluid plates, the lid comprising a hot fluid hole communicating with the hot fluid inlet or the hot fluid outlet of the outermost hot fluid plate, and a cold fluid hole communicating with the cold fluid circuit to define the cold fluid inlet or the cold fluid outlet.

31. The heat exchanger of claim **27**, comprising a lid disposed on an outermost one of the hot fluid plates, the lid comprising a hot fluid hole communicating with the hot fluid inlet or the hot fluid outlet of the outermost hot fluid plate, wherein the cold fluid outlet is a central cold fluid outlet formed through the lid, and the lid further comprising a radial channel communicating with the central cold fluid outlet and an outer cold fluid outlet communicating with the radial channel at a distance from the central cold fluid outlet.

32. The heat exchanger of claim **27**, comprising a body comprising a lid disposed on an outermost one of the hot fluid plates and a cold fluid plenum extending from the lid along the longitudinal direction and surrounded by the central holes, the lid comprising a hot fluid hole communicating with the hot fluid inlet or the hot fluid outlet of the outermost hot fluid plate, wherein the cold fluid plenum is part of the cold fluid circuit.

33. The heat exchanger of claim **27**, wherein each transverse channel comprises a C-shaped section.

34. A heat exchanger, comprising:

a plurality of hot fluid plates each having a thickness in a longitudinal direction and a planar area in a transverse plane orthogonal to the longitudinal direction, each hot fluid plate comprising a central hole, a hot fluid outlet hole, a cold fluid inlet hole and a cold fluid outlet hole formed through the thickness, the hot fluid outlet hole, the cold fluid inlet hole and the cold fluid outlet hole located at respective radial distances from the central hole, and each hot fluid plate further comprising a hot fluid transverse channel running in the transverse plane from the central hole and radially outward therefrom, around the central hole and to the hot fluid outlet hole; and

a plurality of cold fluid plates each having a thickness in the longitudinal direction and a planar area in the transverse plane, each cold fluid plate comprising a central hole, a hot fluid outlet hole, a cold fluid inlet hole and a cold fluid outlet hole formed through the thickness, and each cold fluid plate further comprising a cold fluid transverse channel running in the transverse plane from the cold fluid inlet hole, around the central hole and to the cold fluid outlet hole, wherein:

the hot fluid plates and the cold fluid plates are stacked along the longitudinal direction in alternating series with each other such that each hot fluid plate is adjacent to at least one of the cold fluid plates and each hot fluid transverse channel is in thermal contact with at least one of the cold fluid transverse channels;

the central holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a hot fluid inlet plenum;

the hot fluid outlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a hot fluid outlet plenum;

the cold fluid inlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a cold fluid inlet plenum;

the cold fluid outlet holes of the hot fluid plates and the cold fluid plates are aligned with each other along the longitudinal direction, forming a cold fluid outlet plenum;

the hot fluid transverse channels establish a plurality of transverse flow paths from the hot fluid inlet plenum to the hot fluid outlet plenum; and

the cold fluid transverse channels establish a plurality of transverse flow paths from the cold fluid inlet plenum to the cold fluid outlet plenum.

35. The heat exchanger of claim **34**, wherein the hot fluid plates and the cold fluid plates each have a thickness on the order of micrometers.

36. The heat exchanger of claim **34**, wherein the hot fluid transverse channels and the cold fluid transverse channels each comprise a C-shaped section.

37. The heat exchanger of claim **34**, wherein:

the alternating series of hot fluid plates and cold fluid plates form a series of hot fluid inlet holes axially spaced along the longitudinal direction, each hot fluid inlet hole bounded by a corresponding one of the hot fluid transverse channels and an adjacent one of the cold fluid plates, and each hot fluid inlet hole defining a transverse flow path from the hot fluid inlet plenum into the hot fluid transverse channel; and

further comprising a cylindrical structure surrounded by the central holes of the hot fluid plates and the cold fluid plates, the cylindrical structure comprising an elongated opening extending in the longitudinal direction and communicating with the hot fluid inlet holes.

38. The heat exchanger of claim **37**, wherein the cylindrical structure is a combustor housing, and the hot fluid inlet plenum is bounded by the elongated opening and defines a gas flow path from an interior of the cylindrical structure to the hot fluid inlet holes.

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