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(54) **COMPRESSED GAS ENERGY STORAGE SYSTEM**

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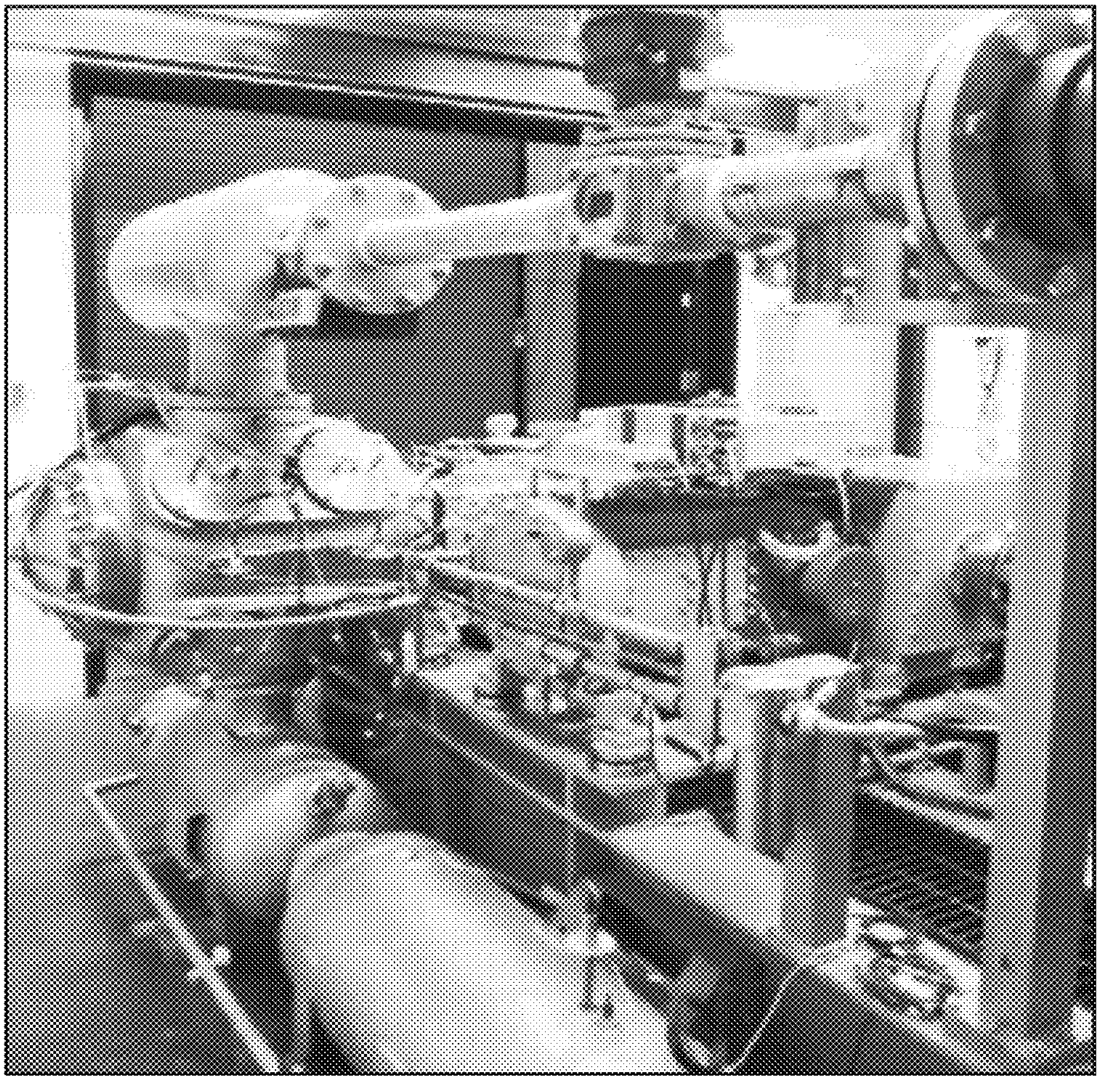
(57) **ABSTRACT**

An apparatus comprises an expander comprising a member moveable within a chamber in response to an expanding gas. A linkage is in communication with the member and configured to transmit out of the chamber, a power of the expanding gas. An element effects gas-liquid heat exchange with the expanding gas. The apparatus is configurable in a first mode of operation in which the member moves in response to the expanding gas as a result of combustion within the chamber, and in a second mode of operation in which the member moves in response to the expanding gas in an absence of combustion within the chamber. Also disclosed is a turbomachine where working fluid and plenum are rotated together, reducing losses from velocity shear. Further disclosed is a turbine comprising a nozzle on a rotatable member, where linear velocity of expanding gas from the nozzle substantially matches member rotational velocity.



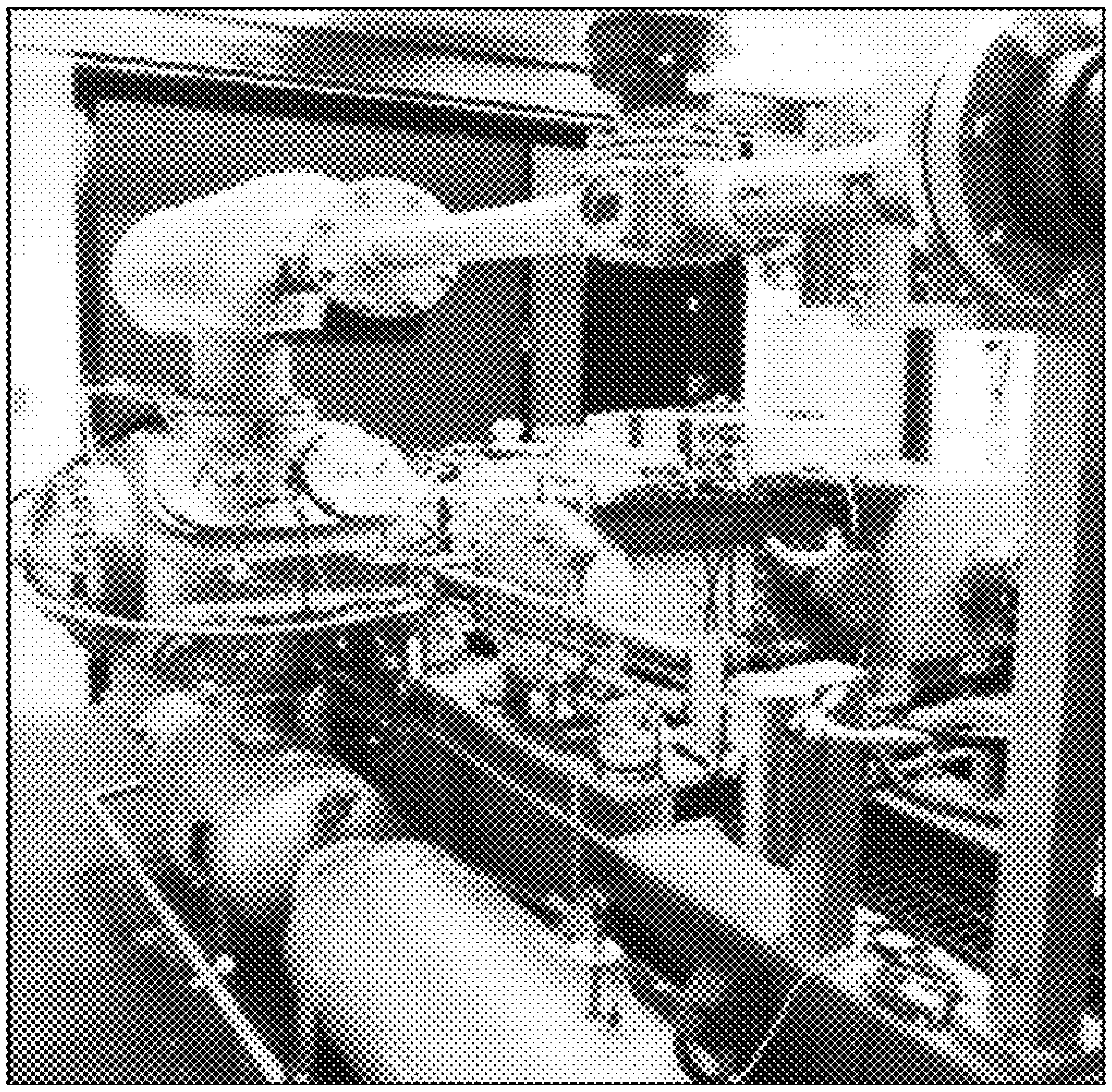


FIG. 1A

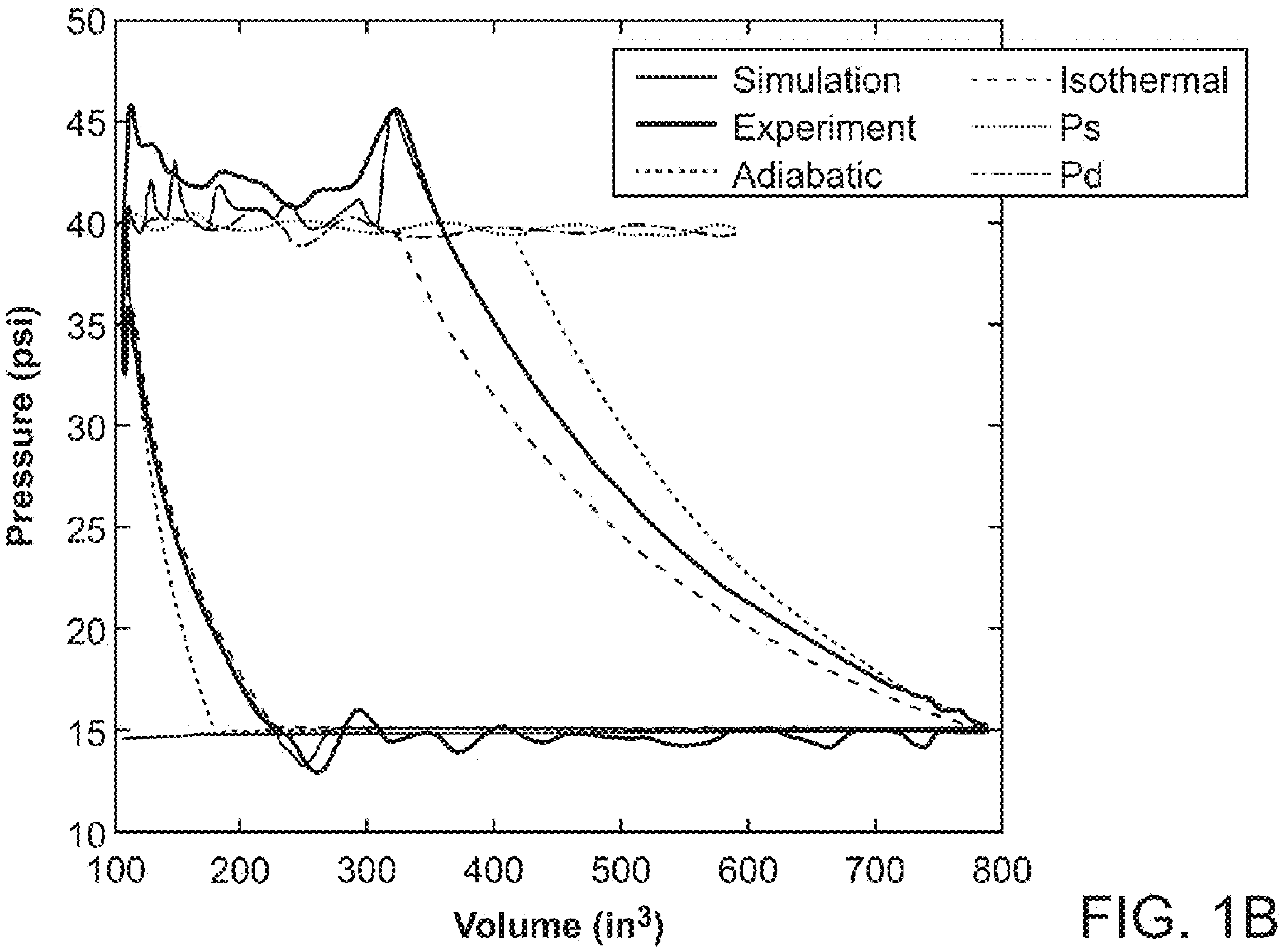

Simulation
Experiment
Adiabatic
Isothermal
Ps
Pd
Pressure (psi)
Volume (in³)
50
45
40
35
30
25
20
15
10
100
200
300
400
500
600
700
800

FIG. 1B

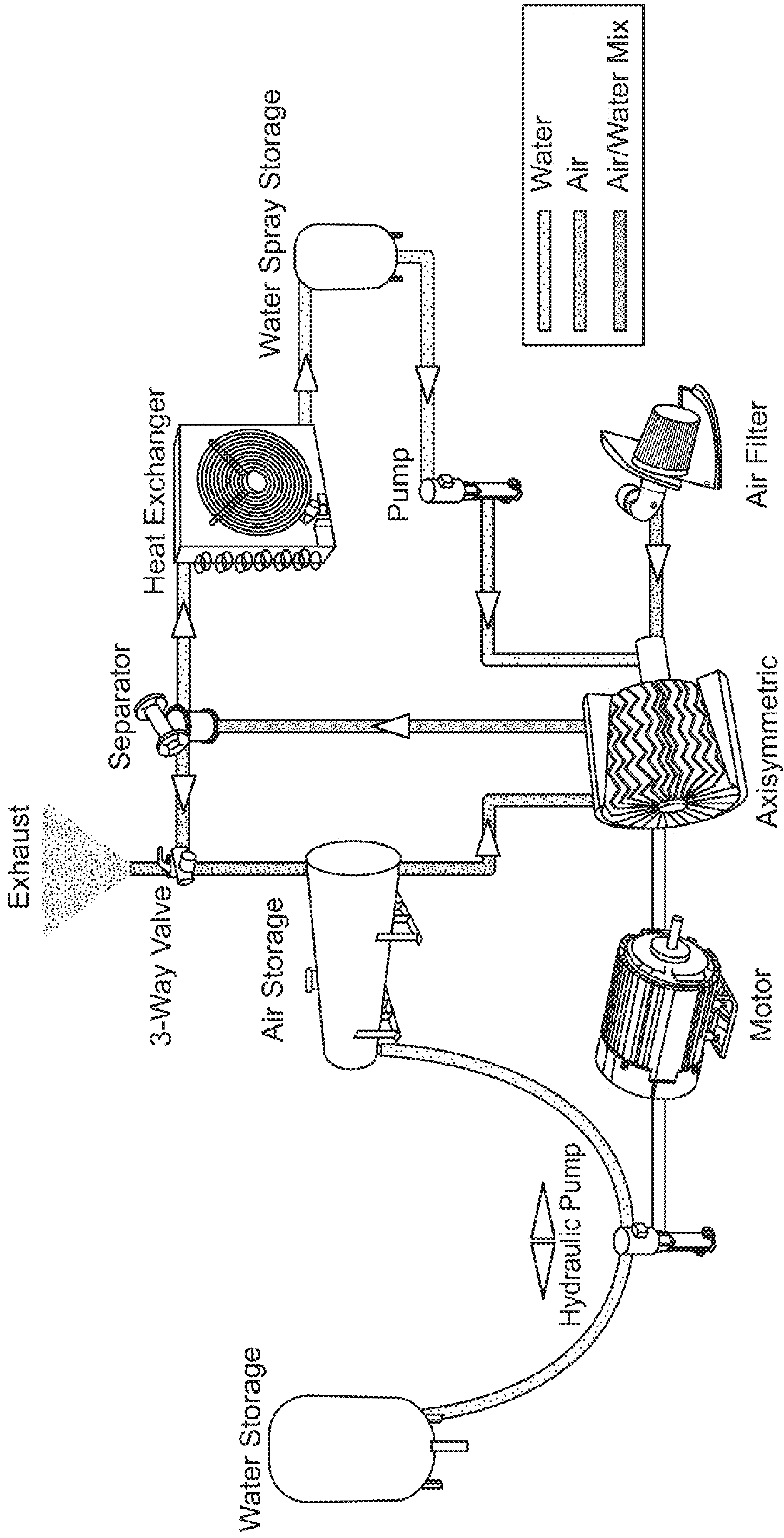

Exhaust
3-Way Valve
Separator
Heat Exchanger
Water Spray Storage
Air Storage
Pump
Water
Air
Air/Water Mix
Water Storage
Hydraulic Pump
Motor
Axisymmetric Compressor/Expander
Air Filter

FIG. 2

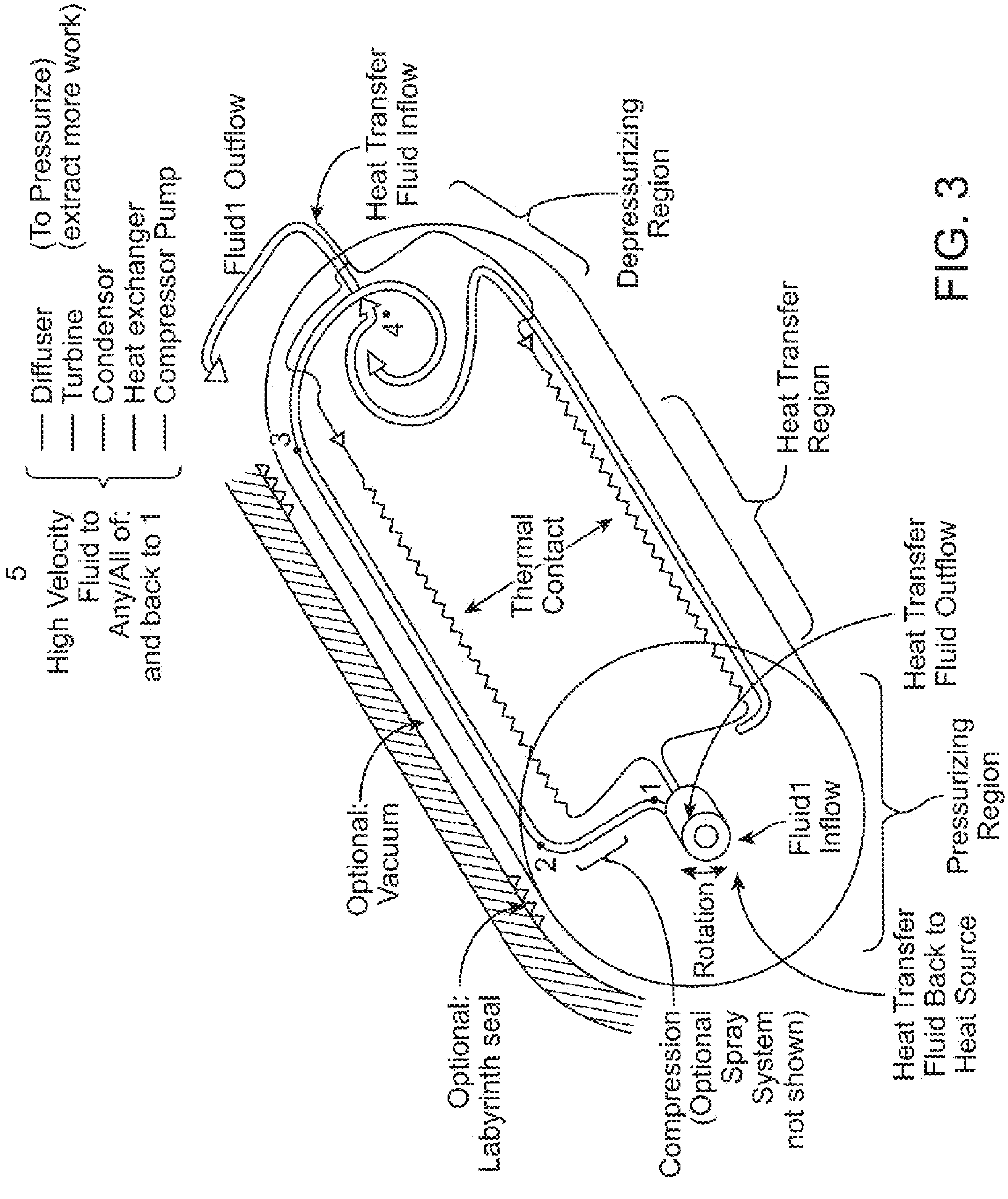

5
High Velocity Fluid to Any/All of: and back to 1
— Diffuser (To Pressurize)
— Turbine (extract more work)
— Condensor
— Heat exchanger
— Compressor Pump
Fluid1 Outflow
Heat Transfer Fluid Inflow
Depressurizing Region
4*
3
Heat Transfer Region
Thermal Contact
Optional: Vacuum
Heat Transfer Fluid Outflow
1
2
Fluid1 Inflow
Pressurizing Region
Rotation
Optional: Labyrinth seal
Compression (Optional Spray System not shown)
Heat Transfer Fluid Back to Heat Source

FIG. 3

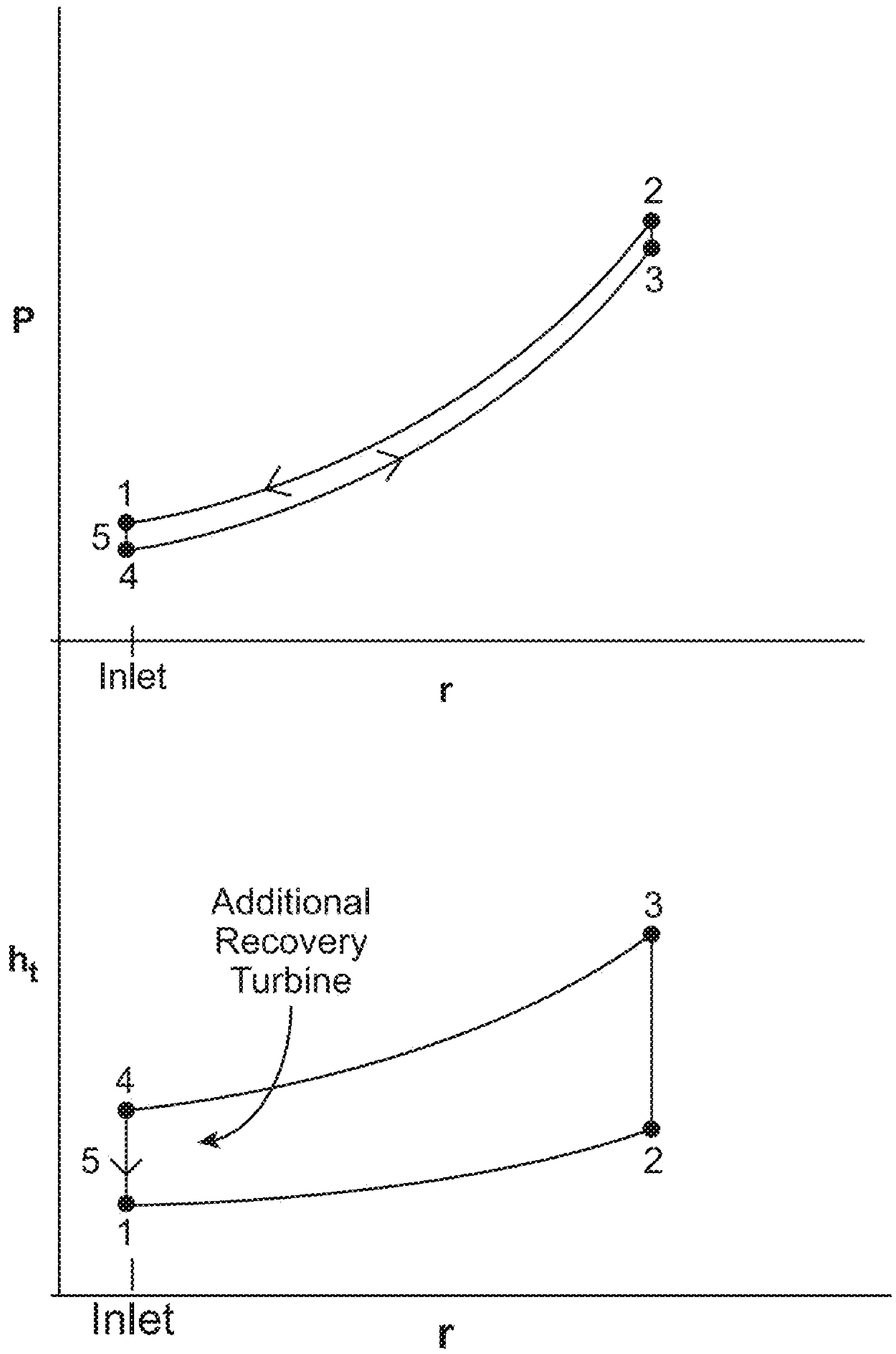

p
2
3
1
5
4
Inlet
r
h_t
Additional Recovery Turbine
3
4
5
2
1
Inlet
r

FIG. 3A

COMPRESSED GAS ENERGY STORAGE SYSTEM

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The instant nonprovisional patent application claims priority to the U.S. Provisional Patent Application No. 61/623,491 filed Apr. 12, 2012 and hereby incorporated by reference in its entirety for all purposes.

BACKGROUND

[0002] Recently, approaches employing compressed gas as an energy storage medium, have emerged. In particular, compressed air is capable of storing energy at densities comparable to lead-acid batteries. Moreover, compressed gas does not involve issues associated with a battery such as limited lifetime, materials availability, or environmental friendliness.

SUMMARY

[0003] In an embodiment, an apparatus comprises an expander comprising a member moveable within a chamber in response to an expanding gas. The apparatus further comprises a linkage in communication with the member and configured to transmit out of the chamber, a power of the expanding gas. An element effects gas-liquid heat exchange with the expanding gas, wherein the apparatus is configurable in a first mode of operation in which the member moves in response to the expanding gas as a result of combustion within the chamber, and in a second mode of operation in which the member moves in response to the expanding gas in an absence of combustion within the chamber. Also disclosed is a turbomachine in which the working fluid and the plenum are rotated together so as to reduce losses from velocity shear. Further disclosed is a turbine comprising a nozzle on a rotatable member, where linear velocity of expanding gas from the nozzle substantially matches a rotational velocity of the member in order to impart efficient operation.

BRIEF DESCRIPTION OF THE DRAWINGS

[0004] FIG. **1**A shows an apparatus.

[0005] FIG. **1**B plots pressure versus volume.

[0006] FIG. **2** shows a schematic view of an energy storage system.

[0007] FIG. **3** shows a simplified view of an embodiment of a turbomachine according to an embodiment.

[0008] FIG. **3**A are plots showing the behavior of the turbomachine of FIG. **3**.

DESCRIPTION

[0009] Certain compressed gas energy storage approaches are described in U.S. Patent Publication No. 2011/0115223 ("the '223 Publication"), which is incorporated by reference in its entirety herein for all purposes. According to the Publication, gas may be compressed in the presence of liquid water as a heat exchange medium. That is, heat generated from the compression of gas is transferred across a gas-liquid boundary (e.g. fine droplets), such that the temperature experienced by the gas remains within a relatively small range over the course of the course of the compression cycle. This enhances the thermodynamic efficiency of the compression process. The transferred heat of gas compression may be retained in the heated water, and may be available for other uses.

[0010] A compressor as described in the Publication, may utilize a reciprocating or rotating moveable member for gas compression. An example of the former is a solid piston connected to a mechanical linkage comprising a piston rod and rotating shaft (e.g. crankshaft). An example of the latter is a rotating turbine, screw, or other structure connected to a mechanical linkage comprising a rotating shaft.

[0011] In certain embodiments, liquid may be introduced directly into the compression chamber for heat exchange. In certain embodiments, liquid may be introduced to gas in a mixing chamber upstream of the compression chamber.

[0012] The core of our proposed technology is the ability to compress and expand air near-isothermally (i.e. with only a small change in temperature). This is done by spraying small water droplets into the air at high water-to-air mass ratios (hereafter, r_w). During compression, droplets absorb heat of compression, necessitating less work to compress the air. During expansion, the water droplets provide added heat to the air, allowing more work to be extracted from the air. If the water droplets are sufficiently small (~50 μm), they provide a large interfacial area for heat exchange between air and water. Subsequently the timescale of heat exchange is reduced (~10 ms), thereby allowing rapid compression or expansion, and ultimately increasing power density. At LightSail Energy, we are currently utilizing this technology in a reciprocating piston-driven process. We have demonstrated effectiveness of near-isothermal compression/expansion at a 100 kW-scale (FIG. **1**A) by spraying water into our cylinders (FIG. **1**B—experimental case compared against simulation). We are currently developing a 1 MW-scale prototype machine. The proposed project uses the abovementioned technology, utilizing water droplets to alleviate the rapid heating/cooling of air during compression/expansion, to develop an energy storage system that is not only efficient, power-dense, and economical, but also scalable into the 100 MW range.

[0013] The mechanism proposed for accomplishing this is to demonstrate near-isothermal compression/expansion using a turbomachine. Incorporated by reference in their entireties herein for all purposes, are U.S. Provisional Patent Application No. 61/536,813 filed Sep. 20, 2012, and U.S. Nonprovisional Patent Application No. 13/786,399 filed Sep. 19, 2012 ("the 399 Application"), disclosing compressed gas energy storage systems using turbines.

[0014] FIG. **2** shows the schematic of the proposed energy storage system. During energy storage, the turbomachine operates as a compressor. Water is sprayed into the compressor, creating a dense fog which will mitigate the overall temperature rise during compression. The compressed air water mixture then passes through a separator, which sends air to a storage tank, and water to a heat exchanger for reuse. During power delivery, the turbomachine operates as a turbine. Compressed air from the tank delivers power by turning the shaft of the turbine while water is sprayed into the turbine.

[0015] Our approach is unique and innovative due to some key features:

1) Near-isothermal processes are inherently more efficient.

2) Ericsson and Carnot cycles can be economically implemented with this technology, allowing us to run as heat engine at temperatures <140C.

3) Sprayed water droplets substantially increase heat exchange rate, and therefore power density.

4) Turbomachines are capable of producing 100× more power than their reciprocating piston-driven counterparts. This reduces foot-print, and may ultimately reduce cost.

5) Temperature variation in air is restricted by this process, potentially reducing design complexity and allowing cheaper materials to be used for components. 6) Lower temperature variations limit restrictions on pressure ratios. Higher pressure ratios can lead to higher power-densities.

[0016] Target Level of Performance

[0017] To get to a level appropriate for industrial consideration, we are planning to demonstrate near-isothermal compression and expansion in a small 10 to 50 kW turbomachine (microturbine) with 10 to 20 stages. We will spray water into the air in the form of 5 to 100 μm droplets, either upstream of the turbomachine or into the compressor/turbine itself.

[0018] Spray nozzles can be installed on the sidewalls of the housing, the blades, the shaft, or the stators. Our main target is to design a rotor that survives several hundred hours of testing. Rotor blades can be made of high-hardness materials such as a ceramic including alumina, zirconia, or silicon glass. An alternative option is to coat the moving parts with a high-hardness coating such as DLC (diamond-like carbon). We can use thin blades without internal cooling because of the limited temperature variation. These thin blades could be inexpensive and low-mass, allowing materials such as carbon composites to be practical. The low cost would allow for a practical machine even if blades need to be replaced on a yearly schedule through regular maintenance. Thin blades also ease the design of a reversible turbomachine. Our target efficiency is benchmarked by our current near-isothermal reciprocating engine: upwards of 90% thermal efficiency. This translates to a temperature rise of less than 30C for pressure ratio of 6. This can be achieved by spraying 50 μm water droplets at $r_w=3$.

[0019] Technology Readiness Level

[0020] The proposed concept has proven successful in reciprocating piston-driven machine. Basic calculations and analysis have been done for a turbomachine, but no attempt has been made experimentally to spray water at high r_w into turbomachines. Upon successful completion of this project, the key high-risk features of the design will have been addressed. We will operate a near-isothermal turbomachine prototype in our facility. If efficiencies are high enough (e.g. more than ~85% oneway), it would also be possible to recover energy from waste heat.

[0021] Current State-of-the-Art Technology

[0022] Existing compressed air energy storage technologies have several major limitations: high cost ($850/kW), low round trip efficiency (about 55%), need for geology suitable for underground storage, low power-density, or the requirement to burn fossil fuel during power delivery. Battery technologies have issues with chemicals and short lifetime. Our technology addresses these shortcomings: High pressure operation makes aboveground storage practical. Our design uses non-toxic materials and has a long operation lifetime (several decades), resulting in lower environmental impact and reduced cost.

[0023] Potential Impact

[0024] If this project proves successful, it could be adopted by power producers worldwide. If storage installations were sized for near average demand (as opposed to peak demand), the costs of both sides of the T&D (Transmission & Distribution) line with decrease significantly. Increased capacity utilization of existing T&D resources may also defer or avoid the need for costly T&D upgrade in many cases, particularly in the case of densely populated areas or at remote locations. LightSail's high-efficiency, scalable, rampable, grid-scale, energy storage:

1) Allows power producers to reduce their use of inefficient peaker plants, reducing greenhouse gas emissions.

2) Allows better integration of renewable energy sources (e.g. wind and solar) into the grid, reducing dependence on foreign oil.

3) Allows the United States to maintain its technological leadership in the grid-scale energy storaue market.

[0025] Key Technical Risks

[0026] 1) Ensuring that the rotor blades survive the impact from the spray droplets, with a reasonable lifetime.

2) Corrosion and wear of the system.

3) Ensuring that a uniform mixture is formed inside the turbomachine, otherwise local hot/cold spots will reduce thermal efficiency. Potentially difficult water nozzle placement (on the shaft, blade, rotor, stator, and housing) is a major risk.

4) Collection of bulk water is a major risk. There might be a compromise between collecting water from the bottom of the turbomachine, leakage, and the overall efficiency.

5) Cavitation is a major risk at high rotor speeds. It is speculated that cavitation would not be as big of a problem at higher air pressures. Therefore, there might be a compromise between the amount of water sprayed into the low pressure stages and the lifetime of the rotors.

6) Designing the turbomachine to run both as an expander and compressor is a risk. However, this is essential for the concept to stay economically competitive.

[0027] Impact of ARPA-E Funding

[0028] Our investors are currently advocating the lower-risk reciprocating machine technology. That option has less overall associated risk, but may be limited to a smaller scale (up to 1 MW). The risk of developing a near-isothermal storage system using the proposed compressor/turbine paradigm is high, but the potential return is being able to enter the large 100 MW-scale energy storage market, as well as the possibility of running as a heat engine.

[0029] Addendum

[0030] During power delivery, an energy storage system can benefit from [waste] hot water if sprayed into the turbine during expansion, or upstream of the turbine.

[0031] Two dedicated units, one compressor and one turbine, may run simultaneously. Air is compressed near-isothermally in the compressor, then is heated by [waste] hot water, and then is expanded while hot water is sprayed. This is an Ericsson cycle (Carnot efficiency) that can recover energy from low-grade waste heat. It can be economical if the one-way efficiency is greater than 85%.

[0032] Integrated Energy Core: Distributed Gas Trigeneration and Energy Storage Technology—Technology Description

[0033] We seek ARPA-E financing to develop a revolutionary hybrid compressed air energy storage and natural gas cogeneration system. We aim to manufacture systems that are both the most economical energy storage systems on the market, but are also the most economical gas cogeneration systems.

[0034] In this way, no matter what natural gas fuel costs may be over a 20-30 year operational lifetime, customers can be assured that they will have purchased the most economically competitive product, compatible with any future gas prices, carbon taxes/credit regime, or renewable energy supply.

[0035] The first part of this system is already far along in R&D: a highly efficient compressed air energy storage system. LightSail Energy is the first and to our knowledge, only organization to demonstrate rapid (>600 RPM), near isothermal (<10 C ΔT) air compression and expansion in reciprocating engines. We achieve this with our innovation of direct, water spray injection during compression and expansion.

[0036] This near-isothermal compression and expansion allows a low-cost energy storage cycle with nearly doubled efficiency from the state of the art (~35% to 70%). Further, because air storage is very inexpensive ($100/kWh with technology available today, and as low as $30/kWh eventually), we believe this has a high probability of being the most competitive energy storage system available. Our most fierce competition: natural gas peakers, and cogeneration.

[0037] We would like to best our competition by developing the most efficient, lowest cost natural gas peaker as well, and in the same device have the option to act as an energy storage system—a hybrid.

[0038] This is conceptually quite a simple task. The most efficient natural gas cogeneration plants, either reciprocating or turbomachinery, compress air, heat it with combustion, expand it at higher pressure or volume, and repeat. The best efficiencies are attained with recuperation—taking the exhaust gases and heating the compressed air before combustion. At small scale, the best of these (e.g. a Capstone M30 microturbine) achieves 25% thermal efficiency.

[0039] The recuperated cycle would improve immensely in both power per machine (and thus cost) and efficiency, simply by doing near isothermal compression. Feeding the compressed air into microturbines with a pressure ratio of 4, we would expect a reduction in compressor energy requirement by 33%. We estimate this would yield efficiencies approaching 35%, and a 40% increase in power per unit cost. This should be extremely competitive as a cogeneration plant, but in addition, simply adding air tanks, post compressor, would allow extremely competitive energy storage at groundbreakingly low cost (<$100/kWh).

[0040] Even further efficiency improvements are possible, because reciprocating machines are absent many of the loss channels of microturbines. Our calculations suggest the attainable efficiency upper limit may be in the 55-65% range. Our goal for this project is to, in two years, in an integrated system, at TRL-6, attain 50% thermal efficiency (typical of large CCGT systems), with a cost structure equal to or lower cost than simple cycle cogeneration systems.

[0041] Funding would allow the development of a high efficiency, high temperature capable reciprocating expander which could also act as a near-isothermal air expander when operated in a different mode.

[0042] The primary technical challenges are in the development of a reciprocating expander than can handle temperature extremes. These extremes need to be sudden, but they are great in magnitude. The same expander that must operate well around 0-40° C. must also operate well at 600-900 C.

[0043] This poses great challenges for seal and valve design. Preliminary studies suggest that ceramic piston seals and anodized cylinder walls may be able to adequately tolerate the temperature extremes, from a thermal expansion and wear standpoint. Seals must be sized to prevent seizing; there is some room in this because some degree of hydrodynamic sealing is possible when running in energy storage and delivery mode.

[0044] Likewise, the valve seating and sealing must be tolerant of temperature extremes.

[0045] Finally, compression and expansion in energy storage and delivery mode provide significant free heating and cooling, respectively.

[0046] Additionally, at minimal added cost:

[0047] Air compression cogenerates heat;

[0048] Air expansion provides cooling;

[0049] Compressed air may provide a refueling infrastructure for compressed air or air/fuel hybrid vehicle using similar technology. This itself would be transformative!

[0050] Expanding with air heated from low grade heat improves efficiency

[0051] A trigeneration energy core could be at the center of every major building, and provide efficient, economical, abundant energy. This would be a transformative innovation.

[0052] The core idea is that the same fundamental device—indeed, the same product—can operate as the best-in-class energy storage system, cogeneration system, waste heat recovery system, car engine, regenerative brake, air engine, air conditioner, heat pump, geothermal generator, and air vehicle refueling device.

[0053] Heat engines and thermodynamic devices power the world; a practical isothermal device is a major advance in all the areas where this is dominant.

[0054] Lightsail Energy is a company developing revolutionary, high efficiency regenerative air energy storage systems. We are the leading company in the area of rapid near-isothermal air compression and expansion, and the first to ever demonstrate ΔT's<10 C at >600 RPM.

[0055] An apparatus according to certain embodiments may comprise an expander comprising a member moveable within a chamber in response to an expanding gas. The apparatus may further comprise a linkage in communication with the member and configured to transmit out of the chamber, a power of the expanding gas. An element may be configured to effect gas-liquid heat exchange with the expanding gas. The apparatus may be configurable in a first mode of operation in which the member moves in response to the expanding gas as a result of combustion within the chamber, and configurable in a second mode of operation in which the member moves in response to the expanding gas in an absence of combustion within the chamber.

[0056] In certain embodiments, the member is moveable to reciprocate within the chamber.

[0057] The linkage may comprise a piston rod and a crankshaft.

[0058] In some embodiments, the member is moveable to rotate within the chamber.

[0059] The member may comprise a turbine blade.

[0060] The element may comprise an orifice in the turbine blade to flow a liquid to the chamber to exchange heat with the expanding gas.

[0061] The chamber may be defined within a rotating casing.

[0062] The linkage may be configured to be in selective communication with an energy source to drive the member to compress gas within the chamber.

[0063] The element may be configured to effect gas-liquid heat exchange with gas being compressed within the chamber.

[0064] Combustion may occur within the expanding gas during the expansion process. In particular, combustion may occur at a controlled rate, and this rate may keep the temperature of the gas constant or nearly constant for a controlled duration of time throughout the expansion process. In particular embodiments, the controlled temperature is maintained just below the limiting tolerable temperature depending upon material properties.

[0065] High Efficiency Shearless Centrifugal Turbomachine Heat Engine—Technology Description

[0066] Our proposed technology is a heat engine designed to economically produce electricity from waste heat at far lower temperatures than are acceptable today. No technology has yet emerged which can efficiently (>10%) and economically (<$3000/kW) produce electricity from heat at ΔT below 140 C.

[0067] We aim to achieve superior economics at low temperatures by making dramatic efficiency improvements by eliminating fluid dynamic, and theimodynainic irreversibilities.

[0068] We target >15% efficiency for AT's of 140 degrees C., at a cost <82000/kW. We believe this is achievable by reducing irreversible loss channels by just 30% from the state of the art efficiency (8-10% efficiency, as compared to 34% Carnot efficiency). Even further advances are possible. This would provide energy at lower cost than coal and CCGT plants.

[0069] The technology we have chosen is a unique reimagining of a centrifugal turbomachine. The vast majority of the efficiency losses in centrifugal turbomachines come from two sources:

1. Viscosity and vortex creation in the zones of greatest advective fluid velocity gradients. In practice, most of this is concentrated in a single area—where the blade-tips approach the inner walls of the plenum casing, and secondarily in the diffuser region.
2. Heat transfer across regions of high ΔT. We aim to virtually eliminate these loss channels.

[0070] We eliminate losses from velocity shear by nearly eliminating advective (Lagrangian) velocity gradients. We spin the fluid, the channels which guide the fluid, and the plenum containing the fluid, as a single monolithic element. Fluid velocity barely changes as we follow along the direction of the flow. There is hardly any shear.

[0071] The whole turbomachine, casing and all, may be rotated in a low vacuum or high vacuum. From a dynamics perspective, the fluid moves in a pattern that is practically solid rotation.

[0072] FIG. **3** shows a simplified view of an embodiment of a turbomachine according to an embodiment. The turbomachine comprises a rotatable casing, that may lie be within a vacuum environment. Optional labyrinth seals are shown.

[0073] The rotating casing encloses an internal space. A first working fluid (Fluid1) enters a first end of the casing defining a pressurizing region. This is shown as point **1**.

[0074] The Fluid**1** then flows in a radially outward direction to reach point **2**. This flow is shown as being through a radial channel in FIG. **3**, but this is not required.

[0075] The Fluid**1** then flows along the axis of rotation through a heat transfer region to point **3**. The Fluid**1** is in thermal contact with a heat transfer fluid during this time.

[0076] The Fluid**1** is then flowed in a radially inward direction to reach point **4** at a second end of the casing comprising a depressurizing region. This flow is shown as being through a spiral channel in FIG. **3**, but this is not required.

[0077] The high velocity Fluid**1** exiting the casing can be flowed to any/all of the following:

[0078] a diffuser (to pressurize);

[0079] a turbine (to extract more work);

[0080] a heat exchanger;

[0081] a compressor/pump; and/or

[0082] back to the point **1**.

[0083] FIG. **3** also shows the flow of a heat transfer fluid into the depressurizing region. The heat transfer fluid travels across the heat transfer region where it is exposed to thermal contact with the Fluid**1**, and then exits the pressurizing region. The heat transfer fluid may then flow back to a heat source.

[0084] FIG. **3**A are plots showing the behavior of the turbomachine of FIG. **3**. Conditions at various specific points (**1**-**4**) within the turbomachine are shown. The upper graph plots pressure (P) versus radial distance (r) from the axis of rotation. The lower graph plots specific total enthalpy (h_T) versus r. It includes the kinetic energy.

[0085] The pressurizing/depressurizing channels are not limited to radial and spiral configurations as shown in the particular embodiment of FIG. **3**. The channels in the heat transfer region may also spiral to control flow speed and reaction forces. It may also have zero or non-zero radial components.

[0086] A diffuser (a manifold intended to slow down and pressurize a flow) is commonly used in turbomachines. However, a diffuser may not be required with particular embodiments of turbomachines as described herein.

[0087] By nearly eliminating velocity shear, we nearly eliminate fluid dynamic irreversibility; avoiding heat and turbulent energy generation that is unable to be recovered in the form of useful work.

[0088] A small motor/pump pumps fluid through the machine or recovers energy from kinetic energy from the flow.

[0089] Heat is supplied as either liquid or vapor through axial bosses, but the high velocity outer plenum casing does not shear against air, nor do the blades shear against the air, or the air against the outer casing. The relative velocity between the heat-carrying fluid and the turbomachine walls is relatively low everywhere, resulting in low viscous losses.

[0090] The working fluid is internally pressurized to improve power density; both the inlet and outlet pressure may be substantially higher than 1 atmosphere.

[0091] Eliminating Thermodynamic Losses

[0092] If heat energy is supplied in the form of steam, the highest efficiency theoretically attainable comes from the ideal Rankine cycle (without superheating), with recuperation. After condensation, there is still hot water with heat available; it is ideal to use the hot water to preheat the fluid before boiling.

[0093] In some embodiments, a single monolithic heat engine would spin in a low vacuum. The condensed working fluid would pressurize as it flows outward radially, be preheated, and then be boiled from heat transferred from condensing steam. The steam would expand as it flows inward radially in the expander part of the heat engine, and its velocity would impact work due to the reaction force. The steam would be returned to a condenser, where it would reject heat, pass through a pump and return to the beginning of the cycle. A secondary turbomachine and optional diffuser may be used to capture energy from excess exhaust velocity.

[0094] We believe such a system could attain order-of-magnitude improvements in cost and efficiency for electricity generation from low temperature waste heat. The machinery is power dense and practical, and the physics are fundamentally lacking major loss channels.

[0095] If heat energy is supplied in the form of liquid, it is thermodynamically ideal to implement a Carnot efficient cycle, such as the Ericsson cycle. Such cycles have been impossible to implement without the ability to compress and expand isothermally. We would implement the Ericsson cycle similarly to what has been described above for the Rankine cycle, but with heating/cooling instead of boiling/condensation and compression rather than pressurization.

[0096] LightSail Energy has demonstrated high speed near-isothermal air compression and expansion in a reciprocating machine by loading air with fine water droplets. We have done analytical work showing this should work in centrifugal turbomachines.

[0097] Key risks may include possible wear due to droplet impact, and/or mass balance with boiling/condensing/multiphase fluid.

[0098] We aim to demonstrate >15% efficiency electrical generation at the 100 kW scale from 140 C ΔT heat. We have an existing test-cell, dynamometer, and machine shop, which has been used to develop isothermal compressed air energy storage technology.

[0099] 1. An apparatus comprising:

[0100] an expander comprising a member moveable within a chamber in response to an expanding gas;

[0101] a linkage in communication with the member and configured to transmit out of the chamber, a power of the expanding gas; and

[0102] an element configured to effect gas-liquid heat exchange with the expanding gas, wherein the apparatus is configurable in a first mode of operation in which the member moves in response to the expanding gas as a result of combustion within the chamber, and in a second mode of operation in which the member moves in response to the expanding gas in an absence of combustion within the chamber.

[0103] 2. An apparatus as in claim **1** wherein the member is moveable to reciprocate within the chamber.

[0104] 3. An apparatus as in claim **2** wherein the linkage comprises a piston rod and a crankshaft.

[0105] 4. An apparatus as in claim **1** wherein the member is moveable to rotate within the chamber.

[0106] 5. An apparatus as in claim **4** wherein the member comprises a turbine blade.

[0107] 6. An apparatus as in claim **5** wherein the element comprises an orifice in the turbine blade to flow a liquid to the chamber to exchange heat with the expanding gas.

[0108] 7. An apparatus as in claim **5** wherein the chamber is defined within a rotating casing.

[0109] 8. An apparatus as in claim **1** wherein the linkage is configured to be in selective communication with an energy source to drive the member to compress gas within the chamber.

[0110] 9. An apparatus as in claim **8** wherein the element is configured to effect gas-liquid heat exchange with gas being compressed within the chamber.

[0111] 10. An apparatus comprising:

[0112] an expander comprising a casing and a member rotatable in response to an expanding gas within the casing;

[0113] a rotating shaft in communication with the member and configured to transmit a power of the expanding gas; and

[0114] an element configured to effect gas-liquid heat exchange with the expanding gas.

[0115] 11. An apparatus as in claim **10** wherein the member comprises a turbine blade.

[0116] 12. An apparatus as in claim **11** wherein the element comprises an orifice in the turbine blade to flow a liquid to the chamber to exchange heat with the expanding gas.

[0117] 13. An apparatus as in claim **10** wherein the element comprises an orifice within the casing.

[0118] 14. An apparatus as in claim **10** wherein the element comprises an orifice within the shaft.

[0119] 15. An apparatus as in claim **10** wherein the shaft is in selective communication with an energy source to drive the member to compress gas within the casing.

[0120] 16. An apparatus as in claim **15** wherein the element is configured to effect gas-liquid heat exchange with gas being compressed within the casing.

[0121] While certain embodiments described above have focused upon introducing liquid in the form of droplets of a size of about 5 μm or greater for heat exchange with expanding gas and/or compressed gas, this is not required. Various embodiments could employ a different conditions in order to effect gas compression and/or expansion within a limited temperature range.

[0122] For example, certain embodiments could employ an evaporating compression/condensing expansion approach. Here, the concept is similar to a quasi-isothermal process, except that a lower amount of water (e.g. 1/10th or less), and smaller droplet sizes (e.g. 1 micron and smaller) are employed.

[0123] In such evaporating compression/condensing expansion, the gas temperature could change within a larger range (e.g. up to about 100° C.). The compression and expansion processes generate little entropy, and thus are efficient, so long as the heat transfer across the phases is across a low temperature difference. This is dependent upon injecting very fine droplets. Additionally, it is necessary for efficient operation to store the heat of the compressed fluid for later use. In some embodiments, this heat is stored in the gas and water vapor/liquid, in other embodiments, the heat is transferred from the compressed fluid to a separate heat storage device, increasing the density in the pressurized fluid storage vessel.

[0124] However, the smaller droplet sizes used by such an embodiment could allow it to be performed in a turbine, without posing the risk of significant wear on turbine blade surfaces. Additionally, small droplets with much less mass will more readily follow the primary airflow, possibly enabling more efficient fluid flows.

What is claimed is:

1. An apparatus comprising:

an expander comprising a casing and a member rotatable in response to an expanding gas within the casing;

a rotating shaft in communication with the member and configured to transmit a power of the expanding gas; and

an element configured to effect gas-liquid heat exchange with the expanding gas.

2. An apparatus as in claim **1** wherein the member comprises a turbine blade.

3. An apparatus as in claim **2** wherein the element comprises an orifice in the turbine blade to flow a liquid to the chamber to exchange heat with the expanding gas.

4. An apparatus as in claim **1** wherein the element comprises an orifice within the casing.

5. An apparatus as in claim **1** wherein the element comprises an orifice within the shaft.

6. An apparatus as in claim **1** Wherein the shaft is in selective communication with an energy source to drive the member to compress gas within the casing.

7. An apparatus as in claim **6** wherein the element is configured to effect gas-liquid heat exchange with gas being compressed within the casing.

8. An apparatus comprising:

a rotating casing enclosing a pressurizing region at a first end, a depressurizing region at a second end opposite to the first end, and a heat transfer region between the first end and the second end, wherein the rotating plenum is configured to,

receive at the first end, an inflow of a first fluid,

receive at the second end an inflow of a heat transfer fluid,

produce at the first end an outflow of the heat transfer fluid, and

produce at the second end an outflow of the first fluid.

9. An apparatus as in claim **8** further comprising a channel to flow the first fluid in a radial direction from the pressurizing region to the heat transfer region.

10. An apparatus as in claim **8** wherein the channel exhibits a spiral configuration.

11. An apparatus as in claim **8** wherein the channel exhibits a radial configuration.

12. An apparatus as in claim **8** further comprising a diffuser configured to receive the first fluid from the depressurizing region.

13. An apparatus as in claim **8** wherein the casing is configured to rotate in a vacuum.

14. An apparatus as in claim **13** further comprising a labyrinth seal in contact with the casing.

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