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(72) Inventor; and

(71) Applicant: **FILIPPONE, Claudio** [US/US]; 8708 48th Place, College Park, MD 20740 (US).

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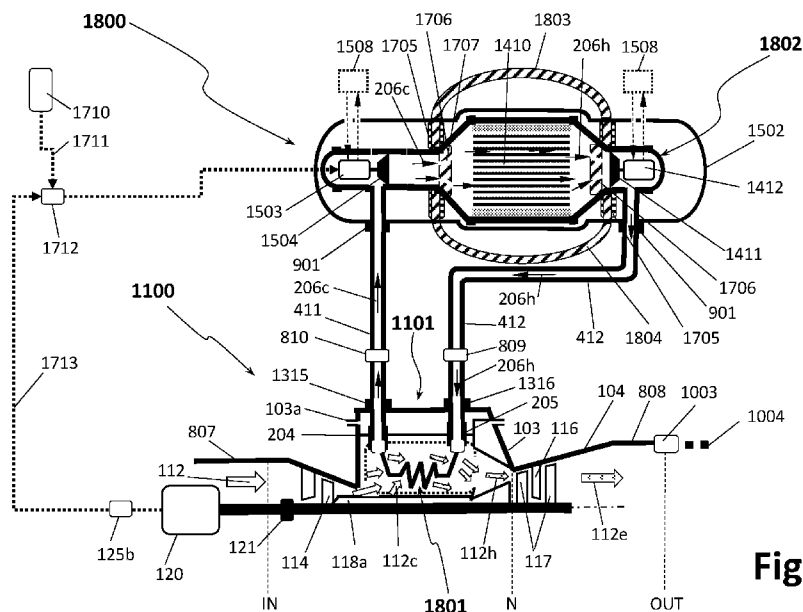


Fig. 18

(57) Abstract: Various exemplary embodiments of a power system for converting thermal energy from a heat source to electricity are disclosed. In one exemplary embodiment, the power conversion system includes a turbine-engine based on fossil-fueled aeroderivative or heavy-duty gas turbine engines coupled to electric generators, retrofitted with a heat exchanger thermally coupled to a carbon-free heat source to convert thermal energy from the carbon-free heat source to the air flowing through the engine compressor and expanding through the turbomachinery of an expander coupled to a mechanical shaft driving the engine compressor and an electric generator.

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SPECIFICATION

CARBON-FREE POWER CONVERSION SYSTEM FOR SUPPLYING HIGH-TEMPERATURE PROCESS HEAT AND ELECTRICITY

CROSS REFERENCE TO RELATED APPLICATIONS

[001] This application claims priority to U.S. Provisional Patent Application No. 62/472,341, filed on June 11, 2023, U.S. Provisional Application No. 63/623,336, filed on January 21, 2024, and U.S. Provisional Application No. 63/639,697, filed on April 28, 2024. Contents of the above-mentioned applications are incorporated herein by reference in their entirety.

TECHNICAL FIELD

[002] The present disclosure relates generally to aeroderivative fossil-fueled or bio-fueled turbine engines, retrofitted with a heat exchanger thermally coupled to a carbon-free energy source for the generation of electrical power.

BACKGROUND

[003] A carbon-free thermal energy source may be represented by nuclear reactors, solar thermal accumulators, geothermal systems, and high-temperature processes thermally coupled to high-temperature working fluids from various industrial applications such as, for example, steel manufacturing. A nuclear reactor generating thermal energy is considered a carbon-free thermal energy source. The nuclear reactor, referred to as “reactor” hereafter, generally includes a nuclear core for producing thermal energy. In some configurations the reactor may be coupled to heat exchangers configured to transfer thermal energy to a Rankine vapor cycle for the conversion of thermal energy from the heat source to electricity. In other configurations the reactor may be coupled to heat exchangers transferring thermal energy to a Brayton gas cycle directly or indirectly coupled to an electric generator for the conversion of thermal energy into electricity. In yet other configurations, the thermal power generated by the heat source can be partitioned to support multiple processes: only process heat generation to support industrial applications requiring process heat; only electric generation, or simultaneously satisfy the requirements for both process heat and electricity supply. Another form of energy from a reactor is represented by the nuclear decay heat. After shutdown, the nuclear fuel within a nuclear core continues to produce thermal energy as a result of nuclear decay characterized by the fission fragments generated up to the last shutdown. More

generally, the amount of decay heat after shutdown is generally proportional to the power generation history and power density of the nuclear core. To avoid overheating of the nuclear core after shutdown, decay heat energy may be transferred from the nuclear core to the environment by heat transfer mechanisms supported by the decay heat removal systems thermally coupled to the nuclear core. These heat removal systems generally require complex piping networks to hydraulically couple the pressure vessel containing the nuclear core to heat exchangers configured inside or outside of the pressure vessel. Further, the coolant circulating between the nuclear core and the heat exchangers may be either actively circulated by electrically driven pumps and/or blowers, or passively circulated via gravity-driven natural circulation mechanisms. The main difference between the thermal energy by the reactor during normal operations versus the thermal energy generated by decay heat is their power rating. The decay heat power rating is approximately 6% of the nominal power the reactor supplied at the moment of shut down, and this percentage decreases exponentially as time elapses.

[004] To summarize, all reactors produce thermal energy that may be transferred by heat transfer means (e.g., heat exchangers, pumps, blowers and hydraulic piping) to the components dedicated to the conversion of thermal-energy to electricity, or to the transfer of thermal energy from the core to a working fluid to provide process heat availability for various industrial applications.

[005] The type of Brayton based engines dedicated to the production of electricity generally employ turbomachinery components, such as compressors and expanders, forming aeroderivative and heavy-duty gas turbines directly or indirectly coupled to electric generators. Aeroderivative engines are intended as derivation of aviation turbojet engines, developed to support aircrafts propulsion, modified to support electric power generation by coupling the rotary components of the turbojet directly or indirectly to an electric generator. Gas turbines may either be derived from aviation engines, or they may be specially designed and optimized to produce electricity by coupling the rotary components of the turbomachinery to an electric generator. The term “gas” includes all types of fossil fuels in liquid, gaseous and particulate form. These types of turbines may be referred to as “land-based” gas-turbines. Overall, land-based gas-turbines may be divided into two general categories: industrial engines and aeroderivative engines. Industrial engines are usually developed for electrical generation or other land-based uses. Aeroderivative engines are generally a derivation of aeronautical turbojet and turbofan turbine engines optimized for the propulsion of aircrafts with also land-based applications as, for example, heavy and military

equipment propulsion (e.g., armored terrestrial and marine vehicles). One of the methods adopted to convert a turbojet engine designed for aircraft propulsion into an aeroderivative gas turbine for electricity production consists of replacing the exhaust nozzle, dedicated to convert thermal energy to thrust, with a fluid dynamically coupled power turbine to generate shaft work. The power turbine is mechanically decoupled from the rotary turbomachinery forming the gas-turbine. The power turbine is mechanically coupled with and drives an electric generator. One of the methods for a turbo-propeller type of gas turbine to be converted into an aeroderivative gas turbine for electrical power generation includes removing the propeller and gearbox from the power turbine and mechanically coupling the power turbine to an electric generator. Another method to convert a turbo-fan gas turbine to an aeroderivative gas turbine for the production of electricity includes removing the fan and replacing it with a low-pressure ratio compressor to supply compressed air to the high-pressure compressor, which provides high-pressure compressed air to the combustors. The nozzle, designed to generate thrust, is also eliminated and the outlet of the expander turbine is hydraulically coupled to a power turbine that is further coupled to an electric generator. All typologies of gas turbines dedicated to the production of electricity represent combustion engines generally converting fossil fuels energy into mechanical or fluid-dynamic energy, defined as the energy represented by a fluid characterized by a certain temperature, pressure and mass flow rate. Burning a mixture formed by air and fossil-fuels generates high-temperature exhaust gases which expand through an expander turbine and convert the fluid dynamic energy of the exhaust gases into shaft work and electricity by i) mechanically coupling the power turbine shaft to an electric generator or ii) by fluid-dynamically coupling the high energy content exhaust gases to a mechanically decoupled power turbine that is further coupled to an electric generator unit. Overall, these types of engines utilize combustion chambers designed to mix and ignite the mixture formed by the oxygen, contained in environmental air, with the fossil fuels supplied for the combustion (e.g., in gaseous, liquid, or particulate form), to generate high-temperature exhaust gases that expand through the expander turbomachinery and/or through the power turbine. The compressor turbomachinery and expander turbomachinery forming these engines may be formed by a single stator and single turbine, or multistage stators and multistage turbines, the type of turbines are generally of the axial type or centrifugal type, and the blading contour is adapted to satisfy turbomachinery requirements associated with the mass flow rate of air to be compressed, amount of fossil fuel and air to be mixed and combusted, the rotary speed, diameter and materials forming the rotary and stationary turbomachinery.

[006] The size of the combustion chambers utilized by these engines varies proportionally to the amount of air and fossil-fuel to be mixed, ignited, and expanded. Therefore, general dimensions of the combustion chambers are proportional to these parameters. A smaller combustion chamber generally processes a smaller amount of air-fuel mixture and produces a proportional amount of power. Vice versa, a larger combustion chamber generally processes a larger air-fuel mixture mass resulting in the expansion of a larger amount of exhaust gases.

[007] Commercial combustion engines represented by aeroderivative, and gas turbines (small or heavy duty) generally do not include a heat exchanger dedicated to transfer thermal-energy from a carbon-free heat source (e.g., not sourced in the combustion of air-fossil-fuels mixtures) to the fluid expanding in the expander or power turbine.

[008] A nuclear reactor may represent a carbon-free heat source that may be coupled to a heat exchanger. The heat exchanger may be configured to transfer thermal energy from the nuclear fuel loaded in a nuclear core to a working fluid (e.g., environmental air, or a suitable fluid supporting process heat operations) compressed by the compressor included in these engines. The working fluid would be heated in the heat exchanger to subsequently expand through the expander turbomachinery, or the power turbine coupled to electric generators to produce electric power.

[009] A high-temperature solar-thermal source may also represent a carbon-free energy source, as well as certain types of a high-temperature geo-thermal energy sources. For non-nuclear and carbon-free heat sources, the working fluid dedicated to support process heat industrial applications may be thermally coupled to the high-temperature carbon-free heat source by means of a heat exchanger to heat up the working fluid.

SUMMARY

[010] Various exemplary embodiments of the present disclosure may provide a thermal-to-electric power conversion system by retrofitting commercial engines formed by aeroderivative and gas-turbines coupled to electric generators by augmenting the energy content represented by the combustion of fossil fuels within gas-turbines' and aeroderivative combustors, by-passing, or entirely replacing the combustors normally included in these engines to increase the working fluids energy content in these engines by means of heat exchangers disposed under various configurations, for example, within retrofitted engine casing, outside of the engine casing, hybrid configurations (partially within and partially outside of the engine casing), or utilizing configurations in which the thermal transfer between the heat source and the working fluid occurs within the heat source casing. The

thermal or heat source transferring thermal energy through the heat exchanger to one or multiple working fluids for conversion to electricity, torque, or as thermal supply to support process heat applications may be represented by carbon-free energy sources (e.g., a nuclear core, solar-thermal, high-temperature geothermal, and waste thermal energy).

[011] The heat exchanger may operate with at least one primary and one secondary side wherein thermal transfer media, represented by working fluids, circulates and exchanges thermal energy transfers between the working fluids and the materials forming the heat exchanger. In one configuration, one of the working fluids circulates in the primary side, the “primary working fluid” of the heat exchanger, without mixing with the working fluid circulating in the secondary side, the “secondary working fluid”. The primary and secondary working fluids are suitable fluids thermally coupled on the primary side to the heat source, with the secondary fluid further thermally coupled to the components forming a power conversion system (e.g., engines represented by modified aeroderivative and gas-turbines components), or a process heat application. For the configurations dedicated to the conversion of thermal energy from the heat source to electricity, the secondary working fluid heated by the primary fluid expands in the modified turbomachinery systems that includes aeroderivative or gas turbine components coupled to electric generators. In one configuration, the secondary working fluid may be environmental air. In this configuration, the primary working fluid and the air may not mix. Accordingly, air, compressed by the engine compressor circulates through the heat source exchanger where thermal energy is transferred from the heat source to the air. In one configuration, the heated compressed air, exiting the secondary side of the heat exchanger, may flow through the engine combustor where a metered amount of fossil-fuel is mixed and ignited by temperature. The result is combustion of the metered amount of fossil fuel. The combined mass of exhaust gases and mass of heated air make up the energy requirement for the engine expander or power turbine to operate at engine-design conditions to convert the combined thermal energy represented by the heated air and the combustion products developed by the combustor into an air-exhaust gases mixture with high energy content driven through static nozzles (e.g., turbomachinery stator) and expand through the components of the expander (e.g., turbomachinery rotor) or those forming the power turbine, thus generating shaft work and fluid dynamic energy. When the expander is directly coupled to a generator, the combined thermal energy represented by the heated air mixed with fossil-fuels combustion products is converted directly into electricity. When the expander outlet drives a power turbine coupled to an electric generator, the combined thermal energy is indirectly converted into electricity as the energy content of the

secondary working fluid is in part utilized to drive the compressor, with the remaining fluid dynamic energy dedicated to drive the power turbine, mechanically decoupled from the rotary components forming the compressor and expander turbine. In another configuration, the heat exchanger thermally coupled via primary side to the heat source and secondary side to the working fluid circulating through the engine, can be configured to transfer a substantial amount of the thermal energy from the carbon-free heat source to the air expanding at the outlet of the heat exchanger secondary circuit. In this configuration, there is no fossil-fuel burning. The compressed heated air, compressed by the compressor driven by the expander, flows directly into the stator and rotary components of the expander or power turbine turbomachinery for direct or indirect conversion of the secondary fluid energy content into electricity.

[012] The present disclosure provides a system that transfers thermal energy from a carbon-free energy source to the compressed air normally generated by the compressor of commercial aeroderivative gas-turbine engines. The system augments, bypasses or eliminates the fossil-fuel combustor normally included in these engines, heats the compressed air through a heat exchanger to increase the air energy content, expands the heated air through the expander and produces shaft work that drives the engine compressor and produces electricity when the expander is coupled to a generator.

[013] In one configuration, the heat exchanger may be positioned within the inner spacing defined by the engine casing forming a pressure boundary normally surrounding the combustor(s) structures utilized by commercial engines (e.g., commercial gas-turbines and derivatives). In this configuration, the body of the heat exchanger may be configured to occupy the volume formed by the inner spacing between the combustor and the engine casing to induce the compressed air or secondary working fluid to flow through the heat exchanger and exchange thermal energy with the primary working fluid circulating through the heat source prior to entering the combustor.

[014] In another configuration, the heat exchanger may be positioned within a retrofitted extended engine casing. The extended casing seals the OEM engine casing and maintains the engine casing pressure boundary while increasing its internal volume to further accommodate internal space for conduits or channels, that do not interfere with the normal operations of the combustor. In this configuration, a larger heat exchanger can be configured to channel the secondary fluid represented by compressed air through the heat exchanger to exchange thermal energy with the primary working fluid prior to the now heated compressed air flows through the combustor.

[015] In another configuration, the engine casing may be configured with hydraulic ports positioned on the extended engine casing walls to enable the compressed air to exit the engine casing through piping hydraulically coupled to an external heat exchanger. In this configuration, the heat exchanger primary fluid circulating through the carbon-free heat source transfers thermal energy to the secondary working fluid outside of the engine casing where its energy content is increased prior to flowing back into the engine casing resulting in heated air flowing through the combustor.

[016] In one configuration, the heat exchanger may replace the combustors and be positioned within the engine casing retrofitted with inlet and outlet ports hydraulically sealing the engine casing for the primary working fluid circulating through the heat source to circulate through the heat exchanger primary side inlet and outlet ports through the engine casing. The heat exchanger may be formed by a printed circuit heat exchanger, for example, formed by diffusion bonded layers with axial channels for the secondary working fluid (e.g., air) to flow through, and radial channels for the primary working fluid to flow through. In this configuration, the heat exchanger is shaped to fit the volume formed by the engine casing inner spacing between the engine casing internals and the engine shaft shroud providing mechanical support to the combustor. The printed circuit heat exchanger may be equipped with axial and radial bellows to eliminate stress points induced by thermal fatigue as the heat exchanger body expands and contracts.

[017] According to an aspect of the present disclosure, a power conversion system for converting thermal energy from a heat source to electricity is provided. Another aspect of the invention may provide a system for the transfer of thermal energy to a process heat application represented, for example, by steel manufacturing. In this configuration the secondary fluid may be circulated through the metal materials to elevate their temperature prior to conducting various steel manufacturing processes.

[018] Additional objects and advantages of the invention will be set forth in part in the description that follows, and in part will be obvious from the description, or may be learned by practice of the invention.

[019] It is to be understood that both the foregoing summary description and the following detailed description are exemplary and explanatory only and are not restrictive of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[020] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate several embodiments of the invention and together with the description, serve to explain the principles of the disclosed invention.

[021] Fig. 1 is a partial functional schematic cross-sectional side view, symmetrical with respect to the longitudinal axis, of an unmodified commercial gas turbine engine coupled to an electric generator, showing multistage compressor and multistage expander rotary and stationary turbomachinery coupled by a shaft, the main combustor and combustion chamber components included within the engine casing with internal flow pathways for the air to flow from the compressor inlet, mix with fossil fuel and ignite in the combustor, and the combustion product outlet the engine from the expander outlet after producing shaft work and electricity.

[022] Fig. 1a is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1.

[023] Fig. 2 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1, with additional retrofitted components to enable extending the engine casing while maintaining the pressure boundary of the OEM engine casing, including a heat exchanger and internal conduits for the heat exchanger to transfer thermal energy from a carbon free heat source to the compressed working fluid compressed by the compressor and flow the heated working fluid through the combustor.

[024] Fig. 3 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1, with retrofitted engine casing components to enable the compressed working fluid from the compressor to circulate outside of the engine casing and return to the engine casing through retrofitted hydraulic ports after the working fluid has been heated by heat transfer with a carbon free heat source so that the heated working fluid is supplied to the combustor.

[025] Fig. 4 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1, with retrofitted engine casing components to enable the compressed working fluid from the compressor to circulate through a heat exchanger positioned within the retrofitted extended casing components, for the heated compressed working fluid to directly expand through a power turbine coupled to an electric generator.

[026] Fig. 5 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1, with retrofitted engine casing components to enable the compressed working fluid from the compressor to circulate through a bypass tube prior to entering the heat

exchanger positioned within the retrofitted extended casing components, for the heated working fluid to directly expand through the expander.

[027] Figs. 5a and 5b are cross sectional views of different sides of the heat exchanger shown in Fig. 5.

[028] Fig. 6 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 5 configured with a heat exchanger and showing the bypass tubing configured with hydraulic ports positioned with retrofitted extended casing components and internal conduits and passageways for compressed working fluid to flow within an inner space into the inlet of the secondary heat exchanger header.

[029] Fig. 7 is a partial functional schematic cross-sectional side view of a simplified engine shown in Fig. 1 configured without a combustor and without a heat exchanger and showing hydraulic ports positioned with retrofitted extended casing components and internal conduits and passageways for compressed working fluid to flow within an inner space into the inlet of the secondary heat exchanger header through the hydraulic ports for direct expansion through the expander.

[030] Fig. 8 is a partial perspective three-dimensional cross-sectional view of the engine of Fig. 6 retrofitted with extended casing showing the internal conduits, heat exchanger, bypass tubing, and thermally insulated piping thermally coupling the heat exchanger to a carbon-free heat source.

[031] Fig. 8a is a schematic representation of the retrofitted engine casing shown in Fig. 8 including a heat exchanger.

[032] Fig. 8b is a simplified schematic representation of the engine shown in Fig. 8.

[033] Fig. 9 is a perspective view of a carbon-free heat source represented by a nuclear reactor coupled to the retrofitted engine shown in Fig. 8.

[034] Fig. 10 is a cross-sectional schematic view of a gas-turbine engine coupled to electric generators with schematic representation of combustors positioned substantially parallel to the longitudinal axis and inner rotary shaft coupling the compressor to the expander turbomachinery and to the generators via mechanical couplers and a gear box.

[035] Fig. 11 is a cross-sectional view of the engine shown in Fig. 10 retrofitted with a compact heat exchanger replacing the combustors with a compressed working fluid flowing through headers and channels in the longitudinal axial direction and a heat source working fluid flowing through headers and channels in the radial direction.

[036] Fig. 12 is a schematic partial three-dimensional cross-sectional view of the compact or printed circuit heat exchanger shown in Fig. 11 showing the working fluid flow pathways and the heat source working fluid flow pathways.

[037] Fig. 12a shows a simplified cross-sectional schematic view of the heat exchanger shown in Fig. 12.

[038] Fig. 13 is a cross-sectional schematic view of the engine shown in Fig. 10 with the engine hood extended to house a heat exchanger retrofitted within the engine casing to enable the engine to operate with both the combustion gases of a combustor mixed with the heat source working fluid.

[039] Fig. 13a is a cross sectional schematic view of the engine shown in Fig. 10 and Fig. 13 with the engine hood extended to house a chamber for the working fluid aiding the combustion of a combustor and mixed with the combustion gases, with the engine hood extended and equipped with hydraulic ports to hydraulically couple the chamber inside the engine hood to an external heat exchanger.

[040] Fig. 14 shows a carbon-free engine coupled to an external heat exchanger thermally coupled to a carbon-free heat source configured to heat up a heat source working fluid and produce electricity through a full Brayton cycle with intercooler and recuperator heat exchangers.

[041] Fig. 15 shows the carbon-free engine of Fig. 14, coupled to an external heat exchanger thermally coupled to a carbon-free heat source configured to heat up a heat source working fluid and produce electricity through a simple Brayton cycle.

[042] Fig. 16 is a schematic representation of the carbon-free heat source of Fig. 15 coupled to an external heat exchanger through high temperature piping surrounded by low-temperature piping.

[043] Fig. 17 is a schematic representation of the engine shown in Fig. 14 and Fig. 15 coupled to an external heat exchanger integrated within a carbon-free heat source configured to produce thermal power.

[044] Fig. 18 is a schematic representation of the carbon free engine shown in Fig. 11 integrating a compact or printed circuit heat exchanger within the extended hood of the engine directly coupled to the heat source working fluid of a carbon-free heat source comprising a simple Brayton or Rankine cycle.

[045] Fig. 19 is a schematic representation of the engine shown in Fig. 11, directly coupled to the heat source working fluid circulating in two carbon-free heat source unit, where one

heat source unit produces electricity and heats up the heat source working fluid, while the other carbon-free heat source unit only heats up the heat source working fluid.

[046] Fig. 20 is schematic representation of a carbon-free heat source configured as an electric power conversion system and as a thermal energy supply system coupled to a power utilization system.

[047] Fig. 21 is a schematic representation of the carbon-free heat source of Fig. 20 coupled to an electric arc furnace to support a steelmaking processes.

[048] Fig. 22 is a schematic representation of the carbon-free heat source of Fig. 20 and Fig. 21 further coupled to a steelmaking reheating chamber to support steelmaking processes.

[049] While the present invention is described herein with reference to illustrative embodiments for particular applications, it should be understood that the invention is not limited thereto. The preceding description of the disclosed embodiments is provided to enable any person skilled in the art to make or use the claims. Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments and implementations.

DETAILED DESCRIPTIONS

[050] Reference will now be made in detail to the exemplary embodiments of the invention, examples of which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[051] Figs. 1 and 1a illustrate an unmodified, commercial or traditional, fossil-fueled turbine-generator power conversion system, also referred to as engine 100. With reference to Figs. 1 and 1a from left to right, the engine 100 includes a casing 101 formed by an inlet 102 and an outlet for a working fluid 112 to flow through. The casing 103 surrounds the axial compressor axial stator turbomachinery 113 and the compressor rotor turbomachinery 114. The engine casing 103 merges into engine casing 123 which forms the base of the casing structures forming the combustor body 109a, which further merges with casing 104a which surrounds the expander stator turbomachinery 116 and expander rotor turbomachinery 117. The compressor rotor 118a is mechanically coupled to the shaft 118, which is mechanically coupled to a gear box 118c, which is further mechanically coupled to the expander rotor 118b. For most configurations of engine 100, the compressor rotor 118a is mechanically coupled to the expander rotor 118b as the expander rotor 118b drives the compressor rotor 118a. In other configurations, the compressor rotor 118a is directly coupled to the expander

rotor 118b (no gear box 118c). In yet another configuration, the compressor rotor 118a is mechanically decoupled from the expander rotor 119b as it may be driven by an electrical motor coupled through a mechanical coupler 121 as shown for the coupling of shaft 118 to motor-generator 120. The engine casing 123 may be configured to flange extended combustor casing 103 through flange 103a pressure sealed through seals 124. Combustor casing 103 (also referred to as bucket casing 103), is further coupled to the combustor bucket hood 122 (also referred as casing hood 122). Inside the combustor casing 103 the combustor structure 109 is configured to enable compressed working fluid 112 to mix with fossil fuel spray 105s supplied by a fossil fuel supply system 105, where fossil fuel 105a is pressurized inside the combustion chamber 106 to ignite and increase the energy content of the resulting combustion gases and working fluid 112. Starting from left to right, the general functioning of engine 100 is now described. As working fluid 112 is compressed by the compressor turbomachinery 114 and becomes compressed working fluid 112c. This compressed working fluid flows through channels 119b formed within the combustor casing 104 with ducts and internal combustor structures so as to change the direction of the compressed working fluid 112c as shown in channel 109b until it enters the combustion chamber 108, formed by structures with patterned holes where working fluid 112c enters the combustion area 110, mixes with fossil fuel 105a and ignites. The resulting exhaust gases 111 mixed with superheated working fluid 112sh flow within the nozzle conduit 109 to expand out of the nozzle outlet plane indicated by the letter "N" into the expander stator 116 and rotor 116 turbomachinery resulting in a conversion of thermal energy from the superheated working fluid 112sh and combustion gases. At the engine outlet 104, exhaust gases 111e and exhaust working fluid 112e exit the engine. As a result of the expansion of superheated working fluid 112sh and combustion gases 111, the expander rotor 118b drives the compressor rotor 118a producing additional torque to drive the generator 120 which produces electric power at its electric bus 125.

[052] Fig. 1a shows a simplified configuration of engine 100, where the compressor rotor 118a is decoupled from the expander rotor 118b.

[053] Fig. 2 illustrates a retrofitted power conversion system of engine 100 shown in Figs. 1 and 1a, also referred to as engine 200. In this configuration, the internal conduits 109b for the compressed working fluid 112c to flow in are unchanged as part of the engine casing 123, while a series of passageways 109a and 103c are retrofitted within the combustor casing 103 to direct the compressed working fluid 112c into an extended casing 201 flanged to the flanges 103b originally designed to couple the combustor casing 103 to the engine hood 112

of Figs. 1 and 1a. Through the added casing 201 and combustor casing head 202 mechanically and hydraulically coupled through sealed flanges 103b and 203, an extended sealed volume housing the heat source heat exchanger 208 is provided. The added casing 214 further provides an inlet and outlet hydraulic ports for a hot heat source working fluid 206h to flow through inlet 204 and flow out of the extended casing 214 through outlet 205. As hot heat source working fluid 206h flows through superheater 208, it transfers thermal energy to the compressed working fluid 112c without mixing. More specifically, hot heat source working fluid 206 flows through piping 215 with thermal insulation 207h into the superheater inlet header 209. The superheater heat exchanger 208 is formed by a primary inlet header 209 and a primary outlet header 210 coupled to a primary thermodynamic loop where the heat source working fluid 206 circulates, and a secondary inlet header 211 and a secondary outlet header 212 where the compressed working fluid circulates. Superheater heat exchanger 208 may be represented by a printed circuit heat exchanger with primary channels in the “y” direction coupled to the primary inlet and outlet headers 209 and 210 respectively, and secondary channels in the “x” direction coupled to the secondary inlet and outlet headers 211 and 212 respectively. As a result, within the extended volume of the combined casing 214 and casing head 212, housing the superheater heat exchanger body 217, the compressed working fluid 112c is thermally coupled to the heat source working fluid 206, such that as both working fluids flow through the superheater 208, the hot heat source working fluid 206h cools down to cold heat source working fluid 206c and the compressed working fluid 112c becomes compressed hot working fluid 112h prior to mixing with fossil fuel 105a within the combustion chamber 110. The resulting combustion gases 111 and superheated working fluid 112sh flow with higher energy content through the nozzle structures 109 for conditioning both working fluids into the expander turbomachinery 117 generating torque at the expander rotor 115a. This torque can be utilized by coupling expander rotor shaft 115a via mechanical coupler 121 to an electric generator, as shown in Fig. 1, or to the compressor rotor 115 via gear box 118c or to both compressor rotor and to an electric generator. The resulting exhaust working fluid 112e and the exhaust combustion gases 111e at the engine outlet denoted by the “OUT” plane, are characterized by high temperature and higher pressure than that of the working fluid 112 at the engine inlet at the inlet plane denoted by “IN”. As it will be shown in other embodiments of the present disclosure, these working fluids exhaust characteristics at the engine 200 outlet may be utilized to transport thermal energy and flow rate through a thermal utilization system 2003 shown in Fig. 20.

[054] Fig. 3 shows a partial functional schematic cross-sectional view of the engine 100 shown in Fig. 2 with simplified retrofitting modifications as the superheater heat exchanger 208 is disposed outside of engine 200 combustor casing 103. In the configuration shown in Fig. 3, the retrofitted combustor casing 103 is minimally modified, while the combustor header 302 is modified to include hydraulic inlet and outlet ports 304 and 303 respectively. In this configuration, the combustor chamber 106 is surrounded by conduits that 301 to channel the compressed working fluid 112c. This working fluid is compressed by compressor turbo machinery 114 and exits the modified combustor header 302, to be superheated outside of the engine 300. This working fluid then returns as hot working fluid 112h back into the modified combustor header 302 to mix with fossil fuel 105a resulting in combustion gases 111 and superheated working fluid 112sh. The combustion gases 111 and superheated working fluid 112sh then flow through the nozzle structure 109 and expand through the expander turbomachinery to produce torque, and exhaust working fluid 112e and exhaust gases 111e with a controlled energy content. The energy content of these working fluid is proportional to the amount of thermal energy converted to torque at the expander rotary shaft 115a. To summarize, the flow paths developed inside the combustor casing 103 and the combustor header 302 for the compressed working fluid 112c enable this fluid to remain pressurized by the compressor turbomachinery 114 while circulating through external thermally insulated cold piping 306 and hot piping 305.

[055] Fig. 4 is a partial functional schematic cross-sectional side view of a simplified engine shown in Figs. 1-3 with a retrofitted engine casing 402 coupled to the combustor casing 103 by flange 103b on one end, and to the combustor header 202 on the other end by flange 203 sealed by seals 124. Combustor engine casing 402 further extends the volume inside the combustor casing 103 to substantially entirely eliminate the combustion chamber 106, the fossil fuel system 105 and the fossil fuel 105a normally included in engine 100 in Fig. 1. Accordingly, a larger superheater heat exchanger 401 may be fitted within the extended combined volume formed by coupling combustor casing 103 to combustor casing 402 and to combustor header 202. In this configuration, engine 400 is carbon-free as the compressed working fluid 112c is superheated without combustion of fossil fuels. Similar to the configuration described for engine 200, hot heat source working fluid 206h flows at the inlet 204 of an inlet hydraulic port positioned on the combustor casing 402, through superheater heat exchanger 401 (e.g., a printed heat exchanger with channels as described for engine 200) thermally coupling the compressed working fluid 112c to an external carbon-free energy source. Similar to the functioning principles described for engine 200 in Fig. 2, the

superheater heat exchanger 401 includes primary circuit and secondary circuit inlet and outlet headers 404, 405, 406 and 407 respectively, for the compressed working fluid 112c to be heated up by the hot heat source working fluid 206h. At the outlet header 407, the compressed working fluid 112c energy content has been increased to compressed hot working fluid 112h for this fluid to expand through the expander turbomachinery 117 as described for engines 100, 200 and 300. In this configuration, the torque developed at the expander shaft 115a by the expansion of compressed hot working fluid 112h is converted into electricity by generator 403. In this configuration the generator 403 is thermally insulated from the hot exhaust working fluid 112e, and is cooled by a jacket 408, where an auxiliary coolant circulates. The coolant may circulate through the jacket by piping 410 passing through a hollow mechanical support 409 mechanically coupling the generator 403 to the outlet engine casing 104. The electrical connections 125 for generator 403 may also be routed through the hollow mechanical support 409.

[056] Fig. 5 shows a partial functional schematic cross-sectional view of a simplified engine 500 with a similar functionality as that described in Fig. 4. In this configuration, the combustor header 501 provides hydraulic access to a bypass piping 505 for the compressed working fluid 112c to flow directly into superheater heat exchanger header 509, while hot heat source working fluid 206h circulates into the modified combustor case 402 with less back pressure as inlet and outlet primary headers 204, 205, 507 and 508 may be further extended within the volume constrained by combustor casing 103 dimensions. In this configuration, bypass pressure headers 511a and 511b create a compartment preventing compressed working fluid 112c to mix with hot and cold heat source working fluid 206h and 206c respectively.

[057] Figs. 5a and 5b are cross sectional views of different sides of the heat exchanger shown in Fig.5. Accordingly, Fig 5a shows the inlet header 509 with channels 513 for compressed working fluid 112c to flow through. Fig 5b illustrates the channels 512 of header 508 of a superheater heat exchanger similar to that described in Fig. 4.

[058] Fig. 6 is a partial functional schematic cross-sectional view of a simplified engine 600 with similar operating principles as described for engine 500 shown in Fig. 5. In this configuration, the superheating heat exchanger 604 is not invasive into combustor casing 103 so as to minimize the modification to this component of engine 100 shown in Fig. 1 other than removing all of the original engine manufacturer equipment out of combustor casing 103 and replacing it with a modified nozzle supporting structure 109a.

[059] Fig. 7 is a partial functional schematic cross-sectional view of the simplified engine shown in Fig. 6, where the combustor casing is configured without a combustor and without a superheater heat exchanger, with hydraulic ports positioned on the modified combustor header 501 to enable compressed working fluid 112c to exit the sealed combustor casing to be heated by an external superheater heat exchanger. This configuration is one of the least invasive as it enables recycling of most of the original manufacturer equipment forming the combustor casing, removing all of the combustor equipment inside the combustor casing 701 (e.g., fossil fuel system 105, combustion chamber) and fitting the ducting structure 702 inside the combustor casing 701 to enable the compressed working fluid 112c to exit the combustor casing structure through outlet 705 flowing toward the external superheating heat exchanger denoted by the arrow 706, and returning back for expansion through the expander turbomachinery 117 as denoted by arrow 707 as compressed hot working fluid 112h.

[060] Fig. 8 is a partial perspective three-dimensional cross-sectional view of the engine 600 of Fig. 6 retrofitted with extended casing showing the conduits internal to the modified combustor casing, a configuration of the superheating heat exchanger, bypass tubing, and thermally insulated piping thermally coupling the primary circuit of the superheater heat exchanger to a carbon-free heat source. As shown in this Figure, the compressed working fluid 112c makes a partial flow reversal at the last stage of rotary compressor turbomachinery at location 109b and flows inside an annular channel formed by the inner walls of combustor casing 103 and the modified nozzle structure 515a replacing the combustion chamber denoted by the dashed box prior to flange 103a. The compressed working fluid 112c inlets the bypass tubing 112 at the hydraulic outlet connecting to one end of the bypass tubing 802 and pressurizes the internal volume formed by the inner walls of the combustor header or hood 202 so as to induce the compressed working fluid 112c to inlet the superheater heat exchanger 801 with working principle described in previous Figures. The functions of bypass tube 802 are equivalent to those described for bypass tubes 401 in Fig. 4, 506 in Fig. 5 and 604 in Fig. 6. Flange adapter 803 enables to align the superheater heat exchanger 801 with the rotary axis 119 of engine 800.

[061] Fig. 8a is a schematic representation of the superheating heat exchanger 801 fitted inside the modified combustor casing shown in Fig. 8.

[062] Fig. 8b is a simplified schematic representation of the engine shown in Fig. 8 with functioning principles described in previous Figures.

[063] Fig. 9 is a perspective view of a carbon-free heat source 900 represented by a nuclear reactor coupled to the retrofitted engine shown in Fig. 8, wherein the carbon-free heat source

900 is fitted within a shipping container. In this configuration, a series of hydraulic ports 901 enable thermal coupling of piping 411 and 412 of engine 800 to thermal source 900. In this representation, only one set of piping 411 and 412 are shown to simplify the illustration as the same type of piping is equipping each of the retrofitted combustors shown in this Figure (e.g., 5 times piping 411 and 412 coupling to ports 901).

[064] Fig. 10 is a cross-sectional schematic view of a commercial aero-derivative gas-turbine engine 1000, coupled to electric generators 120 and 403 with schematic representation of combustors positioned substantially parallel to the longitudinal axis and inner rotary shaft 119 coupling the compressor to the expander turbomachinery and to the generators 120 and 403 via mechanical couplers 121 and a gear box 118c as described in previous Figures. This configuration uses hood 1001 to seal the combustors disposed inside of the sealing hood 1001 and the combustor casing 103, the hydraulic coupler 1003 and extended piping 1004 coupled to the engine outlet 808 are provided to indicate a method for transporting the exhaust gases 111e and exhaust working fluid 112e to a thermal power utilization system shown in Figs. 20, 21 and 22.

[065] Fig. 11 is a cross-sectional view of the engine 1000 shown in Fig. 10 retrofitted with a compact heat exchanger 1104 replacing the combustors shown in Fig. 10 for the compressed working fluid 112c flowing through the secondary inlet header 1204 of the compact heat exchanger 1104 (also referred to as superheater 1104), through axial channels 1103 in the axial direction to minimize the formation of backpressure, while the hot heat source working fluid 206h flows through the inlet primary headers 1104a through heat transfer channels in the radial direction. In this configuration, a flow straightener 1102 is positioned at the inlet 807 of engine 1100, 1003a denote the axial channels for the compressed working fluid 112c to flow through, 1103r denote radial channels for the hot heat source working fluid 206h to flow through without mixing with the working fluid 112. The compact heat exchanger is fully comprised within the volume normally occupied by combustors' equipment and, in this configuration, it is formed by at least 2 bodies 1104a and 1104b coupled by a flexible member 1109 to minimize thermal cycling fatigue.

[066] Fig. 12 is a schematic partial three-dimensional cross-sectional view of the compact radial heat exchanger body 1104 shown in Fig. 11, further showing the compressed working fluid 112c flow pathways and the heat source working fluid 206h flow pathways within the channels inside the compact heat exchanger 1200. 1201 denotes the first heat exchanger module (equivalent to 1104a in Fig. 11) and the second module 1202 (equivalent to 1104b in Fig. 11), 1203 is the outlet conduit for the heat source working fluid 112c (after thermal

exchange with the compressed working fluid 112c). 1204 denotes the compressed working fluid inlet header, while 1205 is the compressed working fluid outlet header. 1206 denotes the compact heat exchanger inner diameter and 1207 denotes the outer diameter, while 1208 and 1209 indicate the heat source working fluid inlet and outlet headers respectively.

[067] Fig. 12a shows a simplified cross-sectional schematic view of the heat exchanger shown in Fig. 12.

[068] Fig. 13 is a cross-sectional schematic view of the engine 1000 shown in Fig. 10 with the engine hood extended to house a super heating heat exchanger 1302 (also referred as SH-HEX 1302), retrofitted within the engine 1300 casing to enable the engine 1300 to operate with both the combustion gases produced by combustor chamber 106, mixed with the compressed heat source working fluid 112c. In this configuration 1301 denotes the extended casing equivalent to 214 in Fig. 2), the SH-HEX 1302 is integrated within the hood of engine 1300, while 810 and 809 denote the coupling flanges for the hot heat source working fluid 206h respectively. 1303 denotes the inlet compressed working fluid channel, 1303a represents the internal channel structure nozzle side, 1303b denotes the internal channel structure on the compressor side. 1303st denotes the compressed working fluid 112c channels structures and thermal insulation, 1304 is the external superheater heat exchanger, with 1304p as the primary side of the external superheater heat exchanger 1304 and 1304s as the secondary side of external superheater heat exchanger 1304.

[069] Fig. 13a is a cross sectional schematic view of the engine 1000 shown in Fig. 10 and 1300 shown in Fig. 13, with the engine hood 1101 extended to house a chamber 1309 for the compressed working fluid 112c aiding the combustion of a combustor and mixed with the combustion gases, with the engine hood 1101 extended and equipped with hydraulic ports 1315 and 1316 to hydraulically couple the chamber 1309 inside the engine 1300 to an external heat exchanger 1304, wherein 1305c and 1305h indicated cold and hot conduits, 1306 is the external heat exchanger housing, 1307 and 1308 represent the cold compressed working fluid 112c inlet and outlet ports respectively, while 1309a and 1309b denote the hot

collector and chamber respectively. 1310, 1311, 1312, 1314 represent the external hydraulic ports for the headers of the external heat exchanger, while 1315 and 1316 denote the engine casing outlet and inlet hydraulic ports respectively.

[070] Fig. 14 shows a carbon-free engine 1441 coupled to an external heat exchanger 1306 thermally coupled to a carbon-free heat 1400 configured to heat up a heat source working fluid 206 and produce electricity through a full Brayton cycle with intercooler and recuperator heat exchangers 1407 and 1409 respectively. In this Figure, the carbon-free power generation and conversion plant 1400 is shown.

[071] Fig. 15 shows a power conversion system of the present disclosure. The system may include a turbine-generator engine 1414 (also referred to as aero-derivative 1414, or engine 1414), a heat exchanger 1306 (also referred to as an external heat exchanger 1306 or E-HEX 1306), and a heat source 1500. The heat source 1500 may be any suitable heat source, including, for example, a heat source obtained by a core with fission or fusion nuclear fuel, a heat source represented by a solar collector, or a heat source represented by industrial processes producing waste thermal energy. The heat source may be referred to as a carbon-free heat source. For illustrative purposes, a fission nuclear reactor is used as an example heat source. The principles and embodiments apply to any other suitable heat source. The heat source 1500 is thermally coupled to the E-HEX 1306 and the E-HEX 1306 is thermally coupled to the engine 1414 for the production of electricity, the supply of process heat and the supply of pumping power for a working fluid to support process heat applications. The engine 1414 is formed by turbine-generator components disposed within an engine body or an engine casing 103 (also referred to as casing 103). The casing 103 may include an inlet 807. A working fluid (also referred to as "WF") 112 may flow through the compressor turbo machinery 114 and 113, and may be compressed by the compressor turbo machinery 114 and 113 into a compressed WF 112c inside the casing 103. The compressed WF 112c circulates in a pressurized state within an engine hood 1101 (also referred to as "engine hood 1101"). The engine hood 1101 includes a hydraulic outlet port 1316 and a hydraulic inlet port 1315, and is coupled to the engine casing 103 through sealing flanges 103a. The compressed WF 112c at the outlet of the compressor turbo-machinery flow straightener and conditioners 113, flows out of the hydraulic port 1315 through a WF cold piping 1305c, into the E-HEX 1306 through an inlet port 1307, which forms a part of the E-HEX secondary header 1304s. As the

compressed WF 112c circulates within the E-HEX 1306, it exchanges thermal energy with a heat source Working Fluid (referred to as “HS-WF”) 206 and thermally couples the engine 1414 to the heat source 1500. Thermal coupling between the compressed WF 112c and hot HS-WF 206h may be obtained through thermal coupling with E-HEX surfaces 1304. The HS-WF 206 may be any suitable fluid in gaseous, liquid or supercritical form, including, for example helium, water, liquid metals, molten salts, sCO₂ (supercritical carbon dioxide). Prior to relatively cold HS-WF 206c circulating back from an E-HEX outlet port 1312, through cold HS-WF piping 411, into a heat source Pressure Vessel 1501, cold HS-WF 206c may be further cooled down through a cooler heat exchanger (also referred to as “C-HEX”) 1401, wherein the HS-WF 206 transfers thermal energy to a Coolant Working Fluid (also referred to as “CWF”) 1402, which may be represented by air, water or any suitable fluid in gaseous, liquid or supercritical form. When HS-WF 206 is represented by a gas (e.g. Helium), a turbo-machinery 1503 may be represented by a fan-, recirculator- or a compressor-driven by a motor 1503. When HS-WF 206 is represented by a liquid (e.g., water, liquid metal, supercritical and other suitable coolants), the turbo-machinery 1504 may be represented by a pump impeller driven by the motor 1503. As HS-WF 206 is compressed and circulates within a Heat Source Heat Exchanger (also referred to as “HS-HEX”) 1410, it increases its energy content and flows through the outlet of HS-HEX disposed within the pressure vessel 1501 as a high-temperature HS-WF 206ht, prior to expanding in an expander turbo-machinery 1411. The HS-HEX 1410 may be thermally coupled to any heat source, including the heat source represented by a nuclear core, in which fission or fusion nuclear fuel generates thermal energy. As the high-temperature HS-WF 206ht expands through a turbo-machinery 1411, its energy content decreases proportionally to the amount of thermal energy converted to electricity through an electric generator 1412. For example, when there is no conversion of electricity through the electric generator 1412, the high-temperature HS-WF 206ht may not change its energy content. When even a fraction of the high-temperature HS-WF 206ht is converted into electricity through mechanical coupling between the expander turbo machinery 1411 and the electric generator 1412, the energy content of this fluid is reduced and becomes hot HS-WF 206h. In the following description, it is assumed that a portion of the energy content of the HS-WF exiting the HS-HEX is converted into electric power distributed via electric cable and tree-phase or DC electric buses 1417 that may be coupled to the electric generator-motor 120 of engine 1414. When the electromagnetic rotary machines referred to as motor 1503, generator 1412 and generator 120 are formed by induction rotors or permanent magnets rotors, these machines can switch from motors to generators

depending on whether the electromagnetic rotor is providing torque to turbomachinery, also referred to as motoring, or the turbomachinery supplies torque to the electromagnetic rotor, also referred to as generating.

[072] The hot HS-WF 206h, discharged by the turbo machinery 1411, circulates through the HS-WF hot piping 412 through a hydraulic port 901 coupled to an Outer Shell Pressure Vessel 1502. As a result, the hot HS-WF 206h flows into an E-HEX inlet port 1314, which is a part of an E-HEX primary header 1304p. As a result of thermal transfer from the hot HS-WF 206h to the compressed cold WF 112c, HS-WF 206h energy content is further decreased and becomes cold HS-WF 206c. In this configuration, the compressed WF 112c circulating back into the pressure vessel 1501, represents the Ultimate Heat Sink of the Heat Source 1410. As a result of thermal transfer from HS-WF 206h to WF 112c this working fluid becomes hot WF 112h. Hot WF 112h circulates through hot piping 1305h into the modified engine hood 1101 through the inlet port 1316. Hot piping 1305h and portions of ducting inside the engine hood 1101 are thermally insulated. Thermal insulation is also utilized to thermally insulate the cold WF 112c from the hot WF 112h through thermally insulated structural components 1303st inside engine hood 1101.

[073] As compressed hot WF 112h flows inside the engine hot WF 112h collector 1309a, it is fluid-dynamically conditioned through internal channel structures 1303a and nozzle conduit 109 in order for hot WF 112h to flow at optimal thermodynamic and fluid dynamic conditions out of nozzle plan N. A hot WF chamber 1309 and its internal conduits thermally insulated from the engine compressor rotor 118a, engine shaft 118 and compressed WF inlet conduit 109b may be configured to form the nozzle supporting structures to condition hot WF 112h for expansion through one or multiple turbo-machinery expander rotary components 117.

[074] To summarize, as hot WF 112h flows out of secondary E-HEX header 1304s through hydraulic port 1308, it flows through hot WF piping 1305h into hydraulic port 1316 of modified engine hood 1101, and pressurizes casing 103 sealed by hood 1101 through sealing flanges 103a coupling the engine casing 103 to the engine hood 1101. Within casing 103, a series of internal conduits physically separate and thermally insulate the cold WF 112c from the hot WF 112h through the internal insulated channel 1303b on the compressor side, and flow conditioning pathway 1303a combined with the nozzle structure 109 to further condition hot WF 112h prior to expansion through expander rotary turbomachinery 117. Thus, hot WF 112h exits the nozzle plane N and is further conditioned by stationary multistage or single stage turbo machinery 116 and expands through multistage or single stage rotor 117. As hot

WF 112h expands, its energy content is reduced proportionally to the amount of thermal energy converted into mechanical energy at the shaft 118. When there is no thermal-to-mechanical energy transfer to shaft 118, the temperature of hot WF 112h does not substantially change and exhaust WF 112e temperature is similar to the temperature of WF 112h. When rotor turbo-machinery 117 transfers mechanical energy to shaft 118 a portion of this energy is employed by the compressor rotor 118a for the compressor to compress WF 112, the remaining energy may be converted into electricity by generator 120, for distribution by power cable and three-phase AC or DC electrical buses 125, and/or to compress exhaust WF 112e into process heat tubing 1004 coupled to the engine outlet 808 through hydraulic coupler 1003 to transport exhaust WF 112e at a controlled temperature, based on the amount of WF 112h converted to electricity via generator 120, to support process heat applications as, for example, shown in Figures 20-22.

[075] As a result, the carbon-free heat source energy of the present invention is configured to convert thermal energy represented by the HS-WF 206ht into electricity directly via electric generator 1503, indirectly via generator 120 and into exhaust WF 112e at a desired working pressure and temperature. WF 112e can be intubated, through piping via hydraulic coupler 1003 to process heat piping 1004, and transported to support process heat applications as it will be described in Figures 22, 23 and 24.

[076] Fig. 16 is a schematic representation of the carbon-free heat source of Fig. 15 coupled to an external heat exchanger 1306 through high temperature piping 1305h surrounded by low-temperature piping 1305c.

[077] Fig. 17 is a schematic representation of the engine 1414 shown in Fig. 14 and Fig. 15 coupled to an external heat exchanger 1702 integrated within a carbon-free heat source 1700 configured to produce thermal power.

[078] Fig. 18 is a schematic representation of the carbon free engine 1100 shown in Fig. 11 integrating a compact or printed circuit heat exchanger 1200 also denoted as 1801 in this Figure, within the extended hood 1101 of the engine 1100 directly coupled to the heat source working fluid 206 of a carbon-free heat source 1800 comprising a simple Brayton or Rankine cycle.

[079] Fig. 19 is a schematic representation of the engine 1100 shown in Fig. 11, directly coupled to the heat source working fluid 206 circulating in two carbon-free heat source units, where heat source unit 1400 produces electricity and heats up the heat source working fluid 206, while the other carbon-free heat source unit 1900 only heats up the heat source working fluid 206.

[080] Fig. 20 shows a system for electric and thermal power conversion and power utilization according to an embodiment of the present disclosure. The system may also be referred to as a thermal and electric power conversion and utilization system 2000S, which may include a thermal energy source 2000 (also referred to as heat source 2000 or HS 2000), a first power conversion system 2001 (also referred to as PCS 2001), a second power conversion system 2002 (also referred to as PCS 2002), and a thermal and electric power utilization system 2003. The heat source 2000 may be any suitable heat source, including, for example, a heat source obtained by a core with fission or fusion nuclear fuel, a heat source represented by a solar collector, or a heat source represented by industrial processes producing waste thermal energy. The heat source 2000 may be referred to as a carbon-free heat source 2000. For illustrative purposes, a fission nuclear reactor, as also described in Figs. 9 and 14-19, is used as an example heat source, and an electric arc furnace and a long steel product re-heating station (shown in Fig. 22) are used as an example of thermal and electric power utilization system. The principles and embodiments apply to any suitable heat source where thermal energy may be utilized for conversion to electricity and to support any suitable high- and low-temperature industrial process, in which the utilization of process heat (e.g., electric and high-temperature process heat for hydrogen production) may be implemented.

[081] The carbon-free heat source 2000 may be formed by an intermediate heat exchanger 2007 (also referred to as I-HEX 2007), thermally coupled to a heat source heat exchanger 2004 (also referred to as source heat exchanger 2004 or Source-HEX 2004), where the I-HEX 2007 and the Source-HEX 2004 may be disposed within a modular container 2039 to reduce the balance of plant outside of container 2039 and to ease transport. I-HEX 2007 and Source-HEX 2004 are thermally coupled through heat transfer media 2005 and heat transfer media C2006. The Source-HEX 2004 may be disposed within the source pressure vessel 2046. The heat transfer media 2006 and the I-HEX 2007 may be disposed within a pressure vessel 2008. Pressure vessels 2046 and 2008 may be flanged together through a flange 2047 or be merged into a single pressure vessel should the selected heat transfer media 2005 and 2006 be the same or compatible. Heat transfer media 2005 and 2006 may be represented by any suitable gaseous, liquid or supercritical fluids utilizing convective and conductive heat transfer mechanisms, as well as by solid materials utilizing thermal radiative and conductivity heat transfer mechanisms. The Source-HEX 2004 may be configured to generate thermal energy through thermal coupling of the heat transfer media 2005 with any typology of fission or fusion fuels. Through the heat source working fluid 206 (also referred to as HS-WF 206), the

I-HEX 2007 is thermally coupled to the process heat exchanger 2030 (also referred to as P-HEX 2030), which may be disposed within a modular container 2041, which houses the PCS 2002. HS-WF 206 may be any suitable working fluid as those utilized as heat transfer media 2005 and 2006. HS-WF 206 thermally couples the thermal energy source 2000, PCS 2001, PCS 2002 and the power utilization system 2003. For illustrative purposes, when HS-WF 206 is at a high energy thermodynamic state (e.g., high-temperature, high-pressure and high mass-flowrate), it is represented by dashed arrows. Alternatively, when HS-WF 206 is at a low energy thermodynamic state, it is represented by solid arrows. HS-WF 206 may circulate through containers 2039 that houses the source heat exchanger 2004, container 2040, housing PCS 2001, and container 2041 that houses PCS 2002, by operation of pump 2011 of PCS 2001. For configurations in which HS-WF 206 is a gaseous working fluid, pump 2011 may be configured as a compressor 2011. The flow rate of high energy content HS-WF circulating out of I-HEX 2007 may be controlled by a three-way valve 1901 actuated by a control system (not shown in Fig. 20). Depending on how valve 1901 is actuated, a substantial amount of the hot HS-WF 206 inventory may circulate directly into the P-HEX 2030 for thermal energy transfer to the process heat working fluid 2016 (also referred to as PH-WF 2016).

Alternatively, valve 1901 may be actuated to enable partial flow or shutoff the PH-WF circulation within PCS 2002. In this configuration, a substantial amount (e.g., substantially all) of the energy content represented by PH-WF may be converted into electricity by turbine-generator 2013. More generally, by actuating valve 1901, the electric and thermal power system operators (e.g., human users or machines, robots) determine the amount of thermal energy from Source-HEX 2004 that may be converted to electricity by PCS 2001, versus the amount of thermal energy transferred to the PCS 2002 and to the PH-WF 2016. The turbine-generator 2013, housed within container 2040, is part of a Rankine or Brayton thermodynamic cycle. For example, if the HS-WF 206 represents a working fluid in a gaseous form, the power conversion components forming the PCS 2001 support the operations of a Brayton cycle. If the HS-WF 206 is represented by a working fluid in a liquid form, the power conversion components forming the PCS 2001 support the operations of a Rankine cycle. Accordingly, when the PCS 2001 operates as a Brayton cycle, the turbomachinery of the turbine-generator assembly 2013 may be represented by axial or centrifugal turbines, the pressure tank 2012 may be utilized to support HS-WF 206 inventory control operations, for example, through actuation of valves to reduce or increase the inventory of gaseous HS-WF 206 (pressure tank 2012 valves are not shown in Fig. 20). To complete the thermodynamic closed-loop forming the PCS 2001, the cooler heat exchanger

2009 may reset the HS-WF 206 minimum Brayton cycle temperature and pressure. In this configuration, the cooler heat exchanger 2009 may be represented by a radiator, through which HS-WF 206 circulates on one side of the cooler heat exchanger, with fluids representing the Ultimate Heat Sink, for example, environmental air or water, circulated on the other side of the cooler heat exchanger 2009, further aided by active fans or pumps. When the HS-WF 206 is represented by a working fluid in a liquid form or a two-phase fluid (e.g., water-steam), the turbine-generator 2013 may be represented by a traditional vapor-powered turbine driving an electric generator, the cooler heat exchanger 2009 and the HS-WF 206 reservoir 2010 become part of the Rankine cycle condenser, and the pressure tank 2012 may be represented by a pressurizer. The thermal-hydraulic couplings between containers 2039, 2040, and 2041 are not shown in Fig. 20. These hydraulic couplings may be represented by hydraulic ports 901 as shown, for example, in Fig. 9.

[082] Therefore, when pump 2011 (or compressor 2011 for gaseous HS-WF 206), and actuated three-way valve 1901 is set to circulate HS-WF 206 through the P-HEX 2030, it thermally couples the thermal energy source 2000 to the PCS 2002 through thermal transfer from HS-WF 206 to PH-WF 2016. Accordingly, PH-WF 2016 flows through inlet 2045 of the compressor-recirculator housing 2051 as a result of the pressure variations induced by motor-driven compressor 2014. The rotary drive for the turbomachinery of the motor-driven compressor 2014 may be supplied by electricity generated by the PCS 2001, electricity generated by the turbine-generator 2021. Alternatively, the compressor-recirculator turbomachinery 114 can be driven by shaft 118a as shown in Figs. 5-7, and 11, 13, 13a, 17-19 when the generator 120 is disconnected from mechanical coupler 121. For the example shown in Fig. 20, the compressor-recirculator turbomachinery 114 is driven by an electric motor with multiple electric energy source, as represented by the PCS 2001 and the PCS 2002, where electric power is controlled and distributed across the electric and thermal conversion system 2000S through the power supply 1710 which may be coupled to the power grid or system 2000S microgrid, for example, represented by electrical connections 2042.

[083] As PH-WF 2016 is compressed by compressor turbomachinery 114, it flows through the one circuit of the P-HEX 2030 (e.g. heat exchanger secondary circuit), without mixing with the HS-WF 206 circulating on the other circuit of this heat exchanger (e.g., heat exchanger primary circuit). Depending on the position of vent valve 2023 and the position of hot PH-WF flow regulator valve 2023a, substantially all of the inventory, or a part of the inventory, of hot PH-WF 2016h flows through inlet 2037 of power utilization system 2003. Assuming vent valve 2023 of PCS 2002 is set to the closed position, all of the inventory of

the hot PH-WF 2016h, flows out of outlet 2043 interfacing the PCS 2002 with the arc furnace piping 2052, into the furnace 2032. When actuated valve 2023a is open, hot PH-WF 2016h flows inside furnace 2032 through inlet 2037 as a result of compressor turbomachinery 114. Once inside the furnace 2032, PH-WF 2016h, transfers its thermal energy to the materials to be melted into liquid steel to support industrial steelmaking operations. These materials are transformed from solids at environmental temperature to liquid through very high temperature induced by electric arcs. As electrodes 2036 are lowered and contact the conductive metal materials to be melted, a high temperature area 2028 is formed. By continuing this process for a time period, substantially all of the solid materials inside the furnace may change their thermodynamic state from solid to liquid, which may need substantial energy. By elevating the energy content of the materials to be melted prior to the steelmaking materials becoming liquid steel 2050 through electric powered electrodes 2036, the total electric consumption at the electrodes 2036 is reduced proportionally to the amount of energy transferred from the thermal energy source 2000, to the power utilization system 2003 via PH-WF 2016h. By lowering the electrodes 2036 into the materials inside the furnace 2032 preheated by the PH-WF 2016h, these materials melt with lower energy consumption. The electric arcs induced by the electrodes 2036, when lowered into the metal materials to be melted until a liquid metal 2050 with the desired properties is formed, require less time to reach the desired liquid steel properties. During this steel processing phase, the hot PH-WF 2016h flows inside the furnace 2032, heats up the solid materials to be melted into liquid steel, and continues to flow out of the furnace 2032 through outlet 2038 and return PH-WF piping 2017. As PH-WF 2016h flows through return piping 2017, it flows through a filtering system 2029 configured to trap contaminants from the materials to be melted inside the furnace. Filtered PH-WF 2016f flows through heat exchanger 2033 disposed within or thermal-hydraulically coupled to return flow piping 2017, to cool down prior to entering inlet 2045 of the PCS 2002. Part of the thermal energy transferred by PH-WF 2016f is converted into electricity by turbine-generator 2021 (e.g., based on a Rankine or Brayton power cycle), while a portion of this energy is rejected to the environment through condenser heat exchanger 2022, (for Rankine configurations), or radiator heat exchanger 2022 (for Brayton configurations), thermally rejecting heat via fan 2018. The fan 2018 may be disposed at PCS 2002 outlet 2019, where environmental cooling fluids (e.g. water or air) flow through PCS 2002 inlet 2020.

[084] As liquid steel outlets furnace 2032 through gate 2048, begins forming desired shapes through steel processing and shaping equipment 2025 which processes the soft hot steel

2049. After processing the soft hot steel 2049 through a series of steelmaking equipment 2205, it become a final product 2206 with a desired shape and dimensions (e.g., rebars, slabs, I-beams, E-beams and other shapes forming industrial steel products).

[085] When the liquid steel reaches the desired properties for the particular steel alloy to be processed, the electrodes 2036 are lifted and electrically disconnected via electric bus 2035, and the liquid steel gate 2048 is opened for a duration of time proportional to the amount of liquid steel 2050 to be processed while emptying the furnace. During this steel manufacturing phase, there is no need to supply electricity via electrodes 2036 and also no need to transfer thermal energy via PH-WF 2016h into furnace 2032. A lower electrical power rating may still be needed to run the steelmaking equipment 2205. During this steelmaking phase, the actuated PH-WF valve 2023a is closed, while the actuated vent valve 2023 is opened. With these valves configured as described, the hot PH-WF 2016h transfers its energy to heat exchanger 2024 of the PCS 2022. During the emptying of liquid steel from the furnace 2032, the carbon-free thermal energy source 2000, the PCS 2001, and PCS 2002 may be configured to produce electricity to be distributed to the power grid or system 2000s microgrid to support steel re-heating as shown in Fig. 22, via electric buses 1710, and power conditioner 2035. As re-heating processes may need hot PH-WF 2016h, a controlled flow of PH-WF 2016h is provided through manifold 2053 for thermal hydraulic coupling with hot PH-WF hot piping 2027 as, for example, shown in Fig. 22.

[086] Fig. 21 shows a simplified configuration with schematic and top view representations of the system for electric and thermal power conversion and power utilization 2000s shown in Fig. 20. Fig. 21 further shows multiple thermal and electrical energy sources and power conversion systems according to another embodiment of the present disclosure. The system shown in Fig. 21 may also be referred to as a thermal and electric power conversion and utilization system 2100. Fig. 21 shows a top view of building 2101, housing multiple thermal energy sources configured as, for example, heat sources 900, 1700 and 1400, described in Figs. 9, 14 and 17 respectively, a power conversion system 2002, described in Fig. 20, an underground Independent Spent Fuel Storage Installation (ISFSI) 2012, as defined by the U.S. Nuclear Regulatory Commission, an electric power transformer 2035 to condition the electricity produced by the power conversion system 2002 and supply it to the electric and thermal power utilization system 2003, a thermally insulated piping system 2027 for a working fluid 2016h at high temperature to flow directly from the thermal sources 900, 1700 and 2100, or indirectly through the process heat exchanger 2030 (also referred to as P-HEX 2030) of power conversion system 2002 shown in Fig. 20, a power utilization system 2003

represented by a furnace 2032, and a thermally insulated flow return piping system 2017 thermal-hydraulically coupled to the furnace 2032 for the working fluid 2016h with a lower energy content to return to the power conversion system 2002.

In the configuration of the system for electric and thermal power conversion and power utilization 2100, the thermal energy sources 900, 1700 and 1400 are disposed within prefabricated building 2101, underground and vertically. Each of the thermal energy sources 900, 1700 and 1400 may be configured to produce thermal energy only, electricity only, or both: process heat and electricity. Furthermore, thermal energy source can be configured to produce electricity to supply power transformer 2035 with conditioned electricity to drive the furnace electrodes 2036, while thermal energy sources 1700 may be configured to produce process heat and electricity to satisfy peak power requirements characteristic of the highly variable electrical load represented by the operations of electrodes 2036, and thermal energy source 1400 may be configured to supply only thermal energy to furnace 2032. One of the objectives of the present disclosure is to provide a thermal and electric power station collocated with the steel manufacturing plant, wherein the thermal energy sources 900, 1400, 1700 are configured to satisfy the highly variable energy profile requirements represented by steelmaking processes. Building 2101 may be represented by a prefabricated building 2101, wherein all of its construction components can be manufactured at a factory for ease of a rapid installation. The thermal energy sources 900, 1400 and 1700 may be installed by lowering and mechanically securing them within underground shafts. Multi-purpose crane 2103 may be equipped with shaft tunneling equipment to expedite excavation, positioning and operations of the thermal energy sources housed within building 2101. The thermal and electric power conversion and utilization system 2100 results in a small footprint inclusive of the steel manufacturing plant represented by the furnace 2032 and steelmaking equipment, for example, shown in Fig. 22, with building 2101 altogether within the power generation and steelmaking plant comprised within the plant security fence 2104. The building 2101 shown in Fig. 21 is configured to house three thermal power sources and one ISFSI. As this is a prefabricated design for the building, extending it to accommodate additional thermal energy sources, for example, to satisfy increased steel production capabilities may be done at low cost. The operations and functions of the thermal energy sources 900, 1400 and 1700, as well as those of the power conversion system 2002 and power utilization system 2003 are described in greater detail in Fig. 20.

[087] Fig. 22 shows a representation of an application of the thermal and electric power conversion and power utilization systems 2000a and 2001 described in Fig. 20 and Fig. 21

respectively as a thermal generator to supply thermal energy to reheat steel during steelmaking processes. Fig. 22 shows a top view of the building 2101 described in Fig. 21 and a schematic representation of a reheating chamber 2200. The building 2101 houses the thermal energy sources and power conversion systems to supply a process heat working fluid 2016 (also referred to as PH-WF 2016), to re-heat steel that cools down as it undergoes steelmaking processes. As described in Fig. 20, the high-temperature piping 2027 supplies process heat in the form of working fluid 2016h to the inlet 2037 of furnace 2032, with controlled valves 2023a and 2023 regulating the working fluid 2016h flowrate supplied to the furnace and to the power conversion system 2022. This configuration enables the thermal and electric power conversion and utilization system 2000S to rapidly “switch” from thermal to electric power production and vice-versa repeatedly and at a high rate to satisfy the intermittent operating power profile of the furnace 2032. Furthermore, in Fig. 20, the thermally insulated piping 2027 is coupled to the process heat working fluid manifold 2053 (also referred to as PH-WF manifold 2053) and to the furnace inlet 2037. In Fig. 22, the PH-WF manifold 2053 is coupled to thermally insulated piping 2027 through valve 2023a, however, this is just an exemplary configuration, as the PH-WH manifold 2053 may be hydraulically coupled anywhere along the high temperature piping 2027 and configured to regulate a portion of the flow of working fluid 2016 into the re-heating steelmaking equipment represented by steel processing reheating chamber 2200 and a portion of the flow of working fluid 2016 into the furnace inlet 2037.

[088] Traditionally, steelmaking re-heating chambers may be configured with a fossil fuel burner or electrical heaters, or a combination of both. The fossil fuel burner operates similarly to the injection system 105a shown in Figs. 1-3, 10 and 13 for the engine 100 and several of the engine configurations described in the present disclosure, where an oxygen containing mixture is mixed with a fossil fuel (e.g., methane) to generate high-temperature combustion gases. In a steel reheating chamber, the combustion gases are then utilized to elevate the temperature of the steel being processed. For illustrative purposes, in Fig. 22, the steel being reheated within the steel processing reheating chamber walls or containment 2209, is assumed to be a steel slab 2226 processed by steel processing equipment 2205 from left to right of the representation as indicated by the solid black arrows. As steel slab 2206 is processed by steel processing equipment 2205, the slab is worked to obtain the desired shape, dimensions and steel hardening. As steel slab 2206 is formed and moves from the furnace outlet 2048 shown in Fig. 20, through the steelmaking plant equipment 2205, it cools down by natural heat transfer with the surrounding environment. One, or multiple, steel processing

reheating chambers 2200 (also referred to as reheating chambers 2200), are disposed throughout the steelmaking plant to increase the temperature of the steel being processed to ensure it remains sufficiently soft while being processed. The PH-WF 2016 supplied to the steel processing reheating chamber 2200 may provide all, or a portion, of the thermal energy needed to maintain the steel being processed sufficiently soft. Accordingly, the steel processing reheating chamber 2200 may be configured to operate with the PH-WF 2016 standalone, or a combination of “thermal energy suppliers” within the reheating chamber walls 2209 represented by the PH-WF 2016, a combustion system, operating as described for various engine 100 configurations of the present disclosure, and electric heaters driven by electrical power (combustors and electrical heaters within the walls of the reheating chamber 2209 are not shown in Fig. 22). In the configuration shown in Fig. 22, the thermal and electric power station included within the building 2101 described in Fig. 21, supplies compressed high-temperature PH-WF 2016 at its outlet 2043 through thermally insulated piping 2027 to a flow regulating valve 2023a which controls the flowrate of PH-WF 2016 flowing into the furnace inlet 2037 and the flowrate of PH-WF 2016 distributed by manifold 2053 to manifold 2202 via thermally insulating piping 2027 to the reheating chamber inlets 2203. Once inside the reheating chamber 2200, the PH-WF 2016 transfers thermal energy to the steel slab 2206 mainly through convective and radiative heat transfer mechanisms. As a result, the steel slab is found as relatively low temperature steel slab 2206lt when it enters the reheating chamber 2200, and its temperature increases as it moves through the reheating chamber 2200 to exit the reheating chamber as a relatively high temperature steel slab 2206ht. As the reheating chamber 2200 is pressurized by the PH-WF 2016, flexible seals 2207 minimize the loss of PH-WF 2016 at the reheating chamber processed steel inlet 2210 and outlet 2211. After transferring thermal energy to the steel being processed inside the reheating chamber 2200, the PH-WF 2016 is collected by the PH-WH 2016 collector 2204 at the PH-WF 2016 working fluid outlet of the reheating chamber 2200. The collector 2204 is at a lower pressure as it is hydraulically coupled to the inlet 2045 of power conversion system 2002 shown in Fig. 20. The PH-WH 2016 exhausting from the reheating chamber 2200 flows through the return flow piping 2017, filter 2029 and back into the thermal electric power station PH-WF inlet 2045, where it enters the compressor turbomachinery 114 described in Fig. 20.

CLAIMS

WHAT IS CLAIMED IS:

1. A power conversion system, comprising:

an engine including an engine casing, a first compressor, and a first expander coupled with the first compressor through a shaft, wherein an inner space of the engine casing defines an engine chamber for a first working fluid to circulate, and wherein the first compressor is configured to compress the first working fluid into the engine chamber;

an inlet and an outlet for the first working fluid to flow into and out of the engine casing;

a heat exchanger coupled with the engine, wherein the heat exchanger is configured to heat up the first working fluid compressed into the engine chamber by the first compressor, and wherein the heated first working fluid drives the first expander to rotate; and

a first electric generator coupled to the first expander and configured to generate electricity, wherein the first working fluid discharged from the first expander exits the engine casing with a temperature and a pressure proportional to the amount of electricity produced by the first generator;

an energy source disposed inside a pressure vessel, wherein the energy source is configured to transfer thermal energy to a second working fluid circulating inside the heat exchanger;

a motor, a second compressor, and a second expander, wherein the motor is configured to drive the second compressor, and the second expander is configured to drive a second electric generator, wherein the motor, the second compressor, the second expander, and the second electric generator are disposed within the pressure vessel.

2. A system, comprising:

an engine including an engine casing including an inlet and an outlet and defining an engine chamber, a first compressor disposed adjacent the inlet of the engine casing, wherein the first compressor is configured to compress a first working fluid into the engine chamber;

a first heat exchanger disposed inside the engine and is coupled with a heat source, wherein the first heat exchanger is configured to heat up the first working fluid compressed into the engine chamber by the first compressor;

a furnace coupled with the outlet of the engine chamber through piping, wherein the heated first working fluid flows through the piping into the furnace, wherein the first working fluid transfers thermal energy to metal forming materials disposed within the furnace, to elevate the temperature of the metal forming materials;

a second heat exchanger (2007) thermally coupled to the first heat exchanger (2030);

a second working fluid (S-WF 206) circulating between the first heat exchanger and the second heat exchanger;

a third heat exchanger (source heat exchanger 2004) thermally coupled to the second heat exchanger;

a first power conversion system (PCS 2001) including a first turbine-generator (2013) coupled to the second heat exchanger (2007), wherein the first turbine generator is configured to convert thermal energy from the second working fluid to electricity;

a second valve (2023) regulating the first working fluid (2016h)

a piping to return the first working fluid to the engine casing inlet to the first compressor;

a second power conversion system including a second turbine-generator (2021) configured to convert thermal energy of the first working fluid into electricity;

a fourth heat exchanger (2033) configured to transfer waste thermal energy carried by the first working fluid discharged from the furnace to a fifth heat exchanger (2024).

3. A power generation and steelmaking plant system, comprising:

a building collocated with a steelmaking plant system, wherein the building is configured to house a thermal energy source and a power conversion system;

a heat exchanger including a primary circuit and a secondary circuit, the primary circuit being thermally coupled by a first working fluid to the thermal energy source, and the secondary circuit being thermally coupled to the steelmaking plant system by a second working fluid;

a power transformer;

a turbine-generator system configured to convert thermal energy of the first working fluid into electricity and supply the electricity to the power transformer, wherein the power transformer is configured to condition the electricity;

a compressor with an inlet and an outlet for the second working fluid to flow through, the compressor being configured to be driven by expansion of the second working fluid;

a thermally insulated piping coupled to the outlet of the compressor and to the steelmaking plant system to supply compressed working fluid to the steelmaking plant system;

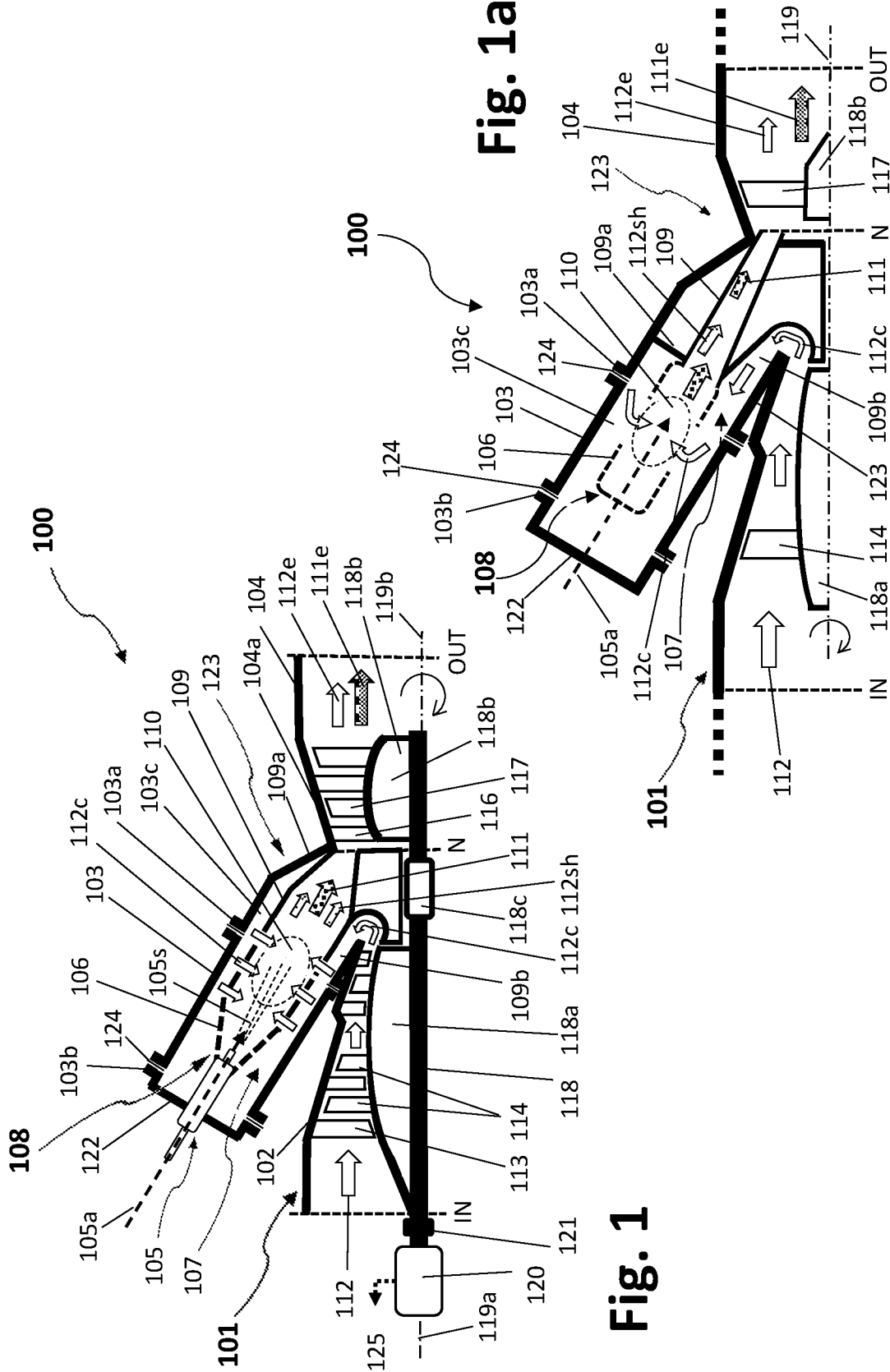
4. A system comprising:

a thermal and electric generator system;

a high-temperature chamber configured for steelmaking;

a piping system coupled with the thermal and electric generator system and the high temperature chamber, wherein the piping system is configured to transport a working fluid from the thermal and electric generator system to the high-temperature chamber, and from the high-temperature chamber to the thermal and electric generator system; and

a control valve configured to control a flowrate of the working fluid within the high-temperature chamber.



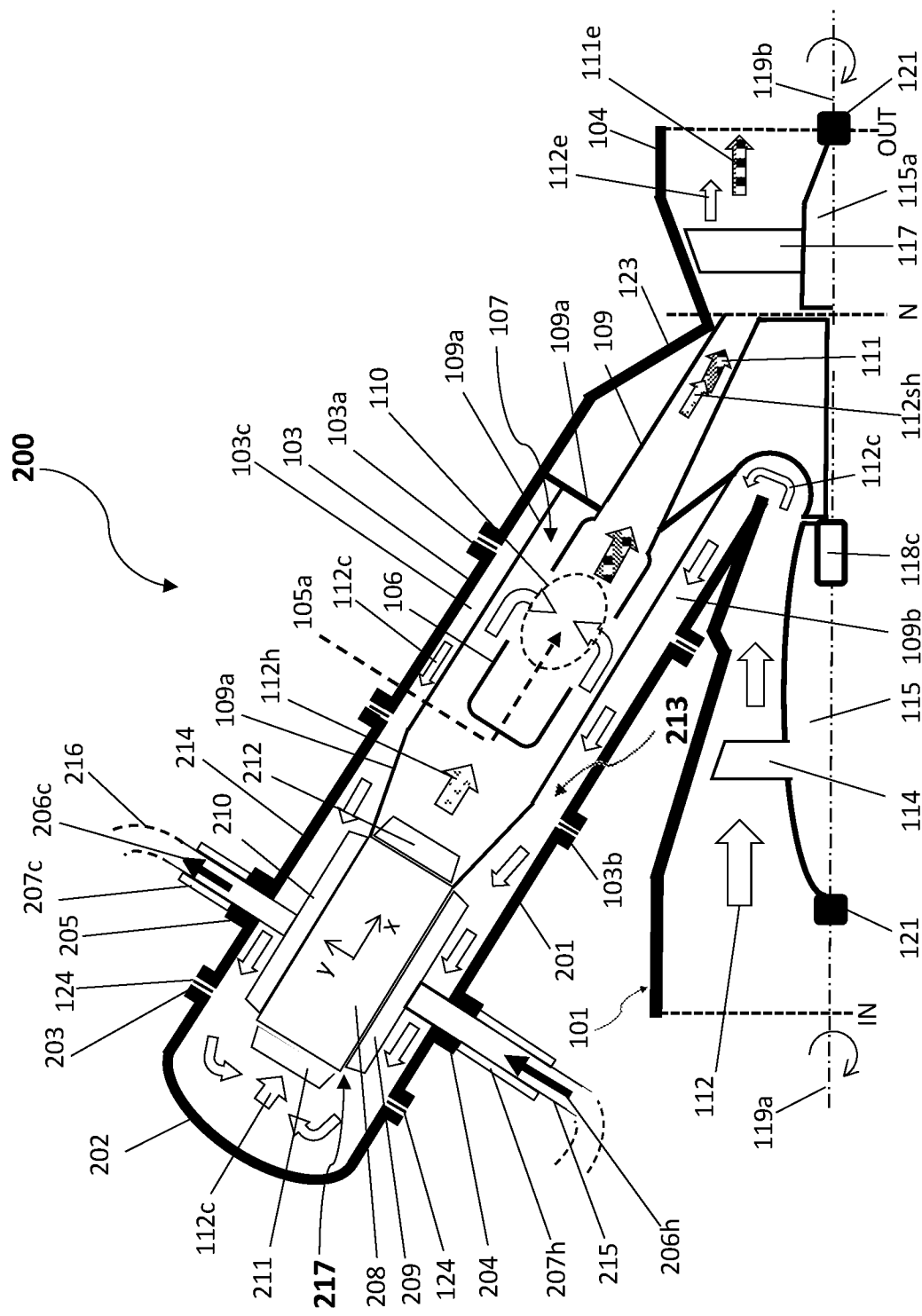


Fig. 2

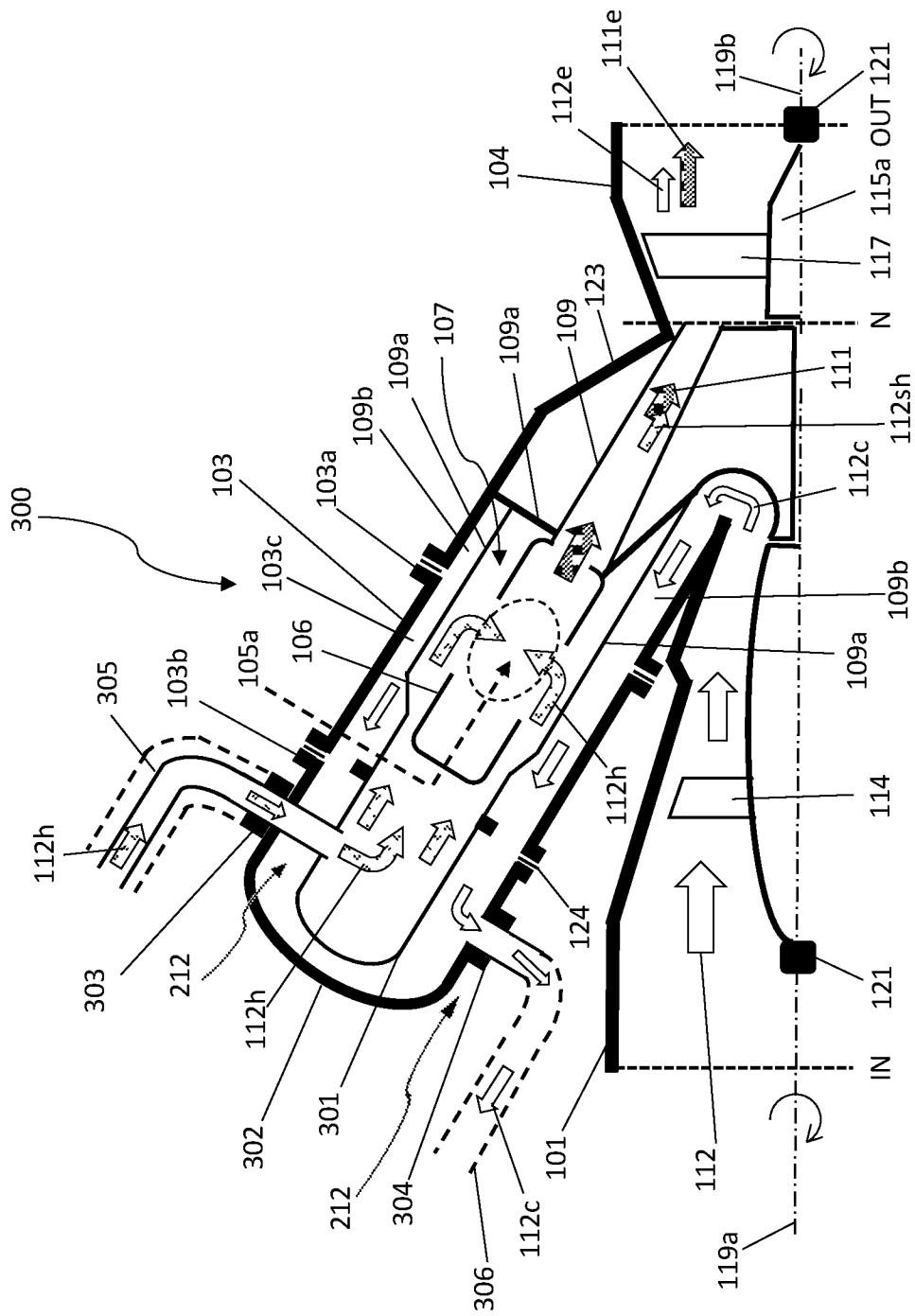


Fig. 3

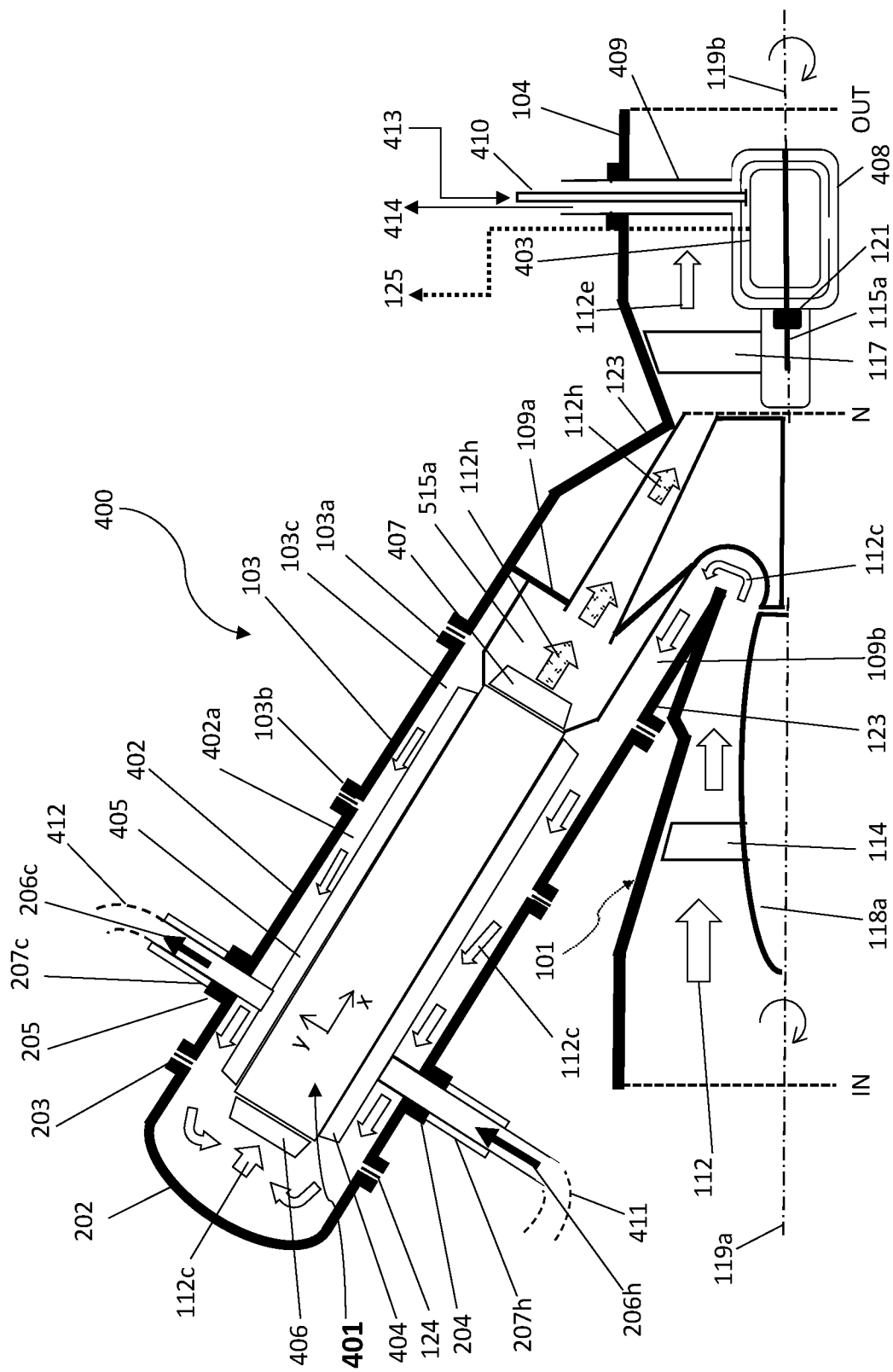
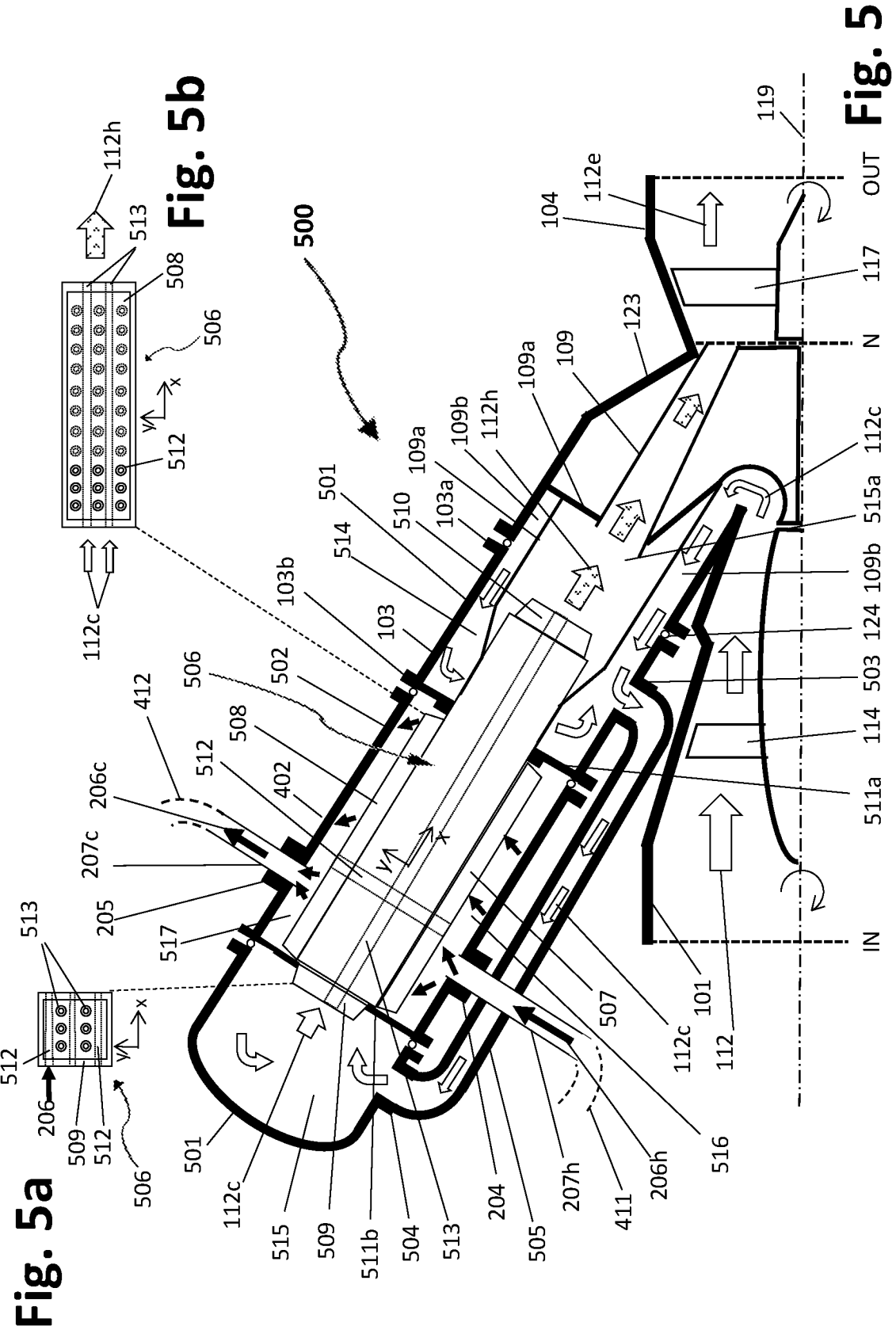


Fig. 4



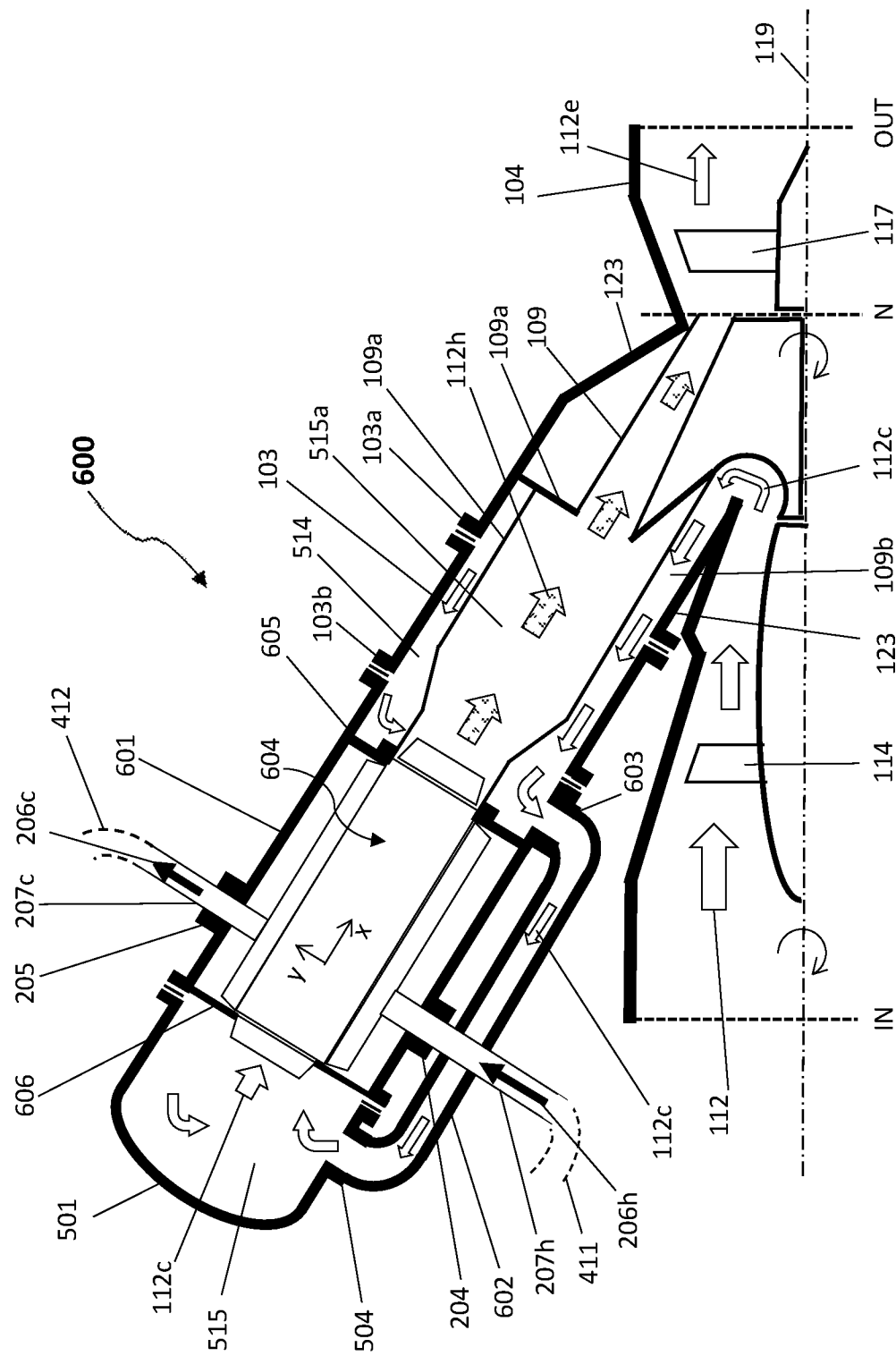


Fig. 6

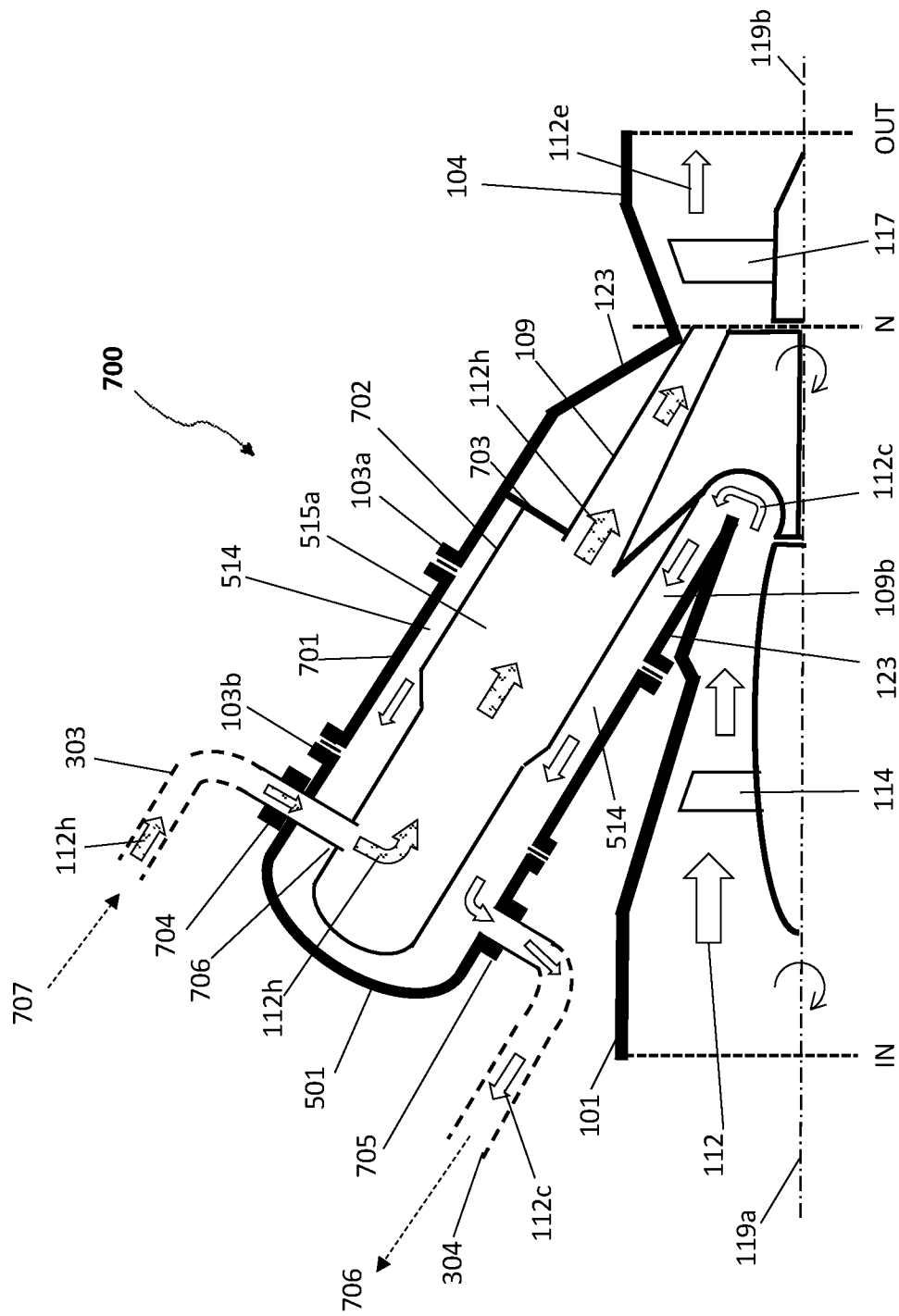
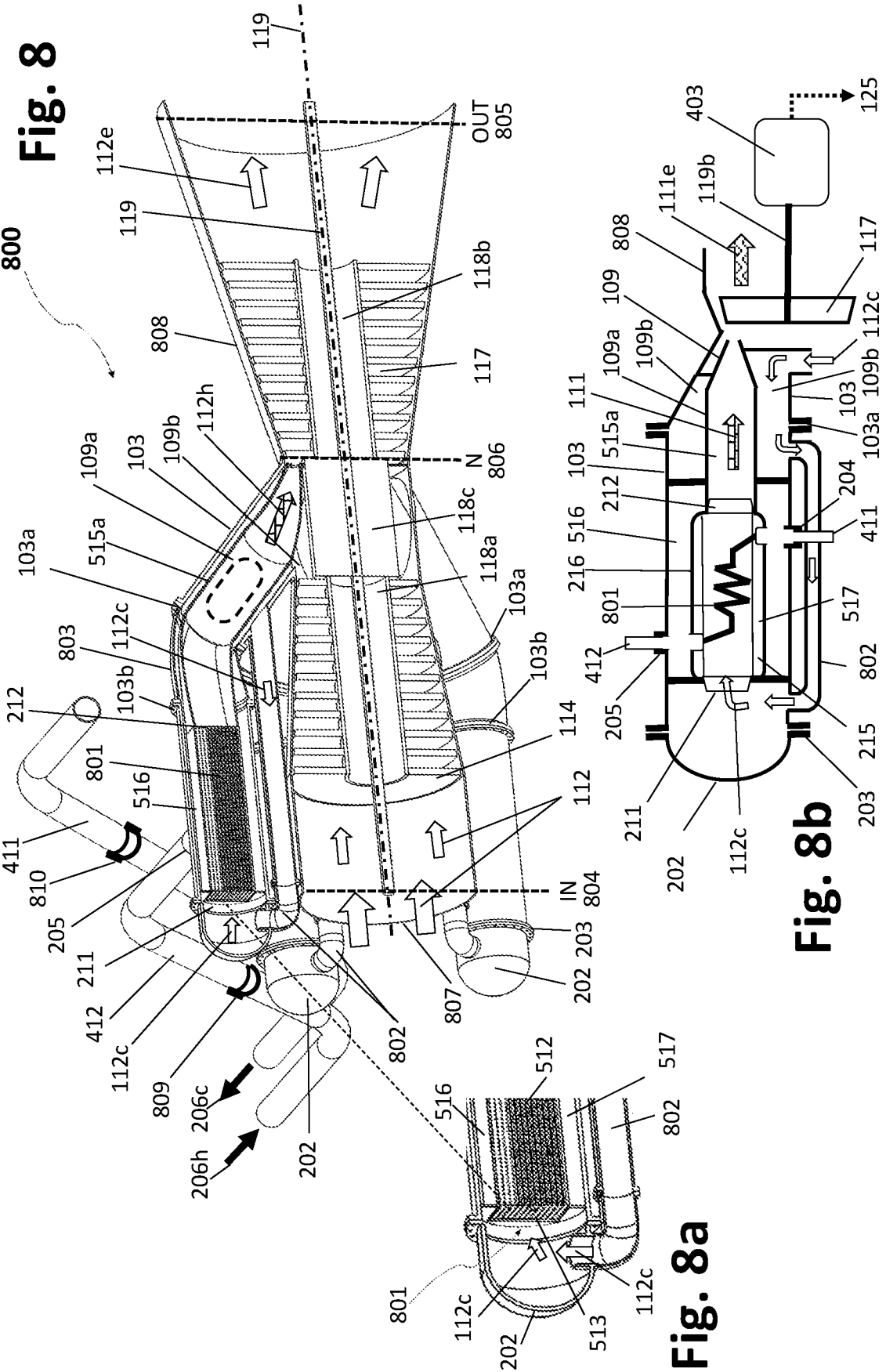


Fig. 7



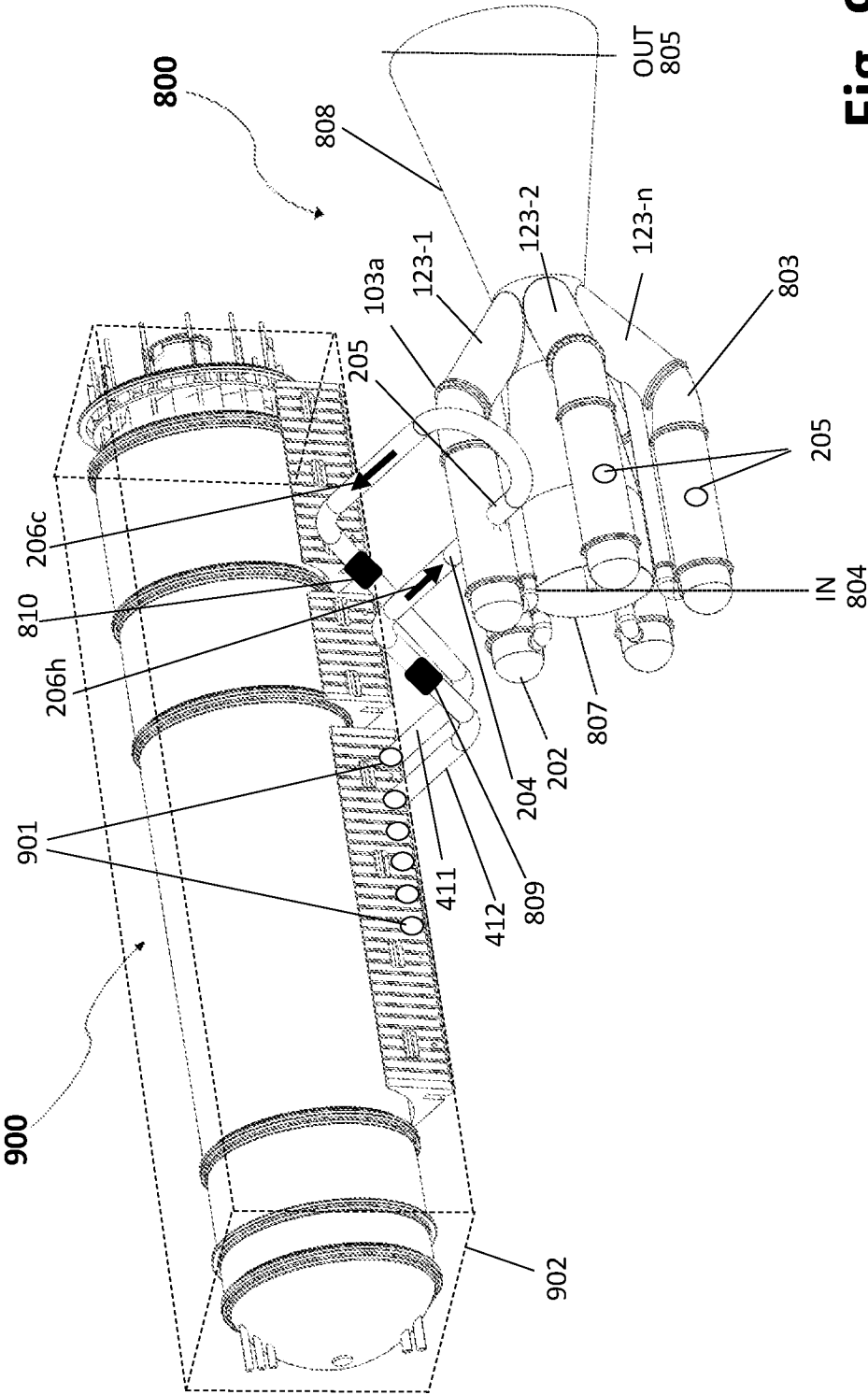


Fig. 9

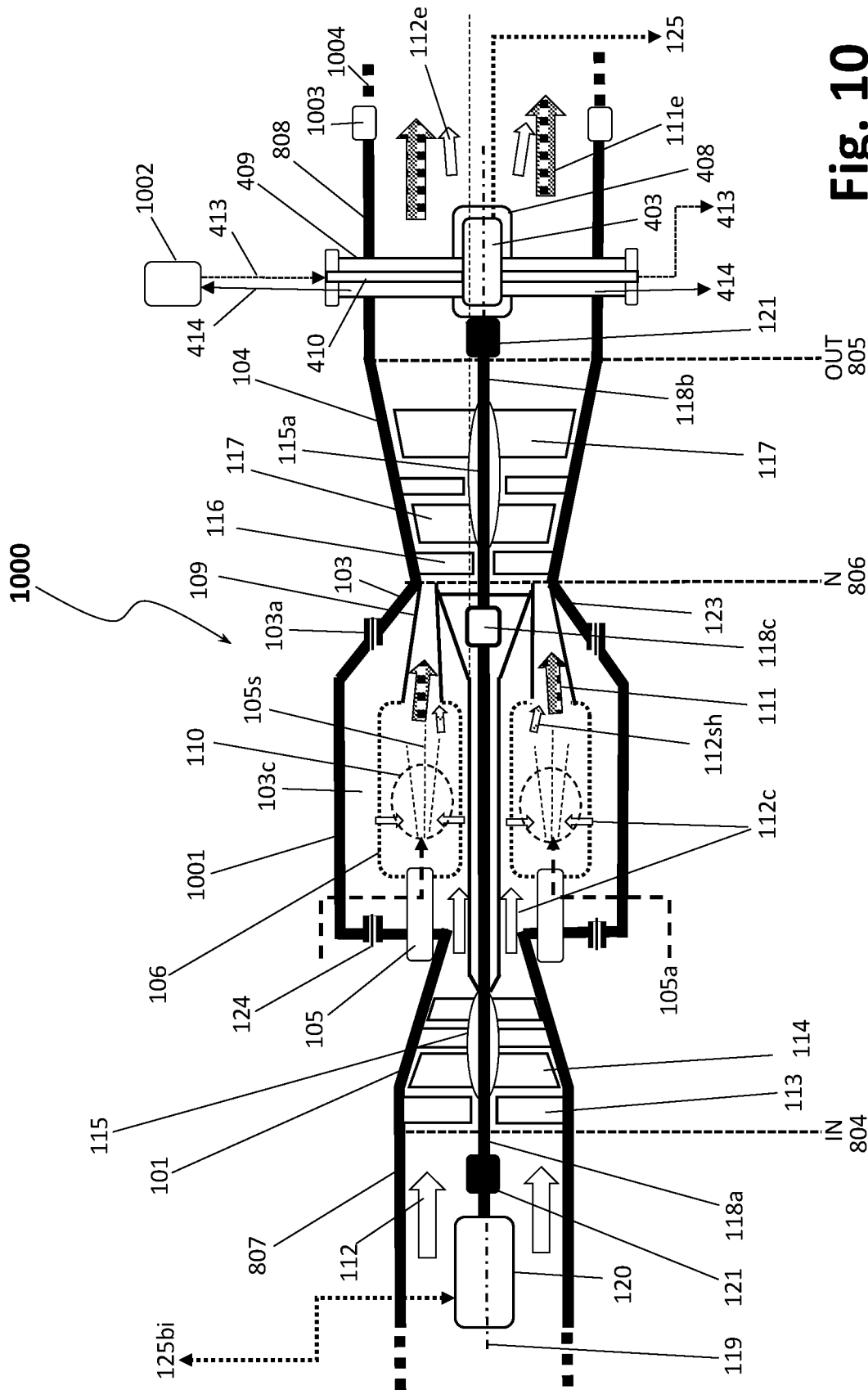


Fig. 10

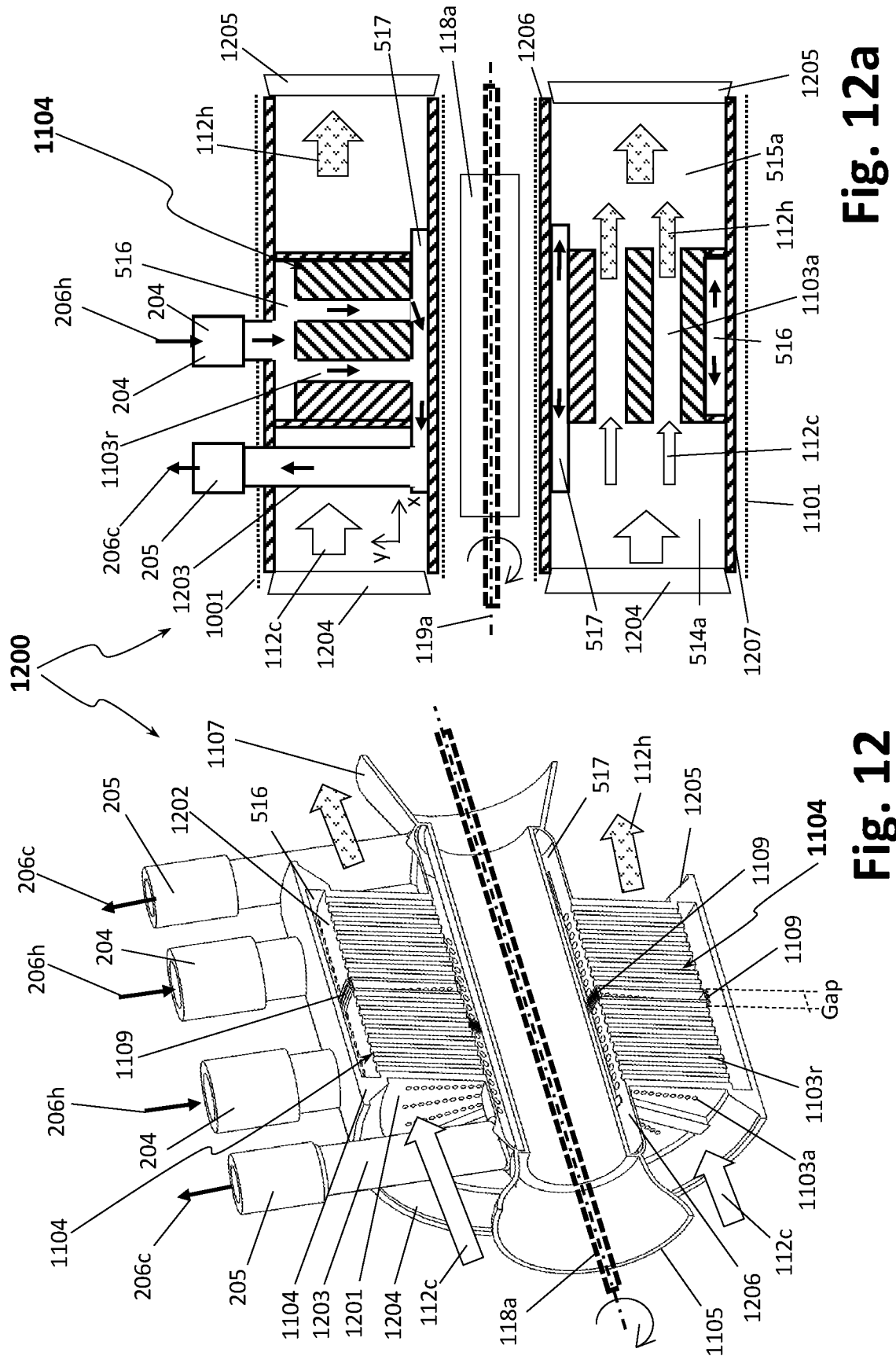
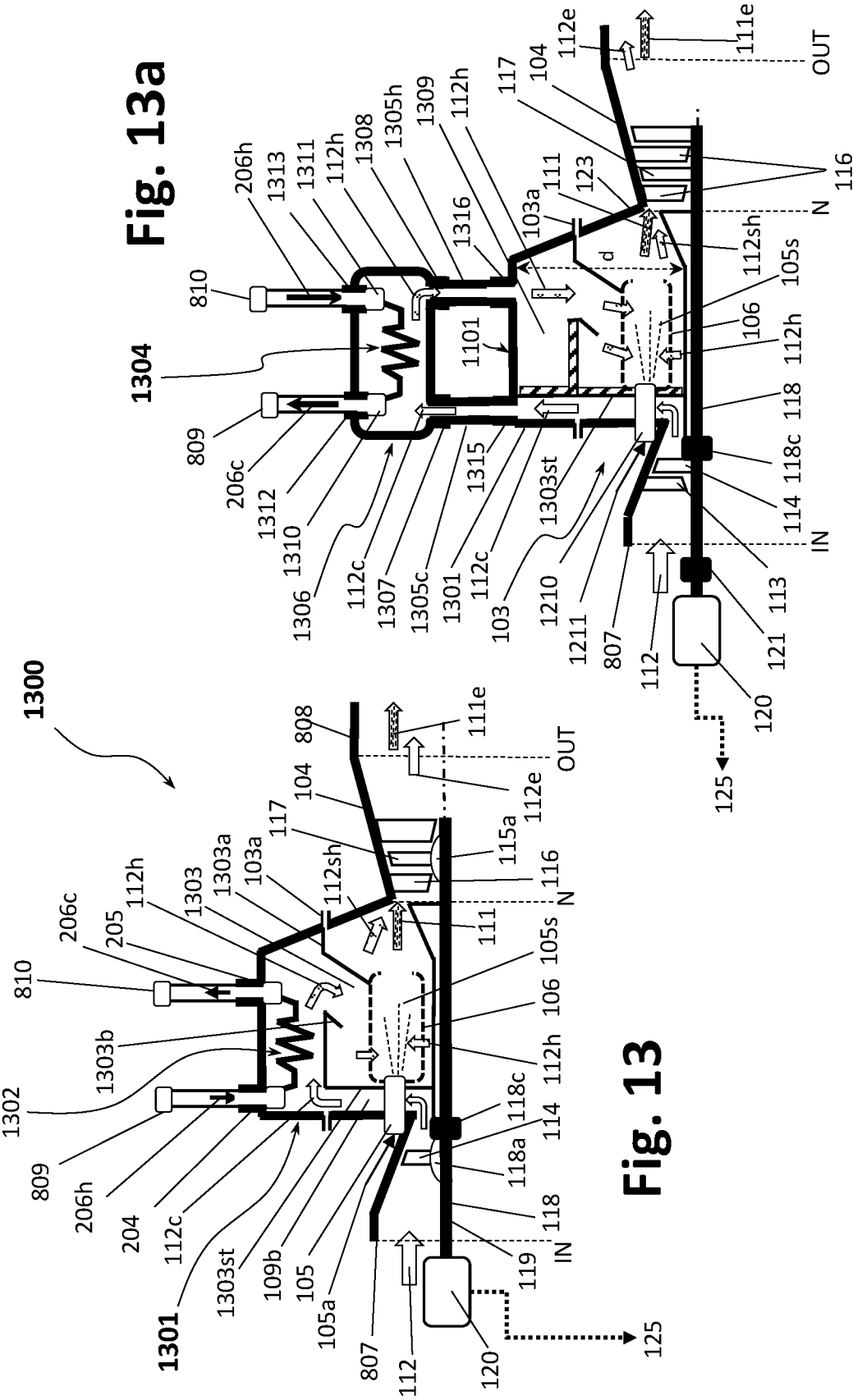


Fig. 12a

Fig. 12



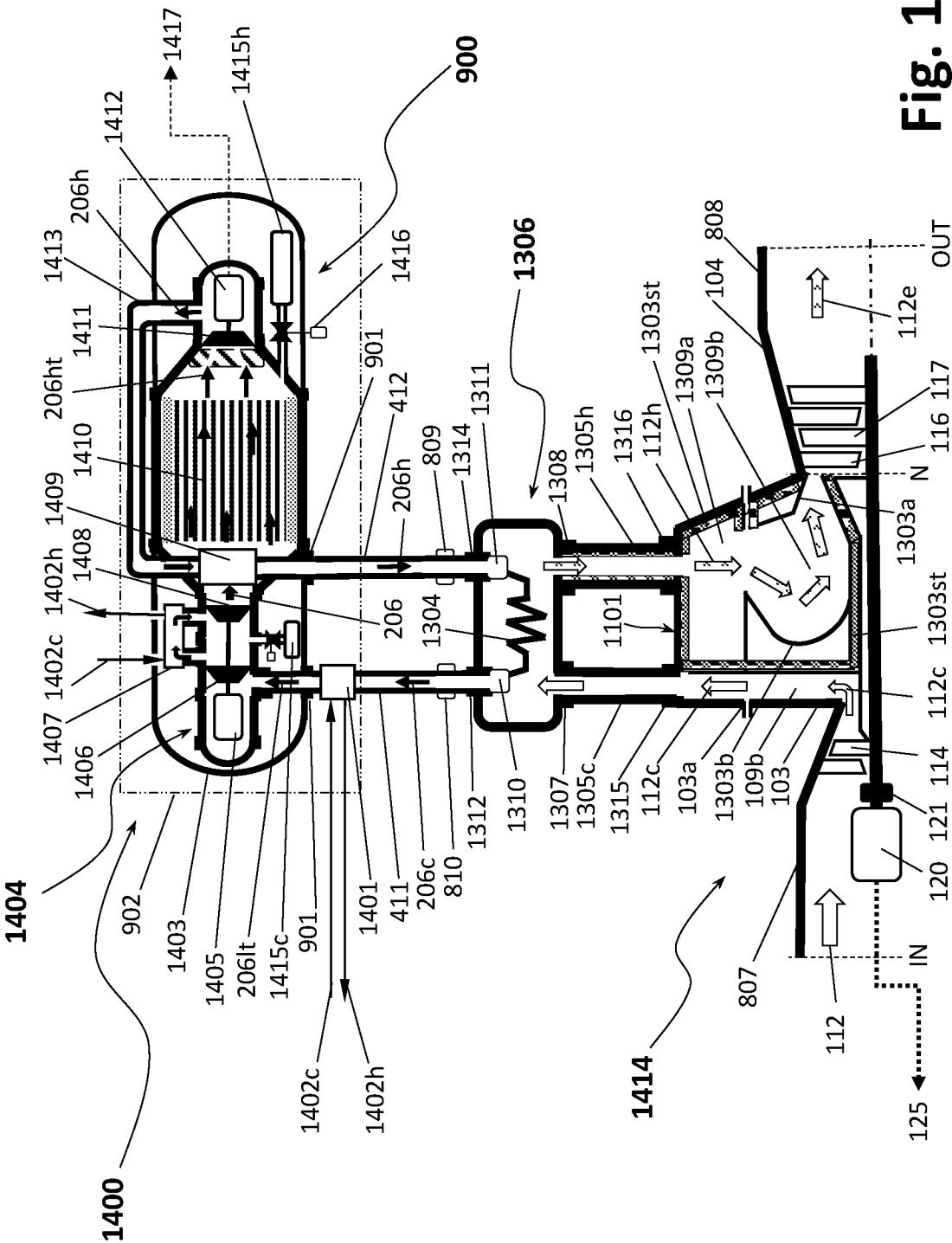
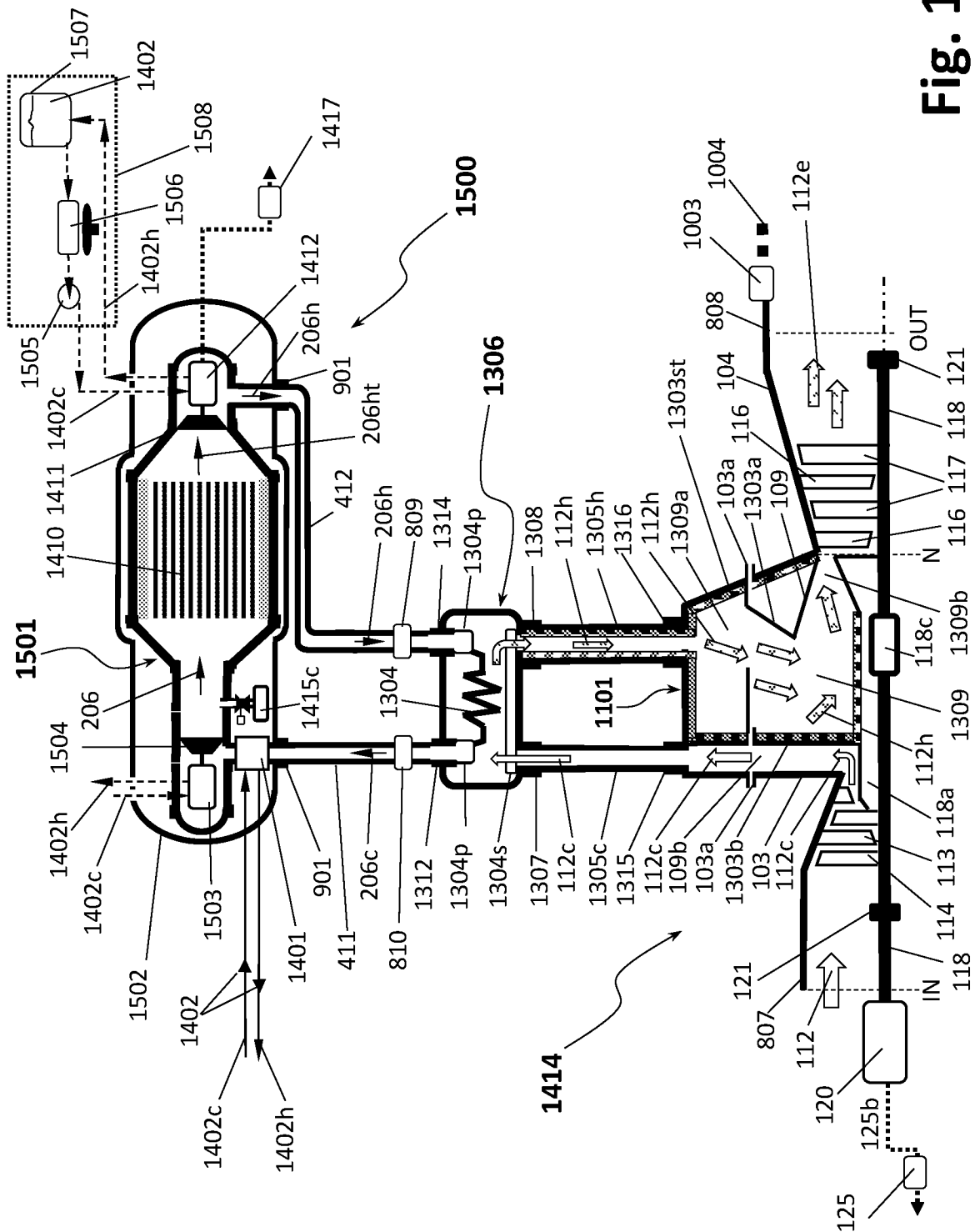


Fig. 14



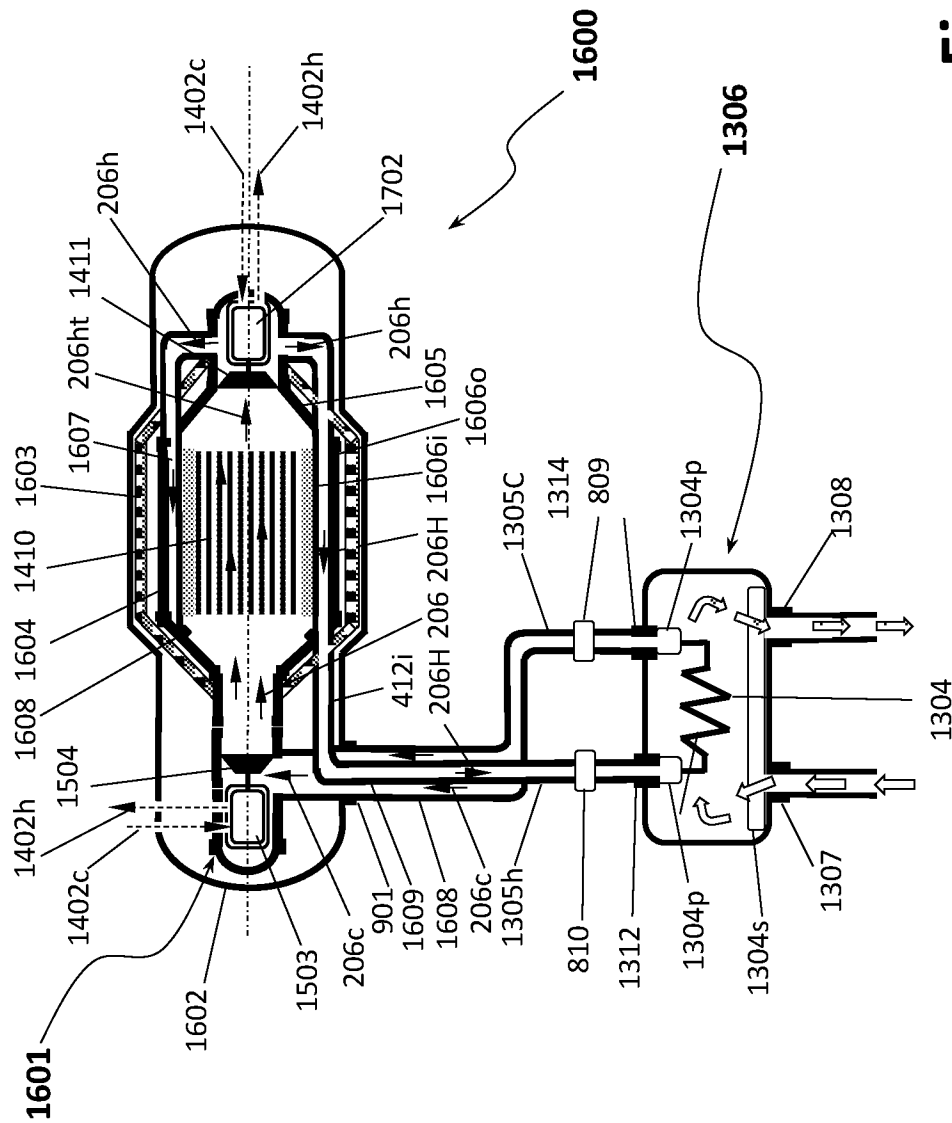
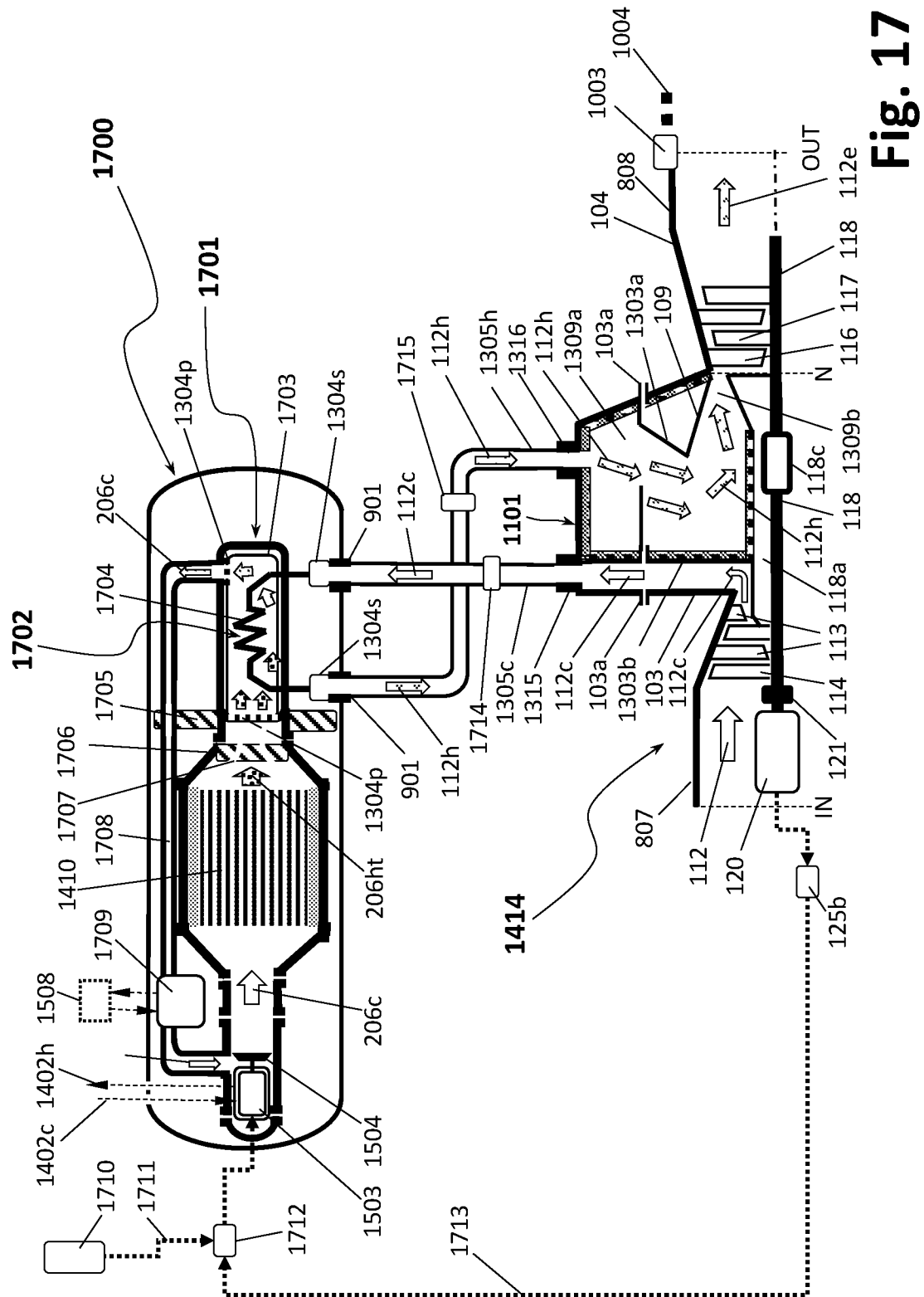


Fig. 16



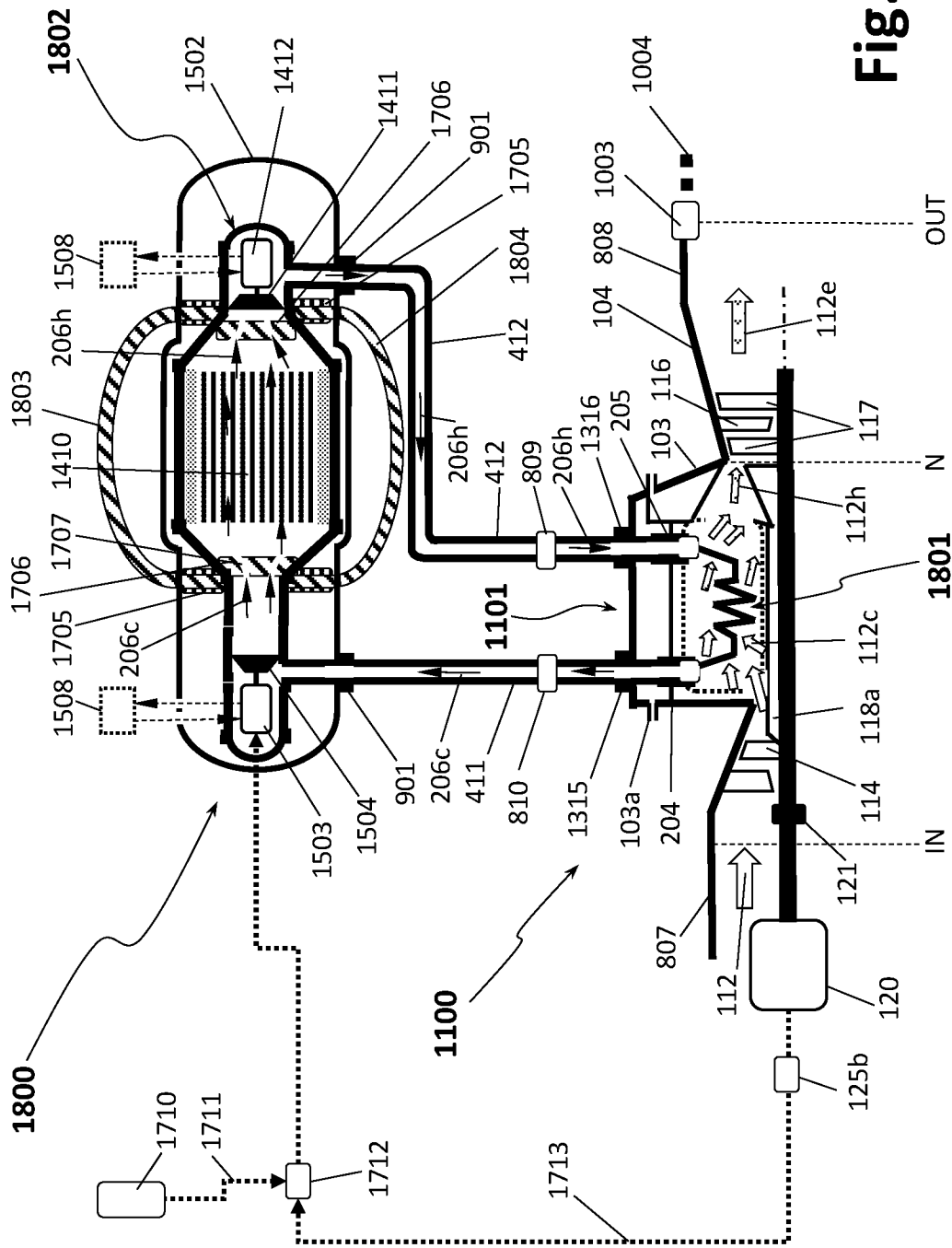


Fig. 18

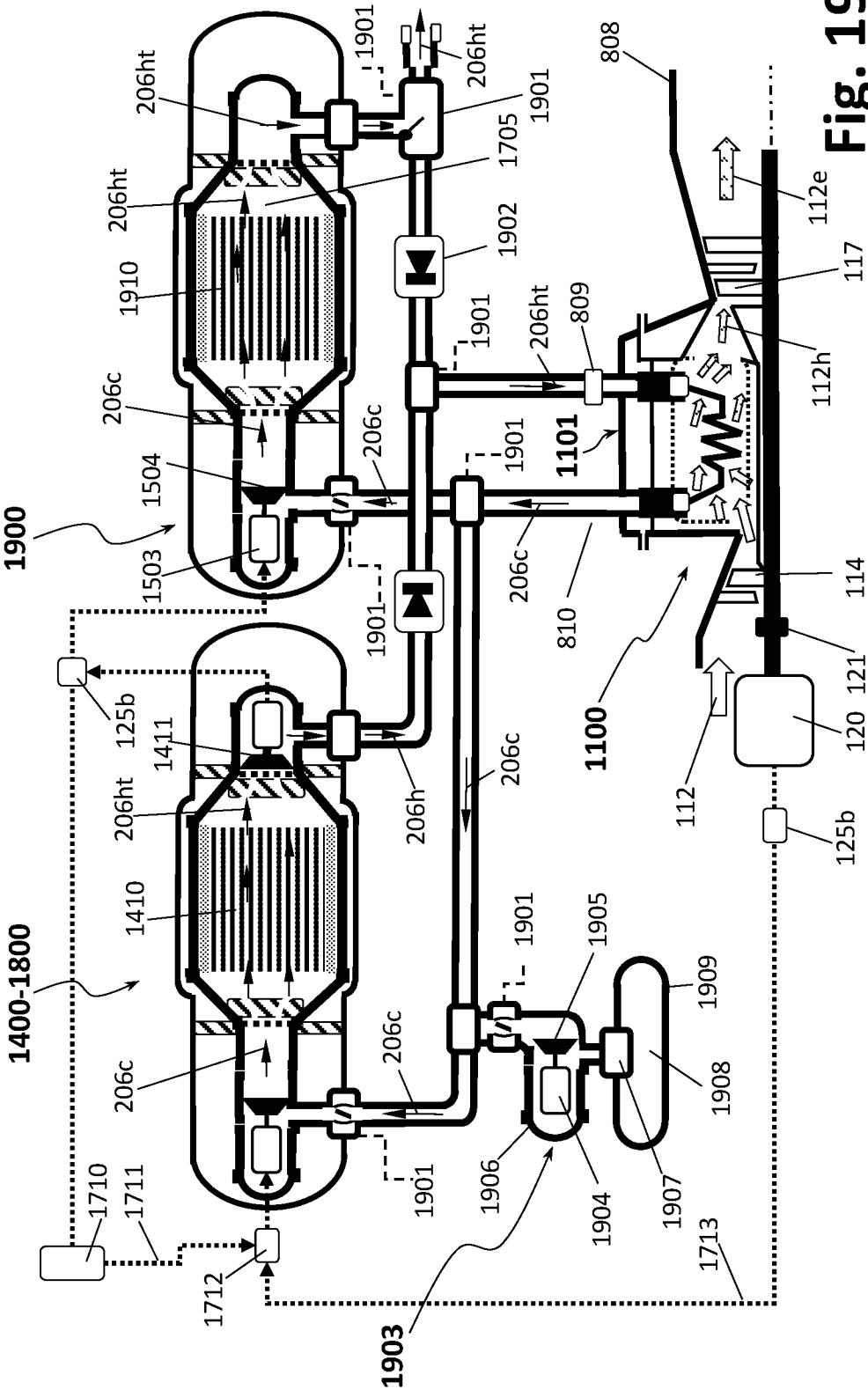
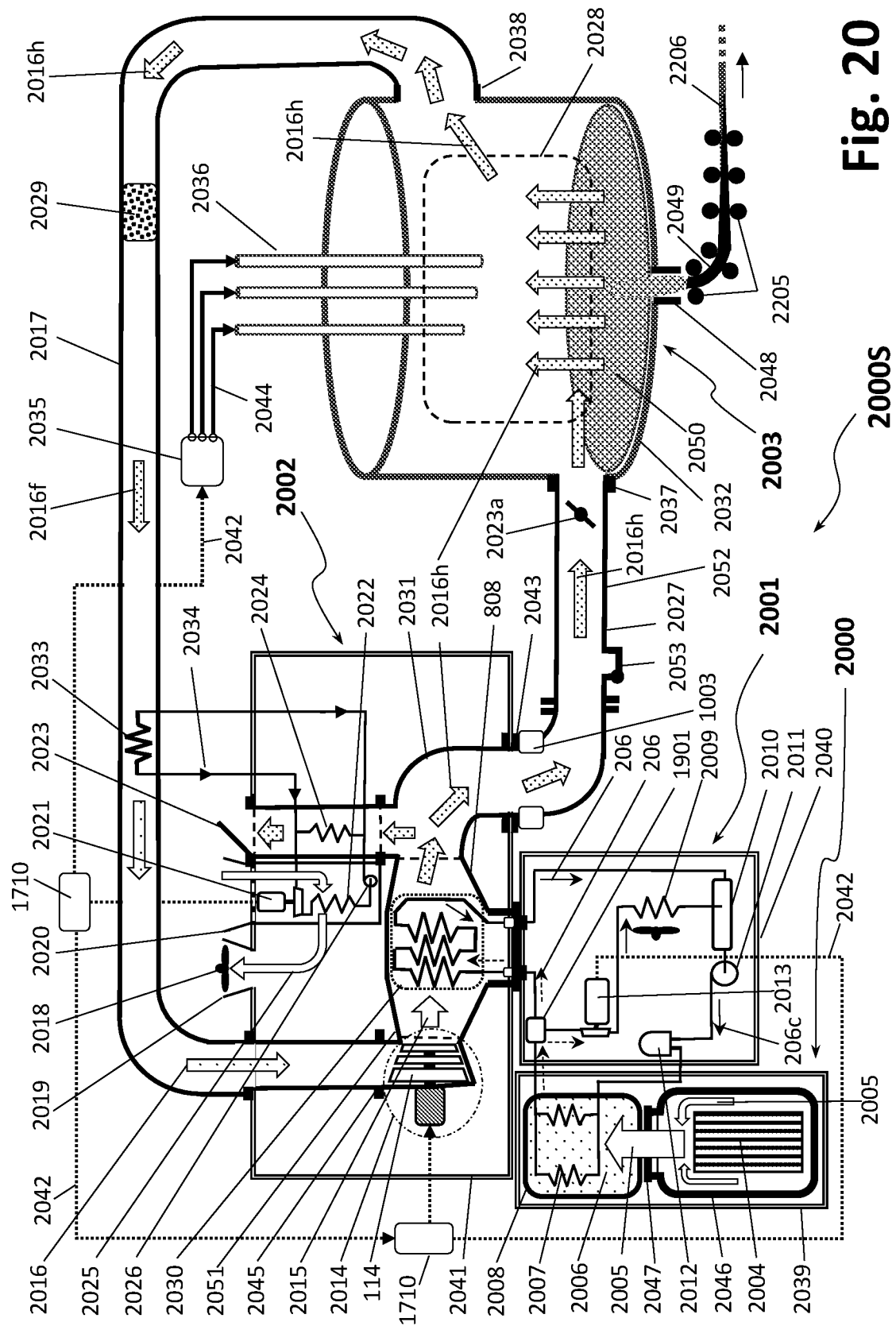
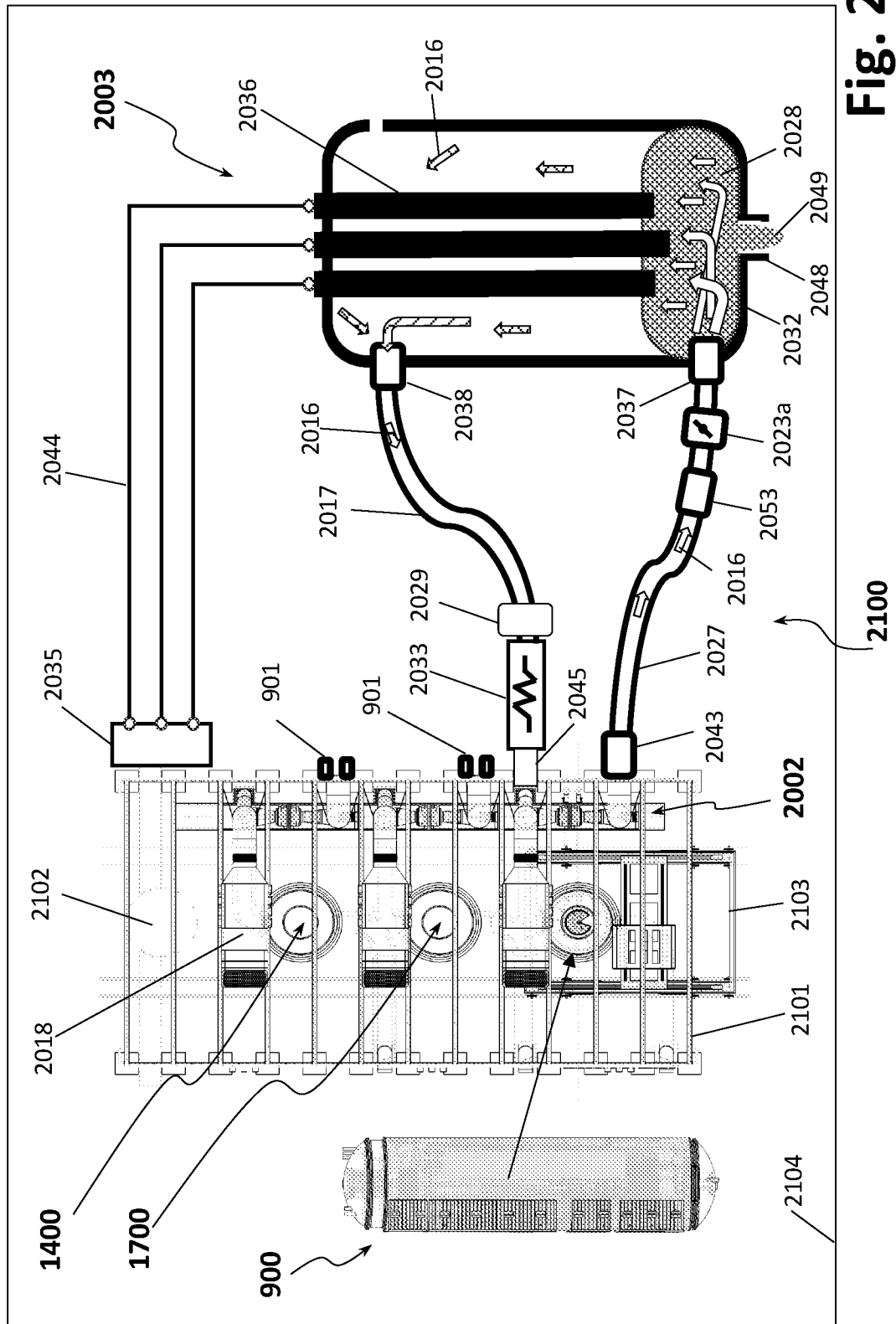


Fig. 19





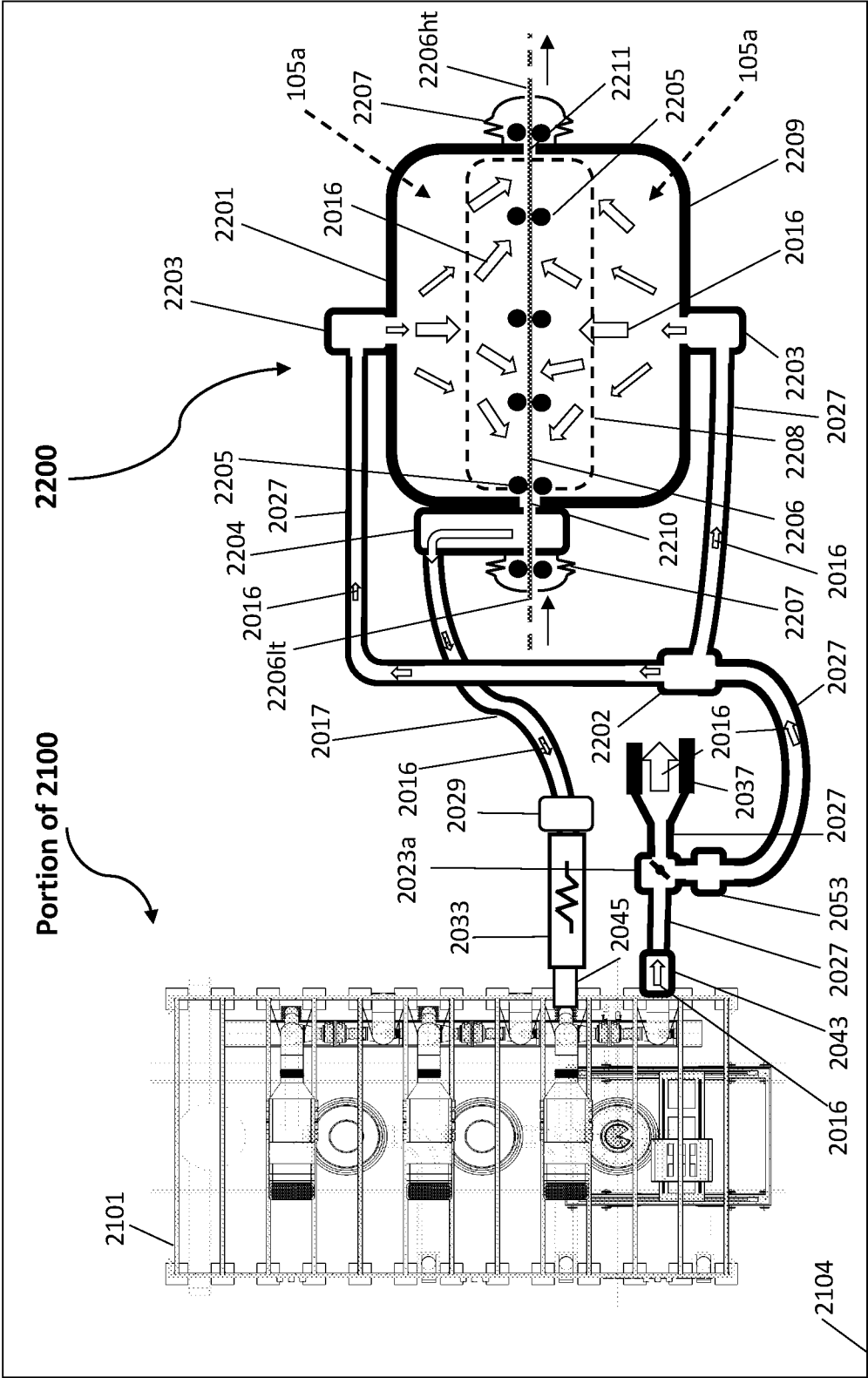


Fig. 22