SYSTEMS AND METHODS FOR ENERGY STORAGE AND RECOVERY USING GAS EXPANSION AND COMPRESSION

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ABSTRACT
In various embodiments, energy-storage systems are based upon an open-air arrangement in which pressurized gas is expanded in small batches from a high pressure of, e.g., several hundred atmospheres to atmospheric pressure. The systems may be sized and operated at a rate that allows for near isothermal expansion and compression of the gas.
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**FIG. 8**
Water Spray requirements degree C per kilowatt

Flow Rate degree C per kilowatt (GPM C/kW)

drop diameter (mm)

FIG. 24B
FIG. 31C
SYSTEMS AND METHODS FOR ENERGY STORAGE AND RECOVERY USING GAS EXPANSION AND COMPRESSION

CROSS-REFERENCE TO RELATED APPLICATIONS


STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support under IIP-0810590 and IIP-0923633 awarded by the NSF. The government has certain rights in the invention.

FIELD OF THE INVENTION

[0003] In various embodiments, the present invention relates to pneumatics, hydraulics, power generation, and energy storage, and more particularly, to compressed-gas energy-storage systems and methods using pneumatic and/or hydraulic cylinders.

BACKGROUND OF THE INVENTION

[0004] As the world’s demand for electric energy increases, the existing power grid is being taxed beyond its ability to serve this demand continuously. In certain parts of the United States, inability to meet peak demand has led to inadvertent brownouts and blackouts due to system overload and deliberate “rolling blackouts” of non-essential customers to shunt the excess demand. For the most part, peak demand occurs during the daytime hours (and during certain seasons, such as summer) when business and industry employ large quantities of power for running equipment, heating, air conditioning, lighting, etc. During the nighttime hours, demand for electricity is often reduced significantly, and the existing power grid in most areas can usually handle this load without problem.

[0005] To address the lack of power at peak demand, users are asked to conserve where possible. Power companies often employ rapidly deployable gas turbines to supplement production to meet demand. However, these units burn expensive fuel sources, such as natural gas, and have high generation costs when compared with coal-fired systems, and other large-scale generators. Accordingly, supplemental sources have economic drawbacks and, in any case, can provide only a partial solution in a growing region and economy. The most obvious solution involves construction of new power plants, which is expensive and has environmental side effects. In addition, because most power plants operate most efficiently when generating a relatively continuous output, the difference between peak and off-peak demand often leads to wasteful practices during off-peak periods, such as over-lighting of outdoor areas, as power is sold at a lower rate off peak. Thus, it is desirable to address the fluctuation in power demand in a manner that does not require construction of new plants and can be implemented either at a power-generating facility to provide excess capacity during periods of peak demand, or on a smaller scale on-site at the facility of an electric customer (allowing that customer to provide additional power to itself during peak demand, when the grid is over-taxed).

[0006] Another scenario in which the ability to balance the delivery of generated power is highly desirable is in a self-contained generation system with an intermittent generation cycle. One example is a solar panel array located remotely from a power connection. The array may generate well for a few hours during the day, but is nonfunctional during the remaining hours of low light or darkness.

[0007] In each case, the balancing of power production or provision of further capacity rapidly and on-demand can be satisfied by a local back-up generator. However, such generators are often costly, use expensive fuels, such as natural gas or diesel fuel, and are environmentally damaging due to their inherent noise and emissions. Thus, a technique that allows storage of energy when not needed (such as during off-peak hours), and can rapidly deliver the power back to the user is highly desirable.

[0008] A variety of techniques is available to store excess power for later delivery. One renewable technique involves the use of driven flywheels that are spun up by a motor drawing excess power. When the power is needed, the flywheels’ inertia is tapped by the motor or another coupled generator to deliver power back to the grid and/or customer. The flywheel units are expensive to manufacture and install, however, and require a degree of costly maintenance on a regular basis.

[0009] Another approach to power storage is the use of batteries. Many large-scale batteries use a lead electrode and acid electrolyte, however, and these components are environmentally hazardous. Batteries must often be arrayed to store substantial power, and the individual batteries may have a relatively short life (3-7 years is typical). Thus, to maintain a battery storage system, a large number of heavy, hazardous battery units must be replaced on a regular basis and these old batteries must be recycled or otherwise properly disposed of. Energy can also be stored in ultracapacitors. A capacitor is charged by line current so that it stores charge, which can be discharged rapidly when needed. Appropriate power-conditioning circuits are used to convert the power into the appropriate phase and frequency of A.C. However, a large array of such capacitors is needed to store substantial electric power. Ultracapacitors, while more environmentally friendly and...
longer lived than batteries, are substantially more expensive, and still require periodic replacement due to the breakdown of internal dielectrics, etc.

Another approach to storage of energy for later distribution involves the use of a large reservoir of compressed air. Storing energy in the form of compressed gas has a long history and components tend to be well tested, reliable, and have long lifetimes. The general principle of compressed-gas or compressed-air energy storage (CAES) is that generated energy (e.g., electric energy) is used to compress gas (e.g., air), thus converting the original energy to pressure potential energy; this potential energy is later recovered in a useful form (e.g., converted back to electricity) via gas expansion coupled to an appropriate mechanism. Advantages of compressed-gas energy storage include low specific-energy costs, long lifetime, low maintenance, reasonable energy density, and good reliability.

By way of background, a so-called compressed-air energy storage (CAES) system is shown and described in the published thesis entitled “Investigation and Optimization of Hybrid Electricity Storage Systems Based Upon Air and Supercapacitors,” by Sylvain Lemfoeuter-Gatisi, Ecole Polytechnique Federale de Lausanne (20 Oct. 2006) (hereafter “Lemfoeuter-Gatisi”), Section 2.2.1, the disclosure of which is hereby incorporated herein by reference in its entirety. As stated by Lemfoeuter-Gatisi, “the principle of CAES derives from the splitting of the normal gas turbine cycle—where roughly 60% of the produced power is used to compress air—into two separated phases: The compression phase where lower-cost energy from off-peak base-load facilities is used to compress air into underground salt caverns and the generation phase where the pre-compressed air from the storage cavern is preheated through a heat recuperator, then mixed with oil or gas and burned to feed a multistage expander turbine to produce electricity during peak demand. This functional separation of the compression cycle from the combustion cycle allows a CAES plant to generate three times more energy with the same quantity of fuel compared to a simple cycle natural gas power plant.

Lemfoeuter-Gatisi continues, “CAES has the advantages that it doesn’t involve huge, costly installations and can be used to store energy for a long time (more than one year). It also has a fast start-up time (9 to 12 minutes), which makes it suitable for grid operation, and the emissions of greenhouse gases are lower than that of a normal gas power plant, due to the reduced fuel consumption. The main drawback of CAES is probably the geological structure reliance, which substantially limits the usability of this storage method. In addition, CAES power plants are not emission-free, as the pre-compressed air is heated up with a fossil fuel burner before expansion. Moreover, CAES plants are limited with respect to their effectiveness because of the loss of the compression heat through the inter-coolers, which must be compensated during expansion by fuel burning. The fact that conventional CAES still rely on fossil fuel consumption makes it difficult to evaluate its energy round-trip efficiency and to compare it to conventional fuel-free storage technologies.”

A number of variations on the above-described compressed air energy storage approach have been proposed, some of which attempt to heat the expanded air with electricity, rather than fuel. Others employ heat exchange with thermal storage to extract and recover as much of the thermal energy as possible, therefore attempting to increase efficiencies. Still other approaches employ compressed gas-driven piston motors that act both as compressors and generator drives in opposing parts of the cycle. In general, the use of highly compressed gas as a working fluid for the motor poses a number of challenges due to the tendency for leakage around seals at higher pressures, as well as the thermal losses encountered in rapid expansion. While heat exchange solutions can deal with some of these problems, efficiencies are still compromised by the need to heat compressed gas prior to expansion from high pressure to atmospheric pressure.

It has been recognized that gas is a highly effective medium for storage of energy. Liquids are incompressible and flow efficiently across an impeller or other moving component to rotate a generator shaft. One energy storage technique that uses compressed gas to store energy, but which uses a liquid, for example, hydraulic fluid, rather than compressed gas to drive a generator, is a so-called closed-air hydraulic-pneumatic system. Such a system employs one or more high-pressure tanks (accumulators) having a charge of compressed gas, which is separated by a movable wall or flexible bladder membrane from a charge of hydraulic fluid. The hydraulic fluid is coupled to a bi-directional impeller (or other hydraulic motor/pump), which is itself coupled to a combined electric motor/generator. The other side of the impeller is connected to a low-pressure reservoir of hydraulic fluid. During a storage phase, the electric motor and impeller force hydraulic fluid from the low-pressure hydraulic fluid reservoir into the high-pressure tank(s), against the pressure of the compressed air. As the incompressible liquid fills the tank, it forces the air into a smaller space, thereby compressing it to an even higher pressure. During a generation phase, the fluid circuit is run in reverse and the impeller is driven by fluid escaping from the high-pressure tank(s) under the pressure of the compressed gas.

This closed-air approach has an advantage in that the gas is never expanded to or compressed from atmospheric pressure, as it is sealed within the tank. An example of a closed-air system is shown and described in U.S. Pat. No. 5,579,640, the disclosure of which is hereby incorporated herein by reference in its entirety. Closed-air systems tend to have low energy densities. That is, the amount of compression possible is limited by the size of the tank space. In addition, since the gas does not completely decompress when the fluid is removed, there is still additional energy in the system that cannot be tapped. To make a closed air system desirable for large-scale energy storage, many large accumulator tanks would be needed, increasing the overall cost to implement the system and requiring more land to do so.

Another approach to hybrid hydraulic-pneumatic energy storage is the open-air system. In this system, compressed air is stored in a large, separate high-pressure tank (or plurality of tanks). A pair of accumulators is provided, each having a fluid side separated from a gas side by a movable piston wall. The fluid sides of a pair (or more) of accumulators are coupled together through an impeller/generator/motor combination. The air side of each of the accumulators is coupled to the high pressure air tanks, and also to a valve-driven atmospheric vent. Under expansion of the air chamber side, fluid in one accumulator is driven through the impeller to generate power, and the spent fluid then flows into the second accumulator, whose air side is now vented to atmospheric, thereby allowing the fluid to collect in the second accumulator. During the storage phase, electrical energy can be used to directly recharge the pressure tanks via a compressor, or the accumulators can be run in reverse to pressurize the pressure
tanks. A version of this open-air concept is shown and described in U.S. Pat. No. 6,145,311 (the ’311 patent), the disclosure of which is hereby incorporated herein by reference in its entirety. Disadvantages of open-air systems can include gas leakage, complexity, expense and, depending on the intended deployment, potential impracticality.

[0017] Additionally, it is desirable for solutions that address the fluctuations in power demand to also address environmental concerns and include using renewable energy sources. As demand for renewable energy increases, the intermittent nature of some renewable energy sources (e.g., wind and solar) places an increasing burden on the electric grid. The use of energy storage is a key factor in addressing the intermittent nature of the electricity produced by renewable sources, and more generally in shifting the energy produced to the time of peak demand.

[0018] As discussed, storing energy in the form of compressed air has a long history. However, most of the discussed methods for converting potential energy in the form of compressed air to electrical energy utilize turbines to expand the gas, which is an inherently adiabatic process. As gas expands, it cools off if there is no input of heat (adiabatic gas expansion), as is the case with gas expansion in a turbine. The advantage of adiabatic gas expansion is that it can occur quickly, thus resulting in the release of a substantial quantity of energy in a short time frame.

[0019] However, if the gas expansion occurs slowly relative to the time with which it takes for heat to flow into the gas, then the gas remains at a relatively constant temperature as it expands (isothermal gas expansion). Gas stored at ambient temperature, which is expanded isothermally, recovers approximately three times the energy of ambient temperature gas expanded adiabatically. Therefore, there is a significant energy advantage to expanding gas isothermally. Gas may be not only expanded but compressed either isothermally or adiabatically.

[0020] An ideally isothermal energy-storage cycle of compression, storage, and expansion would have 100% thermodynamic efficiency. An ideally adiabatic energy-storage cycle would also have 100% thermodynamic efficiency, but there are many practical disadvantages to the adiabatic approach. These include the production of more extreme temperatures and pressures within the system, heat loss during the storage period, and inability to exploit environmental (e.g., cogenerative) heat sources and sinks during expansion and compression, respectively. In an adiabatic system, the cost of adding a heat-exchange system is traded against resolving the difficulties of the adiabatic approach. In either case, mechanical energy from expanding gas must usually be converted to electrical energy before use.

[0021] In the case of certain compressed gas energy storage systems according to prior implementations, gas is expanded from a high-pressure, high-capacity source, such as a large underground cavern, and directed through a multi-stage gas turbine. Because significant expansion occurs at each stage of the operation, the gas cools down at each stage. To increase efficiency, the gas is mixed with fuel and ignited, pre-heating it to a higher temperature, thereby increasing power and final gas temperature. However, the need to burn fossil fuel (or apply another energy source, such as electric heating) to compensate for adiabatic expansion substantially defeats the purpose of an otherwise clean and emission-free energy-storage and recovery process.

[0022] While it is technically possible to provide a direct heat-exchange subsystem to a hydraulic/pneumatic cylinder, an external jacket, for example, is not particularly effective given the thick walls of the cylinder. An internalized heat exchange subsystem could conceivably be mounted directly within the cylinder’s pneumatic side; however, size limitations would reduce such a heat exchanger’s effectiveness and the task of sealing a cylinder with an added subsystem installed therein would be significant, and make the use of a conventional, commercially available component difficult or impossible.

[0023] Thus, the prior art does not disclose systems and methods for rapidly compressing and expanding gas isothermally in a manner that allows maximum use of conventional, low-cost components, and which operates in a commercially practicable yet environmentally friendly manner. Furthermore, energy storage and recovery systems could be more widely deployed if they converted the work done by the linear piston motion directly into electrical energy or into rotary motion via mechanical means (or vice versa). In such ways, the overall efficiency and cost-effectiveness of the compressed air system would be increased.

SUMMARY OF THE INVENTION

[0024] In various embodiments, the invention provides an energy storage system, based upon an open-air arrangement, that expands pressurized gas in small batches from a high pressure of several hundred atmospheres to atmospheric pressure. The systems may be sized and operated at a rate that allows for near-isothermal expansion and compression of the gas. The systems may also be scalable through coupling of additional accumulator circuits and storage tanks as needed. Systems and methods in accordance with the invention may allow for efficient near-isothermal high compression and expansion in a manner that provides a high energy density.

[0025] Embodiments of the invention provide a system for storage and recovery of energy using an open-air hydraulic/pneumatic accumulator and intensifier arrangement implemented in at least one circuit that combines an accumulator and an intensifier in communication with a high-pressure gas storage reservoir on the gas-side of the circuit, and a combination fluid motor/pump coupled to a combination electric generator/motor on the fluid side of the circuit. In a representative embodiment, an expansion/energy recovery mode, the accumulator of a first circuit is first filled with high-pressure gas from the reservoir, and the reservoir is then cut off from the air chamber of the accumulator. This gas causes fluid in the accumulator to be driven through the motor/pump to generate electricity. Excess gas is driven into either an opposing intensifier or an accumulator in an opposing second circuit, whose air chamber is vented to atmosphere. As the gas in the accumulator expands to mid-pressure, and fluid is drained, the mid-pressure gas in the accumulator is then connected to an intensifier with a larger-area air piston acting on a smaller area fluid piston. Fluid in the intensifier is then driven through the motor/pump at still-high fluid pressure, despite the mid-pressure gas in the intensifier air chamber. Fluid from the motor/pump is exhausted into either the opposing first accumulator or an intensifier of the second circuit, whose air chamber may be vented to atmosphere as the corresponding fluid chamber fills with exhausted fluid. In a compression/energy storage stage, the process is reversed and the fluid motor/pump is driven by the electric component to force
fluid into the intensifier and the accumulator to compress gas and deliver it to the tank reservoir under high pressure.

[0026] Embodiments of the present invention also obviate the need for a hydraulic subsystem by converting the reciprocating motion of energy storage and recovery cylinders into electrical energy via alternative means. In some embodiments, the invention combines a compressed-gas energy storage system with a linear-generator system for the generation of electricity from reciprocating motion to increase system efficiency and cost-effectiveness. The arrangement of devices may be used to convert electric energy to potential energy in compressed gas, with similar gains in efficiency and cost-effectiveness.

[0027] Another alternative, utilized in various embodiments, to the use of hydraulic fluid to transmit force between the motor/generator and the gas undergoing compression or expansion is the mechanical transmission of the force. In particular, the linear motion of the cylinder piston or pistons may be coupled to a crankshaft or other means of conversion to rotary motion. The crankshaft may in turn be coupled to, e.g., a gear box or a continuously variable transmission (CVT) that drives the shaft of an electric motor/generator at a rotational speed higher than that of the crankshaft. The continuously variable transmission, within its operable range of effective gear ratios, allows the motor/generator to be operated at constant speed regardless of crankshaft speed. The motor/generator operating point can be chosen for optimal efficiency; constant output power is also desirable. Multiple pistons may be coupled to a single crankshaft, which may be advantageous for purposes of shaft balancing.

[0028] The power output of these systems is governed by how fast the gas can expand isothermally. Therefore, the ability to expand/compress the gas isothermally at a faster rate will result in a greater power output of the system. By adding a heat transfer subsystem to these systems, the power density of said system may be increased substantially. Therefore, energy storage and generation systems in accordance with embodiments of the invention include a heat-transfer subsystem for expediting heat transfer in one or more compartments of the cylinder assembly. In one embodiment, the heat-transfer subsystem includes a fluid circulator and a heat-transfer fluid reservoir. The fluid circulator pumps a heat-transfer fluid into the first compartment and/or the second compartment of the pneumatic cylinder. The heat-transfer subsystem may also include a spray mechanism, disposed in the first compartment and/or the second compartment, for introducing the heat-transfer fluid. In various embodiments, the spray mechanism is a spray head and/or a spray rod.

[0029] Gas undergoing expansion tends to cool, while gas undergoing compression tends to heat. To maximize efficiency (i.e., the fraction of elastic potential energy in the compressed gas that is converted to work, or vice versa), gas expansion and compression should be as near isothermal (i.e., constant-temperature) as possible. Several ways of approximating isothermal expansion and compression may be employed.

[0030] First, droplets of a liquid (e.g., water) may be sprayed into a chamber of the pneumatic cylinder in which gas is presently undergoing compression (or expansion) in order to transfer heat to or from the gas. As the liquid droplets exchange heat with the gas around them, the temperature of the gas is raised or lowered; the temperature of the droplets is also raised or lowered. The liquid is evacuated from the cylinder through a suitable mechanism. The heat-exchange spray droplets may be introduced through a spray head (in, e.g., a vertical cylinder), through a spray rod arranged coaxially with the cylinder piston (in, e.g., a horizontal cylinder), or by any other mechanism that permits formation of a liquid spay within the cylinder. Droplets may be used to either warm gas undergoing expansion or to cool gas undergoing compression. An isothermal process may be approximated via judicious selection of this heat-exchange rate.

[0031] Furthermore, as described in U.S. Pat. No. 7,802,426 (the ’426 patent), the disclosure of which is hereby incorporated by reference herein in its entirety, gas undergoing either compression or expansion may be directed, continuously or in installments, through a heat-exchange subsystem external to the cylinder. The heat-exchange subsystem either heats up to the environment (cool gas undergoing compression) or absorbs heat from the environment (to warm gas undergoing expansion). Again, an isothermal process may be approximated via judicious selection of this heat-exchange rate.

[0032] As mentioned above, some embodiments of the present invention utilize a linear motor/generator as an alternative to the conventional rotary motor/generator. Like a rotary motor/generator, a linear motor/generator, when operated as a generator, converts mechanical power to electrical power by exploiting Faraday’s law of induction: that is, the magnetic flux through a closed circuit is made to change by moving a magnet, thus inducing an electromotive force (EMF) in the circuit. The same device may also be operated as a motor.

[0033] There are several forms of linear motor/generator, but for simplicity, the discussion herein primarily pertains to the permanent-magnet tubular type. In some applications tubular linear generators have advantages over flat topologies, including smaller leakage, smaller coils with concomitant lower conductor loss and higher force-to-weight ratio. For brevity, only operation in generator mode is described herein. The ability of such a machine to operate as either a motor or generator will be apparent to any person reasonably familiar with the principles of electrical machines.

[0034] In a typical tubular linear motor/generator, permanent radially-magnetized magnets, sometimes alternated with iron core rings, are affixed to a shaft. The permanent magnets have alternating magnetization. This armature, composed of shaft and magnets, is termed a translator or mover and moves axially through a tubular winding or stator. Its function is analogous to that of a rotor in a conventional generator. Moving the translator through the stator in either direction produces a pulse of alternating EMF in the stator coil. The tubular linear generator thus produces electricity from a source of reciprocating motion. Moreover, such generators offer the translation of such mechanical motion into electrical energy with high efficiency, since they obviate the need for gear boxes or other mechanisms to convert reciprocal into rotary motion. Since a linear generator produces a series of pulses of alternating current (AC) power with significant harmonics, power electronics are typically used to condition the output of such a generator before it is fed to the power grid. However, such power electronics require less maintenance and are less prone to failure than the mechanical linear-to-rotary conversion systems which would otherwise be required. Operated as a motor, such a tubular linear motor/generator produces reciprocating motion from an appropriate electrical excitation.
In compressed-gas energy storage systems in accordance with embodiments of the present invention, gas is stored at high pressure (e.g., approximately 3000 pounds per square inch gauge (psig)). This gas is expanded into a chamber of a cylinder containing a piston or other mechanism that separates the gas on one side of the cylinder from the other, preventing gas movement from one chamber to the other while allowing the transfer of force/pressure from one chamber to the next. The shaft of the cylinder may be attached to a mechanical load, e.g., the translator of a linear generator. In the simplest arrangement, the cylinder shaft and translator are in line (i.e., aligned on a common axis). In some embodiments, the shaft of the cylinder is coupled to a transmission mechanism for converting a reciprocating motion of the shaft into a rotary motion, and a motor/generator is coupled to the transmission mechanism. In some embodiments, the transmission mechanism includes a crankshaft and a gear box. In other embodiments, the transmission mechanism includes a crankshaft and a CVT. A CVT is a transmission that can move smoothly through a continuum of effective gear ratios over some finite range.

In various embodiments described herein, reciprocating motion is produced during recovery of energy from storage by expansion of gas in pneumatic cylinders. In various embodiments, this reciprocating motion is converted to rotary motion by first using the expanding gas to drive a pneumatic/hydraulic intensifier; the hydraulic fluid pressurized by the intensifier drives a hydraulic rotary motor/generator to produce electricity. (The system is run in reverse to convert electric energy into potential energy in compressed gas.) By mechanically coupling linear generators to pneumatic cylinders, the hydraulic system may be omitted, typically with increased efficiency and reliability. Conversely, a linear motor/generator may be operated as a motor in order to compress gas in pneumatic cylinders for storage in a reservoir. In this mode of operation, the device converts electrical energy to mechanical energy rather than the reverse. The potential advantages of using a linear electrical machine may thus accrue to both the storage and recovery operations of a compressed-gas energy storage system.

In various embodiments, the compression and expansion occurs in multiple stages, using low- and high-pressure cylinders. For example, in expansion, high-pressure gas is expanded in a high-pressure cylinder from a maximum pressure (e.g., approximately 3,000 psig) to some mid-pressure (e.g., approximately 300 psig); then this mid-pressure gas is further expanded further (e.g., approximately 300 psig to approximately 30 psig) in a separate low-pressure cylinder. Thus, a high-pressure cylinder may handle a maximum pressure up to approximately a factor of ten greater than that of a low-pressure cylinder. Furthermore, the ratio of maximum to minimum pressure handled by a high-pressure cylinder may be approximately equal to ten (or even greater), and/or may be approximately equal to such a ratio of the low-pressure cylinder. The minimum pressure handled by a high-pressure cylinder may be approximately equal to the maximum pressure handled by a low-pressure cylinder.

The two stages may be tied to a common shaft and driven by a single linear motor/generator (or may be coupled to a common crankshaft, as detailed below). When each piston reaches the limit of its range of motion (e.g., reaches the end of the low-pressure side of the chamber), valves or other mechanisms may be adjusted to direct gas to the appropriate chambers. In double-acting devices of this type, there is no withdrawal stroke or unpowered stroke: the stroke is powered in both directions.

Since a tubular linear generator is inherently double-acting (i.e., generates power regardless of which way the translator moves), the resulting system generates electrical power at all times other than when the piston is hesitating between strokes. Specifically, the output of the linear generator may be a series of pulses of AC power, separated by brief intervals of zero power output during which the mechanism reverses its stroke direction. Power electronics may be employed with short-term energy storage devices such as ultracapacitors to condition this waveform to produce power acceptable for the grid. Multiple units operating out-of-phase may also be used to minimize the need for short-term energy storage during the transition periods of individual generators.

Use of a CVT enables the motor/generator to be operated at constant torque and speed over a range of crankshaft rotational velocities. The resulting system generates electrical power continuously and at a fixed output level as long as pressurized air is available from the reservoir. As mentioned above, power electronics and short-term energy storage devices such as ultracapacitors may, if needed, condition the waveform produced by the motor/generator to produce power acceptable for the grid.

In various embodiments, the system also includes a source of compressed gas and a control-valve arrangement for selectively connecting the source of compressed gas to an input of the first compartment (or “chamber”) of the pneumatic cylinder assembly and an input of the second compartment of the pneumatic cylinder assembly. The system may also include a second pneumatic cylinder assembly having a first compartment and a second compartment separated by a piston slidably disposed within the cylinder and a shaft coupled to the piston and extending through at least one of the first compartment and the second compartment of the second cylinder and beyond an end cap of the second cylinder and coupled to a transmission mechanism. The second pneumatic cylinder assembly may be fluidly coupled to the first pneumatic cylinder assembly. For example, the pneumatic cylinder assemblies may be coupled in series. Additionally, one of the pneumatic cylinder assemblies may be a high-pressure cylinder and the other pneumatic cylinder assembly may be a low-pressure cylinder. The low-pressure cylinder may be volumetrically larger, e.g., may have an interior volume at least 50% larger, than the high-pressure cylinder assembly.

A further opportunity for increased efficiency arises from the fact that as gas in the high-pressure storage vessel is exhausted, its pressure decreases. Thus, in order to extract as much energy as possible from a given quantity of stored gas, the electricity-producing side of such an energy-storage system must operate over a wide range of input pressures, i.e., from the reservoir’s high-pressure limit (e.g., approximately 3,000 psig) to as close to atmospheric pressure as possible. At lower pressure, gas expanding in a cylinder exerts a smaller force on its piston and thus on the translator of the linear generator (or to the rotor of the generator) to which it is coupled. For a fixed piston speed, this generally results in reduced power output.

In various embodiments, however, power output is substantially constant. Constant power may be maintained with decreased force by increasing piston linear speed. Piston speed may be regulated, for example, by using power elec-
tronics to adjust the electrical load on a linear generator so that translator velocity is increased (with correspondingly higher voltage and lower current induced in the stator) as the pressure of the gas in the high-pressure storage vessel decreases. At lower gas-reservoir pressures, in such an arrangement, the pulses of AC power produced by the linear generator will be shorter in duration and higher in frequency, requiring suitable adjustments in the power electronics to continue producing grid-suitable power.

With variable linear motor/generator speed, efficiency gains may be realized by using variable-pitch windings and/or a switched-reluctance linear generator. In a switched-reluctance generator, the mover (i.e., translator or rotor) contains no permanent magnets; rather, magnetic fields are induced in the mover by windings in the stator which are controlled electronically. The position of the mover is either measured or calculated, and excitation of the stator windings is electronically adjusted in real time to produce the desired torque (or traction) for any given mover position and velocity.

Substantially constant power may also be achieved by mechanical linkages which vary the torque for a given force. Other techniques include piston speed regulation by using power electronics to adjust the electrical load on the motor/generator so that crankshaft velocity is increased, which for a fixed torque will increase power. For such arrangements using power electronics, the center frequency and harmonics of the AC waveform produced by the motor/generator typically change, which may require suitable adjustments in the power electronics to continue producing grid-suitable power.

Use of a CVT to couple a crankshaft to a motor/generator is yet another way to achieve approximately constant power output in accordance with embodiments of the invention. Generally, there are two challenges to the maintenance of constant output power. First is the discrete piston stroke. As a quantity of gas is expanded in a cylinder during the course of a single stroke, its pressure decreases; to maintain constant power output from the cylinder as the force acting on its piston decreases, the piston’s linear velocity is continually increased throughout the stroke. This increases the crankshaft angular velocity proportionately throughout the stroke. To maintain constant angular velocity and constant power at the input shaft of the motor/generator throughout the stroke, the effective gear ratio of the CVT is adjusted continuously to offset increasing crankshaft speed.

Second, pressure in the main gas store decreases as the store is exhausted. As this occurs, the piston velocity at all points along the stroke is typically increased to deliver constant power. Crankshaft angular velocity is therefore also typically increased at all times.

Under these illustrative conditions, the effective gear ratio of the CVT that produces substantially constant output power, plotted as a function of time, has the approximate form of a periodic sawtooth (corresponding to CVT adjustment during each discrete stroke) superimposed on a ramp (corresponding to CVT adjustment compensating for exhaustion of the gas store.)

With either a linear or rotary motor/generator, the range of forces (and thus of speeds) is generally minimized in order to achieve maximize efficiency. In lieu of more complicated linkages, for a given operating pressure range (e.g., from approximately 3,000 psig to approximately 30 psig), the range of forces (torques) seen at the motor/generator may be reduced through the addition of multiple cylinder stages arranged, e.g., in series. That is, as gas from the high-pressure reservoir is expanded in one chamber of an initial, high-pressure cylinder, gas from the other chamber is directed to the expansion chamber of a second, lower-pressure cylinder. Gas from the lower-pressure chamber of this second cylinder may either be vented to the environment or directed to the expansion chamber of a third cylinder operating at still lower pressure, and so on. An arrangement using two cylinder assemblies is shown and described; however, the principle may be extended to more than two cylinders to suit a particular application.

For example, a narrower force range over a given range of reservoir pressures is achieved by having a first, high-pressure cylinder operating between approximately 3,000 psig and approximately 300 psig and a second, large-volume, low-pressure cylinder operating between approximately 300 psig and approximately 30 psig. The range of pressures (and thus of force) is reduced as the square root, from 100:1 to 10:1, compared to the range that would be realized in a single cylinder operating between approximately 3,000 psig and approximately 30 psig. The square-root relationship between the two-cylinder pressure range and the single-cylinder pressure range can be demonstrated as follows.

A given pressure range $R_p$ from high pressure $P_h$ to low pressure $P_l$, namely $R_p = P_h/P_l$, is subdivided into two pressure ranges of equal magnitude $R_e$. The first range is from $P_p$ down to some intermediate pressure $P_i$ and the second is from $P_i$ down to $P_l$. Thus, $R_e = P_p/P_i$. From this identity of ratios, $P_p = (P_i/P_p)^{1/2}$, $P_i = (P_p/P_i)^{1/2}$. $R_e = (P_p/P_i)^{1/2}$. Substituting for $P_i$ in $R_e = P_p/P_i$, we obtain $R_e = (P_p/P_i)^{1/2}$. From this identity, it may be similarly shown that with appropriate cylinder sizing, the addition of a third cylinder/stage reduces the operating pressure range as the cube root, and so forth. In general (and as also set forth herein), $N$ appropriately sized cylinders reduce an original (i.e., single-cylinder) operating pressure range $R_e$ to $R_e^{1/N}$. Any group of $N$ cylinders staged in this manner, where $N=2$, is herein termed a cylinder group.

In various embodiments, the shafts of two or more double-acting cylinders are connected either to separate linear motor/generators or to a single linear motor/generator, either in line or in parallel. If they are connected in line, their common shaft may be arranged in line with the translator of a linear motor/generator. If they are connected in parallel, their separate shafts may be linked to a transmission (e.g., rigid beam) that is orthogonal to the shafts and to the translator of the motor/generator. Another portion of the beam may be attached to the translator of a linear generator that is aligned in parallel with the two cylinders. The synchronized reciprocal motion of the two double-acting cylinders may thus be transmitted to the linear generator.

In other embodiments of the invention, two or more cylinder groups, which may be identical, may be coupled to a common crankshaft. A crosshead arrangement may be used for coupling each of the N pneumatic cylinder shafts in each cylinder group to the common crankshaft. The crankshaft may be coupled to an electric motor/generator either directly or via a gear box. If the crankshaft is coupled directly to an electric motor/generator, the crankshaft and motor/generator may turn at very low speed (very low revolutions per minute, RPM), e.g., 25-30 RPM, as determined by the cycle speed of the cylinders.
Any multiple-cylinder implementation of this invention such as that described above may be co-implemented with any of the heat-transfer mechanisms described earlier.

All of the mechanisms described herein for converting potential energy in compressed gas to electrical energy, including the heat-exchange mechanisms and power electronics described, can, if appropriately designed, be operated in reverse to store electrical energy as potential energy in a compressed gas. Since this will be apparent to any person reasonably familiar with the principles of electrical machines, power electronics, pneumatics, and the principles of thermodynamics, the operation of these mechanisms to store energy rather than to recover it from storage will not be described in many embodiments. Such operation is, however, contemplated and within the scope of the invention and may be straightforwardly realized without undue experimentation.

In an aspect, embodiments of the invention feature an energy storage and generation system including or consisting essentially of a first pneumatic cylinder assembly for compressing gas to store energy and/or expanding gas to recover energy, a motor/generator outside the first cylinder assembly, a transmission mechanism, a heat-transfer subsystem, and a control system for controlling operation of the first pneumatic cylinder assembly to enforce substantially isothermal expansion and compression of gas therein to thereby increase efficiency of the expansion and compression. The first cylinder assembly includes or consists essentially of a first compartment, a second compartment, and a piston separating the compartments. The transmission mechanism is coupled to the piston and the motor/generator and converts reciprocating motion of the piston into rotary motion of the motor/generator and/or converts rotary motion of the motor/generator into reciprocal motion of the piston. The heat-transfer subsystem expedites heat transfer in the first compartment and/or the second compartment of the first pneumatic cylinder assembly. The control system is responsive to at least one system parameter associated with operation of the first pneumatic cylinder assembly.

Embodiments of the invention may include one or more of the following, in any of a variety of combinations. The system may include a shaft having a first end coupled to the piston and a second end coupled to the transmission mechanism (e.g., by a crosshead linkage). The system may include a container for storage of compressed gas after compression and/or supply of compressed gas for expansion thereof, as well as an arrangement for selectively permitting fluid communication of the container with at least one compartment of the first pneumatic cylinder assembly. A second pneumatic cylinder assembly, including or consisting essentially of a first compartment, a second compartment, and a piston separating the compartments (and coupled to the transmission mechanism), may be fluidly coupled to the first pneumatic cylinder assembly (e.g., in series). The second pneumatic cylinder assembly may include a shaft having a first end coupled to the piston of the second pneumatic cylinder assembly and a second end coupled to the transmission mechanism (e.g., by a crosshead linkage).

The transmission mechanism may include or consist essentially of a crankshaft, a crankshaft and a gear box, or a crankshaft and a continuously variable transmission. The heat-transfer subsystem may include a fluid circulator for pumping heat-transfer liquid into the first compartment and/or the second compartment of the first pneumatic cylinder assembly. A mechanism for introducing the heat-transfer fluid (e.g., a spray head and/or a spray rod) may be disposed in the first compartment and/or the second compartment of the first pneumatic cylinder assembly. The transmission mechanism may vary torque for a given force exerted on the transmission mechanism. The system may include power electronics for adjusting a load on the motor/generator. The at least one system parameter may include or consist essentially of a fluid state, a fluid flow, a temperature, and/or a pressure. The system may include one or more sensors that monitor the at least one system parameter, and the control system may be responsive to the sensor(s). The system may include a vent for supply of gas for compression and/or exhausting gas after expansion. Energy stored during compression of gas may originate from an intermittent renewable energy source (e.g., of wind or solar energy). Energy may be recovered via expansion of gas when the intermittent renewable energy source is nonfunctional.

These and other objects, along with the advantages and features of the present invention herein disclosed, will become apparent through reference to the following description, the accompanying drawings, and the claims. Furthermore, it is to be understood that the features of the various embodiments described herein are not mutually exclusive and can exist in various combinations and permutations. Herein, the terms “liquid” and “water” interchangeably connote any mostly or substantially incompressible liquid, the terms “gas” and “air” are used interchangeably, and the term “fluid” may refer to a liquid or a gas unless otherwise indicated. As used herein, the term “substantially” means ±10%, and, in some embodiments, ±5%. A “valve” is any mechanism or component for controlling fluid communication between fluid paths or reservoirs, or for selectively permitting control or venting. The term “cylinder” refers to a chamber, of uniform but not necessarily circular cross-section, which may contain a slightly disposed piston or other mechanism that separates the fluid on one side of the chamber from that on the other, preventing fluid movement from one side of the chamber to the other while allowing the transfer of force/pressure from one side of the chamber to the next or to a mechanism outside the chamber. In the absence of a mechanical separation mechanism, a “chamber” or “compartment” of a cylinder may correspond to substantially the entire volume of the cylinder. A “cylinder assembly” may be a simple cylinder or include multiple cylinders, and may or may not have additional associated components (such as mechanical linkages among the cylinders).

BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings, like reference characters generally refer to the same parts throughout the different views. In addition, the drawings are not necessarily to scale, emphasis instead generally being placed upon illustrating the principles of the invention. In the following description, various embodiments of the present invention are described with reference to the following drawings, in which:

FIG. 1 is a schematic diagram of an open-air hydraulic-pneumatic energy storage and recovery system in accordance with one embodiment of the invention;

FIGS. 1A and 1B are enlarged schematic views of the accumulator and intensifier components of the system of FIG. 1;
[0063] FIGS. 2A-2Q are simplified graphical representations of the system of FIG. 1 illustrating the various operational stages of the system during compression;

[0064] FIGS. 3A-3M are simplified graphical representations of the system of FIG. 1 illustrating the various operational stages of the system during expansion;

[0065] FIG. 4, incorporating, as shown, partial views FIG. 4A and FIG. 4B, is a schematic diagram of an open-air hydraulic-pneumatic energy storage and recovery system in accordance with an alternative embodiment of the invention;

[0066] FIGS. 5A-5N are schematic diagrams of the system of FIG. 4 illustrating the cycling of the various components during an expansion phase of the system;

[0067] FIG. 6 is a generalized diagram of the various operational states of an open-air hydraulic-pneumatic energy storage and recovery system in accordance with one embodiment of the invention in both an expansion/energy recovery cycle and a compression/energy storage cycle;

[0068] FIGS. 7A-7F are partial schematic diagrams of an open-air hydraulic-pneumatic energy storage and recovery system in accordance with another alternative embodiment of the invention, illustrating the various operational stages of the system during an expansion phase;

[0069] FIG. 8 is a table illustrating the expansion phase for the system of FIGS. 7A-7F;

[0070] FIG. 9 is a schematic diagram of an open-air hydraulic-pneumatic energy storage and recovery system including a heat transfer subsystem in accordance with one embodiment of the invention;

[0071] FIG. 9A is an enlarged schematic diagram of the heat transfer subsystem portion of the system of FIG. 9;

[0072] FIG. 10 is a graphical representation of the thermal efficiencies obtained by the system of FIG. 9 at different operating parameters;

[0073] FIG. 11 is a schematic partial cross section of a hydraulic/pneumatic cylinder assembly including a heat transfer subsystem that facilities isothermal expansion within the pneumatic side of the cylinder in accordance with one embodiment of the invention;

[0074] FIG. 12 is a schematic partial cross section of a hydraulic/pneumatic intensifier assembly including a heat transfer subsystem that facilities isothermal expansion within the pneumatic side of the cylinder in accordance with an alternative embodiment of the invention;

[0075] FIG. 13 is a schematic partial cross section of a hydraulic/pneumatic cylinder assembly having a heat transfer subsystem that facilitates isothermal expansion within the pneumatic side of the cylinder in accordance with another alternative embodiment of the invention in which the cylinder is part of a power generating system;

[0076] FIG. 14A is a graphical representation of the amount of work produced based upon an adiabatic expansion of gas within the pneumatic side of a cylinder or intensifier for a given pressure versus volume;

[0077] FIG. 14B is a graphical representation of the amount of work produced based upon an ideal isothermal expansion of gas within the pneumatic side of a cylinder or intensifier for a given pressure versus volume;

[0078] FIG. 14C is a graphical representation of the amount of work produced based upon a near-isothermal expansion of gas within the pneumatic side of a cylinder or intensifier for a given pressure versus volume;

[0079] FIG. 15 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with one embodiment of the invention;

[0080] FIG. 16 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0081] FIG. 17 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with yet another embodiment of the invention;

[0082] FIG. 18 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0083] FIG. 19 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0084] FIGS. 20A and 20B are schematic diagrams of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0085] FIGS. 21A-21C are schematic diagrams of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0086] FIGS. 22A and 22B are schematic diagrams of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0087] FIG. 22C is a schematic cross-sectional view of a cylinder assembly for use in the system and method of FIGS. 22A and 22B;

[0088] FIG. 22D is a graphical representation of the estimated water spray heat transfer limits for an implementation of the system and method of FIGS. 22A and 22B;

[0089] FIGS. 23A and 23B are schematic diagrams of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with another embodiment of the invention;

[0090] FIG. 23C is a schematic cross-sectional view of a cylinder assembly for use in the system and method of FIGS. 23A and 23B;

[0091] FIG. 23D is a graphical representation of the estimated water spray heat transfer limits for an implementation of the system and method of FIGS. 23A and 23B;

[0092] FIGS. 24A and 24B are graphical representations of the various water spray requirements for the systems and methods of FIGS. 22 and 23;

[0093] FIG. 25 is a detailed schematic plan view in partial cross-section of a cylinder design for use in any of the foregoing embodiments of the invention described herein for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system in accordance with one embodiment of the invention;

[0094] FIG. 26 is a detailed schematic plan view in partial cross-section of a cylinder design for use in any of the foregoing embodiments of the invention described herein for expedited heat transfer to gas expanding (or being com-
pressed) in an open-air staged hydraulic-pneumatic system in accordance with one embodiment of the invention;

FIG. 27 is a schematic diagram of a compressed-gas storage subsystem for use with systems and methods for heating and cooling compressed gas in energy storage systems in accordance with one embodiment of the invention;

FIG. 28 is a schematic diagram of a compressed-gas storage subsystem for use with systems and methods for heating and cooling of compressed gas for energy storage systems in accordance with an alternative embodiment of the invention;

FIGS. 29A and 29B are schematic diagrams of a staged hydraulic-pneumatic energy conversion system including a heat transfer subsystem in accordance with one embodiment of the invention;

FIGS. 30A-30D are schematic diagrams of a staged hydraulic-pneumatic energy conversion system including a heat transfer subsystem in accordance with an alternative embodiment of the invention;

FIGS. 31A-31C are schematic diagrams of a staged hydraulic-pneumatic energy conversion system including a heat transfer subsystem in accordance with another alternative embodiment of the invention;

FIG. 32 is a schematic cross-sectional diagram showing the use of pressurized stored gas to operate a double-acting pneumatic cylinder and a linear motor/generator to produce electricity or stored pressurized gas according to various embodiments of the invention;

FIG. 33 depicts the mechanism of FIG. 32 in a different phase of operation (i.e., with the high- and low-pressure sides of the piston reversed and the direction of shaft motion reversed);

FIG. 34 depicts the arrangement of FIG. 32 modified to introduce liquid sprays into the two compartments of the cylinder, in accordance with various embodiments of the invention;

FIG. 35 depicts the mechanism of FIG. 34 in a different phase of operation (i.e., with the high- and low-pressure sides of the piston reversed and the direction of shaft motion reversed);

FIG. 36 depicts the mechanism of FIG. 32 modified by the addition of an external heat exchanger in communication with both compartments of the cylinder, where the contents of either compartment may be circulated through the heat exchanger to transfer heat to or from the gas as it expands or compresses, enabling substantially isothermal expansion or compression of the gas, in accordance with various embodiments of the invention;

FIG. 37 depicts the mechanism of FIG. 32 modified by the addition of a second pneumatic cylinder operating at a lower pressure than the first, in accordance with various embodiments of the invention;

FIG. 38 depicts the mechanism of FIG. 37 in a different phase of operation (i.e., with the high- and low-pressure sides of the pistons reversed and the direction of shaft motion reversed);

FIG. 39 depicts the mechanism of FIG. 32 modified by the addition of a second pneumatic cylinder operating at lower pressure, in accordance with various embodiments of the invention;

FIG. 40 depicts the mechanism of FIG. 39 in a different phase of operation (i.e., with the high- and low-pressure sides of the pistons reversed and the direction of shaft motion reversed);

FIG. 41 is a schematic diagram of a system and related method for substantially isothermal compression and expansion of a gas for energy storage using one or more pneumatic cylinders in accordance with various embodiments of the invention;

FIG. 42 is a schematic diagram of the system of FIG. 41 in a different phase of operation;

FIG. 43 is a schematic diagram of a system and related method for coupling a cylinder shaft to a crankshaft; and

FIGS. 44A and 44B are schematic diagrams of systems in accordance with various embodiments of the invention, in which multiple cylinder groups are coupled to a single crankshaft.

DETAILED DESCRIPTION

In the following, various embodiments of the present invention are generally described with reference to a single accumulator and a single intensifier or an arrangement with two accumulators and two intensifiers and simplified valve arrangements. It is, however, to be understood that the present invention can include any number and combination of accumulators, intensifiers, and valve arrangements. In addition, any dimensional values given are exemplary only, as the systems according to the invention are scalable and customizable to suit a particular application. Furthermore, the terms pneumatic, gas, and air are used interchangeably and the terms hydraulic, fluid, and liquid are also used interchangeably.

FIG. 1 depicts one embodiment of an open-air hydraulic-pneumatic energy storage and recovery system 100 in accordance with the invention in a neutral state (i.e., all of the valves are closed and energy is neither being stored nor recovered. The system 100 includes one or more high-pressure gas/air storage tanks 102a, 102b, . . . 102n. In FIG. 1 and other figures herein, wherever a series of objects is referred to, only a definite number of objects (e.g., two) may be explicitly depicted. Each tank 102 is joined in parallel via a manual valve(s) 104a, 104b, . . . 104n, respectively, to a main air line 108. The valves 104 are not limited to manual operation, but can be electrically, hydraulically, or pneumatically actuated, as can all of the valves described herein. The tanks 102 are each provided with a pressure sensor 112a, 112b, 112n and a temperature sensor 114a, 114b . . . 114n. These sensors 112, 114 can output electrical signals that can be monitored by a control system 120 via appropriate wired and wireless connections/communications. Additionally, the sensors 112, 114 could include visual indicators.

The control system 120, which is described in greater detail with respect to FIG. 4, can be any acceptable control device with a human-machine interface. For example, the control system 120 could include a computer (for example a PC-type) that executes a stored control application in the form of a computer-readable software medium. The control application receives telemetry from the various sensors to be described below, and provides appropriate feedback to control valve actuators, motors, and other needed electromechanical/electronic devices.

The system 100 further includes pneumatic valves 106a, 106b, 106c, . . . 106n that control the communication of the main air line 108 with an accumulator 116 and an intensifier 118. As previously stated, the system 100 can include any number and combination of accumulators 116 and intensifiers 118 to suit a particular application. The pneumatic
valves 106 are also connected to a vent 110 for exhausting air/gas from the accumulator 116, the intensifier 118, and/or the main air line 108.

[0117] As shown in FIG. 1A, the accumulator 116 includes an air chamber 140 and a fluid chamber 138 divided by a movable piston 136 having an appropriate sealing system using sealing rings and other components (not shown) that are known to those of ordinary skill in the art. Alternatively, a bladder type barrier could be used to divide the air and fluid chambers 140, 138 of the accumulator 116. The piston 136 moves along the accumulator housing in response to pressure differentials between the air chamber 140 and the opposing fluid chamber 138. In this example, hydraulic fluid (or another liquid, such as water) is indicated by a partially shaded volume in the fluid chamber 138. The accumulator 116 can also include optional shut-off valves 134 that can be used to isolate the accumulator 116 from the system 100. The valves 134 can be manually or automatically operated.

[0118] As shown in FIG. 1B, the intensifier 118 includes an air chamber 144 and a fluid chamber 146 divided by a movable piston assembly 142 having an appropriate sealing system using sealing rings and other components that are known to those of ordinary skill in the art. Similar to the accumulator piston 136, the intensifier piston 142 moves along the intensifier housing in response to pressure differentials between the air chamber 144 and the opposing fluid chamber 146.

[0119] However, the intensifier piston assembly 142 is actually two pistons: an air piston 142a connected by a shaft, rod, or other coupling means 143 to a respective fluid piston 142b. The fluid piston 142b moves in conjunction with the air piston 142a, but acts directly upon the associated intensifier fluid chamber 146. Notably, the internal diameter (and/or volume) (DAI) of the air chamber for the intensifier 118 is greater than the diameter (and/or volume) (DA) of the air chamber for the accumulator 116. In particular, the surface of the intensifier piston 142a is greater than the surface area of the accumulator piston 136. The diameter of the intensifier fluid piston (DIF) is approximately the same as the diameter of the accumulator piston 136 (DAF). Thus in this manner, a lower air pressure acting upon the intensifier piston 142a generates a similar pressure on the associated fluid chamber 146 as a higher air pressure acting on the accumulator piston 136. As such, the ratio of the pressures of the intensifier air chamber 144 and the intensifier fluid chamber 146 is greater than the ratio of the pressures of the accumulator air chamber 140 and the accumulator fluid chamber 138. In one example, the ratio of the pressures in the accumulator could be 1:1, while the ratio of pressures in the intensifier could be 10:1. These ratios will vary depending on the number of accumulators and intensifiers used and the particular application. In this manner, and as described further below, the system 100 allows for at least two stages of air pressure to be employed to generate similar levels of fluid pressure. Again, a shaded volume in the fluid chamber 146 indicates the hydraulic fluid and the intensifier 118 can also include the optional shut-off valves 134 to isolate the intensifier 118 from the system 100.

[0120] As also shown in FIGS. 1A and 1B, the accumulator 116 and the intensifier 118 each include a temperature sensor 122 and a pressure sensor 124 in communication with each air chamber 140, 144 and each fluid chamber 138, 146. These sensors are similar to sensors 112, 114 and deliver sensor telemetry to the control system 120, which in turn can send signals to control the valve arrangements. In addition, the pistons 136, 142 can include position sensors 148 that report the present position of the pistons 136, 142 to the control system 120. The position and/or rate of movement of the pistons 136, 142 can be used to determine relative pressure and flow of both the gas and the fluid.

[0121] Referring back to FIG. 1, the system 100 further includes hydraulic valves 128a, 128b, 128c, 128d, . . . 128n that control the communication of the fluid connections of the accumulator 116 and the intensifier 118 with a hydraulic motor 130. The specific number, type, and arrangement of the hydraulic valves 128 and the pneumatic valves 106 are collectively referred to as the control valve arrangements. In addition, the valves are generally depicted as simple two-way valves (i.e., shut-off valves); however, the valves could essentially be any configuration as needed to control the flow of air and/or fluid in a particular manner. The hydraulic line between the accumulator 116 and valves 128a, 128b and the hydraulic line between the intensifier 118 and valves 128c, 128d can include flow sensors 126 that relay information to the control system 120.

[0122] The motor/pump 130 can be a piston-type assembly having a shaft 131 (or other mechanical coupling) that drives, and is driven by, a combination electrical motor and generator assembly 132. The motor/pump 130 could also be, for example, an impeller, vane, or gear type assembly. The motor/generator assembly 132 is interconnected with a power distribution system and can be monitored for status and output/input level by the control system 120.

[0123] One advantage of the system depicted in FIG. 1, as opposed, for example, to the system of FIGS. 4 and 5, is that it achieves approximately double the power output in, for example, a 3000-3000 psig range without additional components. Shuffling the hydraulic fluid back and forth between the intensifier 118 and the accumulator 116 allows for the same power output as a system with twice the number of intensifiers and accumulators while expanding or compressing in the 300-3000 psig pressure range. In addition, this system arrangement can eliminate potential issues with self-priming for certain the hydraulic motors/pumps when in the pumping mode (i.e., compression phase).

[0124] FIGS. 2A-2Q represent, in a simplified graphical manner, the various operational stages of the system 100 during a compression phase, where the storage tanks 102 are charged with high pressure air/gas (i.e., energy is stored). In addition, only one storage tank 102 is shown and some of the valves and sensors are omitted for clarity. Furthermore, the pressure shown are for reference only and will vary depending on the specific operating parameters of the system 100.

[0125] As shown in FIG. 2A, the system 100 is in a neutral state, where the pneumatic valves 106 and the hydraulic valves 128 are closed. Shut-off valves 134 are open in every operational stage to maintain the accumulator 116 and intensifier 118 in communication with the system 100. The accumulator fluid chamber 138 is substantially filled, while the intensifier fluid chamber 146 is substantially empty. The storage tank 102 is typically at a low pressure (approximately 0 psig) prior to charging and the hydraulic motor/pump 130 is stationary.

[0126] As shown in FIGS. 2B and 2C, as the compression phase begins, pneumatic valve 106a is open, thereby allowing fluid communication between the accumulator air chamber 140 and the intensifier air chamber 144, and hydraulic valves 128a, 128b are open, thereby allowing fluid communication between the accumulator fluid chamber 138 and the intensifier fluid chamber 146 via the hydraulic motor/pump 130. The
motor/generator 132 (not shown in FIG. 2A; see FIG. 1) begins to drive the motor/pump 130, and the air pressure between the intensifier 118 and the accumulator 116 begins to increase, as fluid is driven to the intensifier fluid chamber 146 under pressure. The pressure or mechanical energy is transferred to the air chamber 144 via the piston assembly 142. This increase of air pressure in the accumulator air chamber 140 pressurizes the fluid chamber 138 of the intensifier 116, thereby providing pressurized fluid to the motor/pump 130 inlet, which can eliminate self-priming concerns.

As shown in FIGS. 2D, 2E, and 2F, the motor/generator 132 continues to drive the motor/pump 130, thereby transferring the hydraulic fluid from the accumulator 116 to the intensifier 118, which in turn continues to pressurize the air between the accumulator and intensifier air chambers 140, 144. FIG. 2F depicts the completion of the first stage of the compression phase. The pneumatic and hydraulic valves 106, 128 are all closed. The fluid chamber 144 of the intensifier 118 is substantially filled with fluid at a high pressure (for example, about 3000 psig) and the accumulator fluid chamber 138 is substantially empty and maintained at a mid-range pressure (for example, about 250 psig). The pressures in the accumulator and intensifier air chambers 140, 144 are maintained at the mid-range pressure.

The beginning of the second stage of the compression phase is shown in FIG. 2G, where hydraulic valves 128b, 128c are open and the pneumatic valves 106 are all closed, thereby putting the intensifier fluid chamber 146 at high pressure in communication with the motor/pump 130. The pressure of any gas remaining in the intensifier air chamber 144 will assist in driving the motor/pump 130. Once the hydraulic pressure equalizes between the accumulator and intensifier fluid chambers 138, 146 (as shown in FIG. 2H) the motor/generator will draw electricity to drive the motor/pump 130 and further pressurize the intensifier fluid chamber 138.

As shown in FIGS. 2I and 2J, the motor/pump 130 continues to pressurize the accumulator fluid chamber 138, which in turn pressurizes the accumulator air chamber 140. The intensifier fluid chamber 146 is at a low pressure and the intensifier air chamber 144 is at substantial atmospheric pressure. Once the intensifier air chamber 144 reaches substantially atmospheric pressure, pneumatic vent valve 106e is opened. For a vertical orientation of the intensifier, the weight of the intensifier piston 142 can provide the necessary backpressure to the motor/pump 130, which would overcome potential self-priming issues for certain motors/pumps.

As shown in FIG. 2K, the motor/pump 130 continues to pressurize the accumulator fluid chamber 138 and the accumulator air chamber 140, until the accumulator air and fluid chambers are at the high pressure for the system 100. The intensifier fluid chamber 146 is at a low pressure and is substantially empty. The intensifier air chamber 144 is at substantially atmospheric pressure. FIG. 2K also depicts the change-over in the control valve arrangement when the accumulator air chamber 140 reaches the predetermined high pressure for the system 100. Pneumatic valve 106a is opened to allow the high pressure gas to enter the storage tanks 102.

FIG. 2I depicts the end of the second stage of one compression cycle, where all of the hydraulic and the pneumatic valves 128, 106 are closed. The system 100 will now begin another compression cycle, where the system 100 shuttles the hydraulic fluid back to the intensifier 118 from the accumulator 116.

FIG. 2M depicts the beginning of the next compression cycle. The pneumatic valves 106 are closed and hydraulic valves 128a, 128d are open. The residual pressure of any gas remaining in the accumulator fluid chamber 138 drives the motor/pump 130 initially, thereby eliminating the need to draw electricity. As shown in FIG. 2N, and described with respect to FIG. 2G, once the hydraulic pressure equalizes between the accumulator and intensifier fluid chambers 138, 146 the motor/generator will draw electricity to drive the motor/pump 130 and further pressurize the intensifier fluid chamber 146. During this stage, the accumulator air chamber 140 pressure decreases and the intensifier air chamber 144 pressure increases.

As shown in FIG. 2O, when the gas pressures at the accumulator air chamber 140 and the intensifier air chamber 144 are equal, pneumatic valve 106b is opened, thereby putting the accumulator air chamber 140 and the intensifier air chamber 144 in fluid communication. As shown in FIGS. 2P and 2Q, the motor/pump 130 continues to transfer fluid from the accumulator fluid chamber 138 to the intensifier fluid chamber 146 and pressurize the intensifier fluid chamber 146. As described above with respect to FIGS. 2D-2F, the process continues until substantially all of the fluid has been transferred to the intensifier 118 and the intensifier fluid chamber 146 is at the high pressure and the intensifier air chamber 144 is at the mid-range pressure. The system 100 continues the process as shown and described in FIGS. 2G-2K, to continue storing high pressure air in the storage tanks 102. The system will perform as many compression cycles (i.e., the shuttling of hydraulic fluid between the accumulator 116 and the intensifier 118) as necessary to reach a desired pressure of the air in the storage tanks 102 (i.e., a full compression phase).

FIGS. 3A-3M represent, in a simplified graphical manner, the various operational stages of the system 100 during an expansion phase, where energy (i.e., the stored compressed gas) is recovered. FIGS. 3A-3M use the same designations, symbols, and exemplary numbers as shown in FIGS. 2A-2Q. It should be noted that while the system 100 is described as being used to compress the air in the storage tanks 102, alternatively, the tanks 102 could be charged (for example, an initial charge) by a separate compressor unit.

As shown in FIG. 3A, the system 100 is in a neutral state, where the pneumatic valves 106 and the hydraulic valves 128 are all closed. The same as during the compression phase, the shut-off valves 134 are open to maintain the accumulator 116 and intensifier 118 in communication with the system 100. The accumulator fluid chamber 138 is substantially filled, while the intensifier fluid chamber 146 is substantially empty. The storage tank 102 is at a high pressure (for example, 3000 psig) and the hydraulic motor/pump 130 is stationary.

FIG. 3B depicts a first stage of the expansion phase, where pneumatic valves 106a, 106c are open. Open pneumatic valve 106a connects the high pressure storage tanks 102 in fluid communication with the accumulator air chamber 140, which in turn pressurizes the accumulator fluid chamber 138. Open pneumatic valve 106c vents the intensifier air chamber 146 to atmosphere. Hydraulic valves 128a, 128d are open to allow fluid to flow from the accumulator fluid chamber 138 to drive the motor/pump 130, which in turn drives the motor/generator 132 (not shown in FIG. 3B), thereby generating electricity. The generated electricity can be delivered directly to a power grid or stored for later use, for example, during peak usage times.
As shown in FIG. 3C, once the predetermined volume of pressurized air is admitted to the accumulator air chamber 140 (for example, 3000 psig), pneumatic valve 106a is closed to isolate the storage tanks 102 from the accumulator air chamber 140. As shown in FIGS. 3C-3F, the high pressure in the accumulator air chamber 140 continues to drive the hydraulic fluid from the accumulator fluid chamber 138 through the motor/pump 130 and to the intensifier fluid chamber 146, thereby continuing to drive the motor/generator 132 and generate electricity. As the hydraulic fluid is transferred from the accumulator air chamber 140, the pressure in the intensifier air chamber 144 decreases until the air in the intensifier air chamber 144 is vented through pneumatic valve 106C.

FIG. 3G depicts the end of the first stage of the expansion phase. Once the accumulator air chamber 140 reaches a second predetermined mid-pressure (for example, about 300 psig), all of the hydraulic and pneumatic valves 128, 106C are closed. The pressure in the accumulator fluid chamber 138, the intensifier fluid chamber 146, and the intensifier air chamber 144 are at approximately atmospheric pressure. The pressure in the accumulator air chamber 140 is maintained at the predetermined mid-pressure.

FIG. 3H depicts the beginning of the second stage of the expansion phase. Pneumatic valve 106B is opened to allow fluid communication between the accumulator air chamber 140 and the intensifier air chamber 144. The predetermined pressure will decrease slightly when the valve 106B is opened and the accumulator air chamber 140 and the intensifier air chamber 144 are connected. Hydraulic valves 128B, 128F are opened, thereby allowing the hydraulic fluid stored in the intensifier to transfer to the accumulator fluid chamber 138 through the motor/pump 130, which in turn drives the motor/generator 132 and generates electricity. The air transferred from the accumulator air chamber 140 to the intensifier air chamber 144 to drive the fluid from the intensifier fluid chamber 146 to the accumulator fluid chamber 138 is at a lower pressure than the air that drove the fluid from the accumulator fluid chamber 138 to the intensifier fluid chamber 146. The area differential between the air piston 142a and the fluid piston 142b (for example, 10:1; see FIG. 1B) allows the lower pressure air to transfer the fluid from the intensifier fluid chamber 146 at a high pressure.

As shown in FIGS. 3I-3K, the pressure in the intensifier air chamber 144 continues to drive the hydraulic fluid from the intensifier fluid chamber 146 through the motor/pump 130 and to the accumulator fluid chamber 138, thereby continuing to drive the motor/generator 132 and generate electricity. As the hydraulic fluid is transferred from the intensifier 118 to the accumulator 116, the intensifier fluid chamber 146, the accumulator air chamber 140, and the accumulator fluid chamber 138 decrease.

FIG. 3L depicts the end of the second stage of the expansion cycle, where substantially all of the hydraulic fluid has been transferred to the accumulator 116 and all of the valves 106, 128 are closed. In addition, the accumulator air chamber 140, the accumulator fluid chamber 138, the intensifier air chamber 144, and the intensifier fluid chamber 146 are all at low pressure. In an alternative embodiment, the hydraulic fluid can be shunted back and forth between two intensifiers for compressing and expanding in the low pressure (for example, about 0-250 psig) range. Using a second intensifier and appropriate valving to utilize the energy stored at the lower pressures can produce additional electricity.

FIG. 3M depicts the start of another expansion phase, as described with respect to FIG. 3B. The system 100 can continue to cycle through expansion phases as necessary for the production of electricity, or until all of the compressed air in the storage tanks 102 has been exhausted.

FIG. 4 is a schematic diagram of an energy storage system 300, employing open-air hydraulic/pneumatic principles according to one embodiment of this invention. The system 300 consists of one or more high-pressure gas/air storage tanks 302a, 302b, ... 302n (the number being highly variable to suit a particular application). Each tank 302a, 302b is joined in parallel via a manual valve(s) 304a, 304b, ... 304n respectively to a main air line 308. The tanks 302a, 302b are each provided with a pressure sensor 312a, 312b, ... 312n and a temperature sensor 314a, 314b, ... 314n that can be monitored by a system controller 350 via appropriate connections (shown generally herein as arrows indicating “TO CONTROLLER”). The controller 350, the operation of which is described in further detail below, can be any acceptable control device with a human-machine interface. In one embodiment, the controller 350 includes a computer 351 (for example a PC-type) that executes a stored control application 353 in the form of a computer-readable software medium. The control application 353 receives telemetry from the various sensors and provides appropriate feedback to control valve actuators, motors, and other needed electromechanical/electronic devices. An appropriate interface can be used to convert data from sensors into a form readable by the computer controller 351 (such as RS-232 or network-based interconnects). Likewise, the interface converts the computer’s control signals into a form usable by valves and other actuators to perform an operation. The provision of such interfaces should be clear to those of ordinary skill in the art.

The main air line 308 from the tanks 302a, 302b is coupled to a pair of multi-stage (two stages in this example) accumulator/intensifier circuits (or hydraulic-pneumatic cylinder circuits) (dashed boxes 360, 362 in FIG. 4B) via automatically controlled (via controller 350), two-position valves 307a, 307b, 307c and 306a, 306b and 306c. These valves are coupled to respective accumulators 316 and 317 and intensifiers 318 and 319 according to one embodiment of the system. Pneumatic valves 306a and 307a are also coupled to a respective atmospheric air vent 310b and 310a. In particular, valves 306c and 307c connect along a common air line 390, 391 between the main air line 308 and the accumulators 316 and 317, respectively. Pneumatic valves 306b and 307b connect between the respective accumulators 316 and 317, and intensifiers 318 and 319. Pneumatic valves 306a, 307a connect along the common lines 390, 391 between the intensifiers 318 and 319, and the atmospheric vents 310b and 310a.

The air from the tanks 302, thus, selectively communicates with the air chamber side of each accumulator and intensifier (referenced in the drawings as air chamber 340 for accumulator 316, air chamber 341 for accumulator 317, air chamber 344 for intensifier 318, and air chamber 345 for intensifier 319). An air temperature sensor 322 and a pressure sensor 324 communicate with each air chamber 341, 344, 345, 322, and deliver sensor telemetry to the controller 350.

The air chamber 340, 341 of each accumulator 316, 317 is enclosed by a movable piston 336, 337 having an appropriate sealing system using sealing rings and other components that are known to those of ordinary skill in the art. The
piston 336, 337 moves along the accumulator housing in response to pressure differentials between the air chamber 340, 341 and an opposing fluid chamber 338, 339, respectively, on the opposite side of the accumulator housing. In this example, hydraulic fluid (or another liquid, such as water) is indicated by a shaded volume in the fluid chamber. Likewise, the air chamber 344, 345 of the respective intensifiers 318, 319 are enclosed by a moving piston assembly 342, 343. However, the intensifier air piston 342a, 343a is connected by a shaft, rod, or other coupling to a respective fluid piston, 342b, 343b. This fluid piston 342b, 343b moves in conjunction with the air piston 342a, 343a, but acts directly upon the associated intensifier fluid chamber 346, 347. Notably, the internal diameter (and/or volume) of the air chamber (DAI) for the intensifier 318, 319 is greater than the diameter of the air chamber (DAA) for the accumulator 316, 317 in the same circuit 360, 362. In particular, the surface area of the intensifier pistons 342a, 343a is greater than the surface area of the accumulator pistons 336, 337. The diameter of each intensifier fluid piston (DFI) is approximately the same as the diameter of each accumulator (DFA). Thus in this manner, a lower air pressure acting upon the intensifier piston generates a similar pressure on the associated fluid chamber as a higher air pressure acting on the accumulator piston. In this manner, and as described further below, the system allows for at least two stages of pressure to be employed to generate similar levels of fluid pressure.

[0147] In one example, assuming that the initial gas pressure in the accumulator is at 200 atmospheres (ATM) (3000 psi—high-pressure), with a final mid-pressure of 20 ATM (300 psi) upon full expansion, and that the initial gas pressure in the intensifier is then 20 ATM (with a final pressure of 1.2 ATM (25-30 psi)), then the area of the gas piston in the intensifier would be approximately 10 times the area of the piston in the accumulator (or 3.16 times the radius). However, the precise values for initial high-pressure, mid-pressure and final low-pressure are highly variable, depending in part upon the operating specifications of the system components, scale of the system and output requirements. Thus, the relative sizing of the accumulators and the intensifiers is variable to suit a particular application.

[0148] Each fluid chamber 338, 339, 346, 347 is interconnected with an appropriate temperature sensor 322 and pressure sensor 324, each delivering telemetry to the controller 350. In addition, each fluid line interconnecting the fluid chambers can be fitted with a flow sensor 326, which directs data to the controller 350. The pistons 336, 337, 342 and 343 can include position sensors 348 that report their present position to the controller 350. The position of the piston can be used to determine relative pressure and flow of both gas and fluid. Each fluid connection from a fluid chamber 338, 339, 346, 347 is connected to a pair of parallel, automatically controlled valves. As shown, fluid chamber 338 (accumulator 316) is connected to valve pair 328c and 328d; fluid chamber 339 (accumulator 317) is connected to valve pair 329a and 329b; fluid chamber 346 (intensifier 318) is connected to valve pair 328a and 328b; and fluid chamber 347 (intensifier 319) is connected to valve pair 329c and 329d. One valve from each chamber 328a, 328b, 329a and 329c is connected to one connection side 372 of a hydraulic motor/pump 330. This motor/pump 330 can be piston-type (or other suitable type, including vane, impeller, and gear) assembly having a shaft 331 (or other mechanical coupling) that drives, and is driven by, a combination electrical motor/generator assembly 332. The motor/generator assembly 332 is interconnected with a power distribution system and can be monitored for status and output/input level by the controller 350. The other connection side 374 of the hydraulic motor/pump 330 is connected to the second valve in each valve pair 328a, 328b, 329a and 329d. By selectively toggling the valves in each pair, fluid is connected between either side 372, 374 of the hydraulic motor/pump 330. Alternatively, some or all of the valve pairs can be replaced with one or more three position, four way valves or other combinations of valves to suit a particular application.

[0149] The number of circuits 360, 362 can be increased as necessary. Additional circuits can be interconnected to the tanks 302 and each side 372, 374 of the hydraulic motor/pump 330 in the same manner as the components of the circuits 360, 362. Generally, the number of circuits should be even so that one circuit acts as a fluid driver while the other circuit acts as a reservoir for receiving the fluid from the driving circuit.

[0150] An optional accumulator 366 is connected to at least one side (e.g., inlet side 372) of the hydraulic motor/pump 330. The optional accumulator 366 can be, for example, a closed-air-type accumulator with a separate fluid side 368 and precharged air side 370. As will be described below, the accumulator 366 acts as a fluid capacitor to deal with transients in fluid flow through the motor/pump 330. In another embodiment, a second optional accumulator or other low-pressure reservoir 371 is placed in fluid communication with the outlet side 374 of the motor/pump 330 and can also include a fluid side 371 and a precharged air side 369. The foregoing optional accumulators can be used with any of the systems described herein.

[0151] Having described the general arrangement of one embodiment of an open-air hydraulic-pneumatic energy storage system 300 in FIG. 4, the exemplary functions of the system 300 during an energy recovery phase will now be described with reference to FIGS. 5A-5N. For the purposes of this operational description, the illustrations of the system 300 in FIGS. 5A-5N have been simplified, omitting the controller 350 and interconnections with valves, sensors, etc. It should be understood that the steps described are under the control and monitoring of the controller 350 based upon the rules established by the application 353.

[0152] FIG. 5A is a schematic diagram of the energy storage and recovery system of FIG. 4 showing an initial physical state of the system 300 in which an accumulator 316 of a first circuit is filled with high-pressure gas from the high-pressure gas storage tanks 302. The tanks 302 have been filled to full pressure, either by the cycle of the system 300 under power input to the hydraulic motor/pump 330, or by a separate high-pressure air pump 376. This air pump 376 is optional, as the air tanks 302 can be filled by running the recovery cycle in reverse. The tanks 302 in this embodiment can be filled to a pressure of 200 ATM (3000 psi) or more. The overall, collective volume of the tanks 302 is highly variable and depends in part upon the amount of energy to be stored.

[0153] In FIG. 5A, the recovery of stored energy is initiated by the controller 350. To this end, pneumatic valve 307c is opened allowing a flow of high-pressure air to pass into the air chamber 340 of the accumulator 316. Note that where a flow of compressed gas or fluid is depicted, the connection is indicated as a dashed line. The level of pressure is reported by the sensor 324 in communication with the chamber 340. The pressure is maintained at the desired level by valve 307c. This
pressure causes the piston 336 to bias (arrow 800) toward the fluid chamber 338, thereby generating a comparable pressure in the incompressible fluid. The fluid is prevented from moving out of the fluid chamber 338 at this time by valves 329c and 329d.

[0154] FIG. 5b is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5a, in which valves are opened to allow fluid to flow from the accumulator 316 of the first circuit to the fluid motor/pump 330 to generate electricity therefrom. As shown in FIG. 5b, pneumatic valve 307c remains open. When a predetermined pressure is obtained in the air chamber 340, the fluid valve 329c is opened by the controller, causing a flow of fluid (arrow 801) to the inlet side 372 of the hydraulic motor/pump 330 (which operates in motor mode during the recovery phase). The motion of the motor 330 drives the electric motor/generator 332 in a generation mode, providing power to the facility or grid as shown by the term “POWER OUT.” To absorb the fluid flow (arrow 803) from the outlet side 374 of the hydraulic motor/pump 330, fluid valve 328c is opened to the fluid chamber 339 by the controller 350 to route fluid to the opposing accumulator 317. To allow the fluid to fill accumulator 317 after its energy has been transferred to the motor/pump 330, the air chamber 341 is vented by opening pneumatic vent valves 306a, 306b. This allows air in the chamber 341, to escape to the atmosphere via the vent 310b as the piston 337 moves (arrow 805) in response to the entry of fluid.

[0155] FIG. 5c is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5b, in which the accumulator 316 of the first circuit directs fluid to the fluid motor/pump 330 while the accumulator 317 of the second circuit receives exhausted fluid from the motor/pump 330, as gas in its air chamber 341 is vented to atmosphere. As shown in FIG. 5c, a predetermined amount of gas has been allowed to flow from the high-pressure tanks 302 to the accumulator 316 and the controller 350 now closes pneumatic valve 307c. Other valves remain open so that fluid can continue to be driven by the accumulator 316 through the motor/pump 330.

[0156] FIG. 5d is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5c, in which the accumulator 316 of the first circuit continues to direct fluid to the fluid motor/pump 330 while the accumulator 317 of the second circuit continues to receive exhausted fluid from the motor/pump 330, as gas in its air chamber 341 is vented to atmosphere. As shown in FIG. 5d, the operation continues, where the accumulator piston 336 drives additional fluid (arrow 800) through the motor/pump 330 based upon the charge of gas pressure placed in the accumulator air chamber 340 by the tanks 302. The fluid causes the opposing accumulator’s piston 337 to move (arrow 805), displacing air through the vent 310b.

[0157] FIG. 5e is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5d, in which the accumulator 316 of the first circuit has nearly exhausted the fluid in its fluid chamber 338 and the gas in its air chamber 340 has expanded to nearly mid-pressure from high-pressure. As shown in FIG. 5e, the charge of gas in the air chamber 340 of the accumulator 316 has continued to drive fluid (arrows 800, 810) through the motor/pump 330 while displacing air via the vent 310b. The gas has expanded from high-pressure to mid-pressure during this portion of the energy recovery cycle. Consequently, the fluid has ranged from high to mid-pressure. By sizing the accumulators appropriately, the rate of expansion can be controlled.

[0158] This is part of the significant parameter of heat transfer. For maximum efficiency, the expansion should remain substantially isothermal. That is, heat from the environment replaces the heat lost by the expansion. In general, isothermal compression and expansion is critical to maintaining high round-trip system efficiency, especially if the compressed gas is stored for long periods. In various embodiments of the systems described herein, heat transfer can occur through the walls of the accumulators and/or intensifiers, or heat-transfer mechanisms can act upon the expanding or compressing gas to absorb or radiate heat from or to an environmental or other source. The rate of this heat transfer is governed by the thermal properties and characteristics of the accumulators/intensifiers, which can be used to determine a thermal time constant. If the compression of the gas in the accumulators/intensifiers occurs slowly relative to the thermal time constant, then heat generated by compression of the gas will transfer through the accumulator/intensifier walls to the surroundings, and the gas will remain at approximately constant temperature. Similarly, if expansion of the gas in the accumulators/intensifiers occurs slowly relative to the thermal time constant, then the heat absorbed by the expansion of the gas will transfer from the surroundings through the accumulator/intensifier walls and to the gas, and the gas will remain at approximately constant temperature. If the gas remains at a relatively constant temperature during both compression and expansion, then the amount of heat energy transferred from the gas to the surroundings during compression will equal the amount of heat energy recovered during expansion via heat transfer from the surroundings to the gas. This transfer is represented by the letter Q and wavy arrows in FIG. 4. As noted, a variety of mechanisms can be employed to maintain an isothermal expansion/compression. In one example, the accumulators can be submerged in a water bath or water/fluid flow can be circulated around the accumulators and intensifiers. The accumulators can alternatively be surrounded with heating/cooling coils or a flow of warm air can be blown past the accumulators/intensifiers. However, any technique that allows for mass flow transfer of heat to and from the accumulators can be employed.

[0159] FIG. 5f is a schematic diagram of the energy storage and recovery system of FIG. 4, showing a physical state of the system 300 following the state of FIG. 5e, in which the accumulator 316 of the first circuit has exhausted the fluid in its fluid chamber 338 and the gas in its air chamber 340 has expanded to mid-pressure from high-pressure, and the valves have been momentarily closed on both the first circuit and the second circuit, while the optional accumulator 366 (shown in FIG. 4) delivers fluid through the motor/pump 330 to maintain operation of the electric motor/generator 332 between cycles. As shown in FIG. 5f, the piston 336 of the accumulator 316 has driven all fluid out of the fluid chamber 338 as the gas in the air chamber 340 has fully expanded (to mid-pressure of 20 ATM, per the example). Fluid valves 329c and 328c are closed by the controller 350. In practice, the opening and closing of valves is carefully timed so that a flow through the motor/pump 330 is maintained. However, in an optional implementation, brief interruptions in fluid pressure can be accommodated by pressurized fluid flow 710 from the optional accumulator 366 in FIG. 4, which is directed
through the motor/pump 330 to the second optional accumulator 367 in FIG. 4) at low-pressure as an exhaust fluid flow 720. In one embodiment, the exhaust flow can be directed to a simple low-pressure reservoir that is used to refill the first accumulator 366. Alternatively, the exhaust flow can be directed to the second optional accumulator 367 in FIG. 4) at low-pressure, which is subsequently pressurized by excess electricity (driving a compressor) or air pressure from the storage tanks 302 when it is filled with fluid. Alternatively, where a large number of accumulator/intensifier circuits (e.g., three or more) are employed in parallel in the system 300, their expansion cycles can be staggered so that only one circuit is closed off at a time, allowing a substantially continuous flow from the other circuits.

[0160] FIG. 5G is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5F, in which pneumatic valves 307b, 306a are opened to allow mid-pressure gas from the air chamber 340 of the first circuit’s accumulator 316 to flow into the air chamber 344 of the first circuit’s intensifier 318, while fluid from the first circuit’s intensifier 318 is directed through the motor/pump 330 and exhausted fluid fills the fluid chamber 347 of second circuit’s intensifier 319, whose air chamber 345 is vented to atmosphere. As shown in FIG. 5G, pneumatic valve 307b is opened, while the tank outlet valve 307e remains closed. Thus, the volume of the air chamber 340 of accumulator 316 is coupled to the air chamber 344 of the intensifier 318. The accumulator’s air pressure has been reduced to a mid-pressure level, well below the initial charge from the tanks 302. The air, thus, flows (arrow 810) through valve 307b to the air chamber 344 of the intensifier 318. This drives the air piston 342a (arrow 830). Since the area of the air-contacting piston 342a is larger than that of the piston 336 in the accumulator 316, the lower air pressure still generates a substantially equivalent higher fluid pressure on the smaller-area, coupled fluid piston 342b of the intensifier 318. The fluid in the fluid chamber 346 thereby flows under pressure through opened fluid valve 329a and into the inlet side 372 of the motor/pump 330. The outlet fluid from the motor pump 330 is directed (arrow 803) through now-opened fluid valve 328a to the opposing intensifier 319. The fluid enters the fluid chamber 347 of the intensifier 319, biasing (arrow 800) the fluid piston 343b (and interconnected gas piston 343a). Any gas in the air chamber 345 of the intensifier 319 is vented through the now-opened vent valve 306a to atmosphere via the vent 310a. The mid-level pressure gas in the accumulator 316 is directed (arrows 810, 820) to the intensifier 318, the piston 342a, of which drives fluid from the chamber 346 using the coupled, smaller-diameter fluid piston 342b. This portion of the recovery stage maintains a reasonably high fluid pressure, despite lower gas pressure, thereby ensuring that the motor/pump 330 continues to operate within a predetermined range of fluid pressures, which is desirable to maintain optimal operating efficiencies for the given motor. Notably, the multi-stage circuits of this embodiment effectively restrict the operating pressure range of the hydraulic fluid delivered to the motor/pump 330 above a predetermined level despite the wide range of pressures within the expanding gas charge provided by the high-pressure tank.

[0161] FIG. 5H is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5G, in which the intensifier 318 of the first circuit directs fluid to the fluid motor/pump 330 based upon mid-pressure gas from the first circuit’s accumulator 316 while the intensifier 319 of the second circuit receives exhausted fluid from the motor/pump 330, as gas in its air chamber 345 is vented to atmosphere. As shown in FIG. 5H, the gas in intensifier 318 continues to expand from mid-pressure to low-pressure. Conversely, the size differential between coupled air and fluid pistons 342a and 342b, respectively, causes the fluid pressure to vary between high and mid-pressure. In this manner, motor/pump operating efficiency is maintained.

[0162] FIG. 5I is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5H, in which the intensifier 318 of the first circuit has almost exhausted the fluid in its fluid chamber 346 and the gas in its air chamber 344, delivered from the first circuit’s accumulator 316, has expanded to nearly low-pressure from the mid-pressure. As discussed with respect to FIG. 5H, the gas in intensifier 318 continues to expand from mid-pressure to low-pressure. Again, the size differential between coupled air and fluid pistons 342a and 342b, respectively, causes the fluid pressure to vary between high and mid-pressure to maintain motor/pump operating efficiency.

[0163] FIG. 5J is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system 300 following the state of FIG. 5I, in which the intensifier 318 of the first circuit has essentially exhausted the fluid in its fluid chamber 346 and the gas in its air chamber 344, delivered from the first circuit’s accumulator 316, has expanded to low-pressure from the mid-pressure. As shown in FIG. 5I, the intensifier’s piston 342 reaches full stroke, while the fluid is driven fully from high to mid-pressure in the fluid chamber 346. Likewise, the opposing intensifier’s fluid chamber 347 has filled with fluid from the outlet side 374 of the motor/pump 330.

[0164] FIG. 5K is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5I, in which the intensifier 318 of the first circuit has exhausted the fluid in its fluid chamber 346 and the gas in its air chamber 344 has expanded to low pressure, and the valves have been momentally closed on both the first circuit and the second circuit in preparation of switching-over to an expansion cycle in the second circuit, whose accumulator and intensifier fluid chambers 339, 347 are now filled with fluid. At this time, the optional accumulator 366 (not shown in FIG. 5K) can deliver fluid through the motor/pump 330 to maintain operation of the motor/generator 332 between cycles. As shown in FIG. 5K, pneumatic valve 307b, located between the accumulator 316 and the intensifier 318 of the circuit 362, is closed. At this point in the above-described portion of the recovery stage, the gas charge initiated in FIG. 5A has been fully expanded through two stages with relatively gradual, isothermal expansion characteristics, while the motor/pump 330 has received fluid flow within a desirable operating pressure range. Along with pneumatic valve 307b, the fluid valves 329a and 328a (and outlet gas valve 307a) are momentarily closed. The above-described optional accumulator 366 (not shown in FIG. 5K), and/or other interconnected pneumatic/hydraulic accumulator/intensifier circuits, can maintain predetermined fluid flow through the motor/pump 330 while the valves of the subject circuits 360, 362 are momentarily closed. At this time, the optional accumulators and reservoirs 366, 367, as shown in FIG. 4, can provide a continuing flow 710 of pressurized fluid.
through the motor/pump 330, and into the reservoir or low-pressure accumulator (exhaust fluid flow 720). The full range of pressure in the previous gas charge being utilized by the system 300.

[0165] FIG. 5L is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5K, in which the accumulator 317 of the second circuit is filled with high-pressure gas from the high-pressure tanks 302 as part of the switch-over to the second circuit as an expansion circuit, while the first circuit receives exhausted fluid and is vented to atmosphere while the optional accumulator 366 delivers fluid through the motor/pump 330 to maintain operation of the motor/generator between cycles. As shown in FIG. 5L, the cycle continues with a new charge of high-pressure (slightly lower) gas from the tanks 302 delivered to the opposing accumulator 317. As shown, pneumatic valve 306c is now opened by the controller 350, allowing a charge of relatively high-pressure gas to flow (arrow 815) into the air chamber 341 of the accumulator 317, which builds a corresponding high-pressure charge in the air chamber 341.

[0166] FIG. 5M is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5L, in which valves are opened to allow fluid to flow from the accumulator 317 of the second circuit to the fluid motor/pump 330 to generate electricity therefrom, while the first circuit’s accumulator 316, whose air chamber 340 is vented to atmosphere, receives exhausted fluid from the motor/pump 330. As shown in FIG. 5M, the pneumatic valve 306d is open and the fluid valves 328e and 329e are opened on the fluid side of the circuits 360, 362, thereby allowing the accumulator piston 337 to move (arrow 816) under pressure of the charged air chamber 341. This directs fluid under high pressure through the inlet side 372 of the motor/pump 330 (arrow 817), and then through the outlet 374. The exhausted fluid is directed (arrow 818) now to the fluid chamber 338 of accumulator 316. Pneumatic valves 307a and 307b have been opened, allowing the low-pressure air in the air chamber 340 of the accumulator 316 to vent (arrow 819) to atmosphere via vent 310a. In this manner, the piston 336 of the accumulator 316 can move (arrow 821) without resistance to accommodate the fluid from the motor/pump outlet 374.

[0167] FIG. 5N is a schematic diagram of the energy storage and recovery system of FIG. 4 showing a physical state of the system following the state of FIG. 5M, in which the accumulator 317 of the second circuit 362 continues to direct fluid to the fluid motor/pump 330 while the accumulator 316 of the first circuit continues to receive exhausted fluid from the motor/pump 330, as gas in its air chamber 340 is vented to atmosphere, the cycle eventually directing mid-pressure air to the second circuit’s intensifier 319 to drive fluid therein. As shown in FIG. 5N, the high-pressure gas charge in the accumulator 317 expands more fully within the air chamber 341 (arrow 816). Eventually, the charge in the air chamber 341 is fully expanded. The mid-pressure charge in the air chamber 341 is then coupled via open pneumatic valve 306d to the intensifier 319, which fills the opposing intensifier 318 with spent fluid from the outlet 374. The process repeats until a given amount of energy is recovered or the pressure in the tanks 302 drops below a predetermined level.

[0168] It should be clear that the system 300, as described with respect to FIGS. 4 and 5A-5N, could be run in reverse to compress gas in the tanks 302 by powering the electric generator/motor 332 to drive the motor/pump 330 in pump mode. In this case, the above-described process occurs in reverse order, with driven fluid causing compression within both stages of the air system in turn. That is, air is first compressed to a mid-pressure after being drawn into the intensifier from the environment. This mid-pressure air is then directed to the air chamber of the accumulator, where fluid then forces it to be compressed to high pressure. The high-pressure air is then forced into the tanks 302. Both this compression/energy storage stage and the above-described expansion/energy recovery stages are discussed with reference to the general system state diagram shown in FIG. 6.

[0169] Note that in the above-described systems 100, 300 (i.e., one or more stages, respectively), the compression and expansion cycle is predicated upon the presence of gas in the storage tanks 302 that is currently at a pressure above the mid-pressure level (e.g., above 20 atmospheres). For system 300, for example, when the prevailing pressure in the storage tanks 302 falls below the mid-pressure level (based, for example, upon levels sensed by tank sensors 312, 314), then the valves can be configured by the controller to employ only the intensifier for compression and expansion. That is, lower gas pressures are accommodated using the larger-area gas pistons on the intensifiers, while higher pressures employ the smaller-area gas pistons of the accumulators, 316, 317.

[0170] Before discussing the state diagram in FIG. 6, it should be noted that one advantage of the described systems according to this invention is that, unlike various prior-art systems, this system can be implemented using generally commercially available components. In the example of a system having a power output of 10 to 500 kW, for example, high-pressure storage tanks can be implemented using standard steel or composite cylindrical pressure vessels (e.g., Compressed Natural Gas 5500-psi steel cylinders). The accumulators can be implemented using standard steel or composite pressure cylinders with moveable pistons (e.g., a four-inch-inner-diameter piston accumulator). Intensifiers (pressure boosters/multipliers) having characteristics similar to the exemplary accumulator can be implemented (e.g., a fourteen-inch booster diameter and four-inch bore diameter single-acting pressure booster available from Parker-Hannifin of Cleveland, Ohio). A fluid motor/pump can be a standard high-efficiency axial piston, radial piston, or gear-based hydraulic motor/pump, and the associated electrical generator is also available commercially from a variety of industrial suppliers. Valves, lines, and fittings are commercially available with the specified characteristics as well.

[0171] Having discussed the exemplary sequence of physical steps in various embodiments of the system, the following is a more general discussion of operating states for the system 300 in both the expansion/energy recovery mode and the compression/energy storage mode. Reference is now made to FIG. 6.

[0172] In particular, FIG. 6 details a generalized state diagram 600 that can be employed by the control application 353 to operate the system’s valves and motor/generator based upon the direction of the energy cycle (recovery/expansion or storage/compression) based upon the reported states of the various pressure, temperature, piston-position, and/or flow sensors. Base State 610 is a state of the system in which all valves are closed and the system is neither compressing nor expanding gas. A first accumulator and intensifier (e.g., 316, 318) are filled with the maximum volume of hydraulic fluid and a second accumulator and intensifier (e.g., 317, 319) are
filled with the maximum volume of air, which may or may not be at a pressure greater than atmospheric. The physical system state corresponding to Base State 1 is shown in FIG. 5A. Conversely, Base State 2 (620) of FIG. 6 is a state of the system in which all valves are closed and the system is neither compressing nor expanding gas. The second accumulator and intensifier are filled with the maximum volume of hydraulic fluid and the first accumulator and intensifier are filled with the maximum volume of air, which may or may not be at a pressure greater than atmospheric. The physical system state corresponding to Base State 2 is shown in FIG. 5K.

[0173] As shown further in the diagram of FIG. 6, Base State 1 and Base State 2 each link to a state termed Single Stage Compression 630. This general state represents a series of states of the system in which gas is compressed to store energy, and which occurs when the pressure in the storage tanks 302 is less than the mid-pressure level. Gas is admitted (from the environment, for example) into the intensifier (318 or 319, depending upon the current base state), and is then pressurized by driving hydraulic fluid into that intensifier. When the pressure of the gas in the intensifier reaches the pressure in the storage tanks 302, the gas is admitted into the storage tanks 302. This process repeats for the other intensifier, and the system returns to the original base state (610 or 620).

[0174] The Two Stage Compression 632 shown in FIG. 6 represents a series of states of the system in which gas is compressed in two stages to store energy, and which occurs when the pressure in the storage tanks 302 is greater than the mid-pressure level. The first stage of compression occurs in an intensifier (318 or 319) in which gas is pressurized to mid-pressure after being admitted at approximately atmospheric (from the environment, for example). The second stage of compression occurs in accumulator (316 or 317) in which gas is compressed to the pressure in the storage tanks 302 and then allowed to flow into the storage tanks 302. Following two stage compression, the system returns to the other base state from the current base state, as symbolized on the diagram by the crossing-over process arrows 634.

[0175] The state Single Stage Expansion 640, as shown in FIG. 6, represents a series of states of the system in which gas is expanded to recover stored energy and which occurs when the pressure in the storage tanks 302 is less than the mid-pressure level. An amount of gas from storage tanks 302 is allowed to flow directly into an intensifier (318 or 319). This gas then expands in the intensifier, forcing hydraulic fluid through the hydraulic motor/pump 330 and into the second intensifier, where the exhausted fluid moves the piston with the gas-side open to atmospheric (or another low-pressure environment). The Single Stage Expansion process is then repeated for the second intensifier, after which the system returns to the original base state (610 or 620).

[0176] Likewise, the Two Stage Expansion 642, as shown in FIG. 6, represents a series of states of the system in which gas is expanded in two stages to recover stored energy and which occurs when pressure in the storage tanks is greater than the mid-pressure level. An amount of gas from storage tanks 302 is allowed into an accumulator (316 or 317), wherein the gas expands to mid-pressure, forcing hydraulic fluid through the hydraulic motor/pump 330 and into the second accumulator. The gas is then allowed into the corresponding intensifier (318 or 319), wherein the gas expands to near-atmospheric pressure, forcing hydraulic fluid through the hydraulic motor/pump 330 and into the second intensifier. The series of states comprising two-stage expansion are shown in the above-described FIGS. 5A-5N. Following two-stage expansion, the system returns to the other base state (610 or 620) as symbolized by the crossing process arrows 644.

[0177] It should be clear that the above-described system for storing and recovering energy is highly efficient in that it allows for gradual expansion of gas over a period that helps to maintain isothermal characteristics. The system particularly deals with the large expansion and compression of gas between high-pressure to near-atmospheric (and the concomitant thermal transfer) by providing this compression/expansion in two or more separate stages that allow for more gradual heat transfer through the system components. Thus little or no outside energy is required to run the system (heating gas, etc.), rendering the system more environmentally friendly, capable of being implemented with commercially available components, and scalable to meet a variety of energy storage/recovery needs. However, it is possible to further improve the efficiency of the systems described above by incorporating a heat transfer subsystem as described with respect to FIG. 9.

[0178] FIGS. 7A-7F depict the major systems of an alternative system/method of expansion/compression cycling an open-air staged hydraulic-pneumatic system, where the system 400 includes at least three accumulators 416a, 416b, 416c, at least one intensifier 418, and two motors/pumps 430a, 430b. The compressed gas storage tanks, valves, sensors, etc. are not shown for clarity. FIGS. 7A-7F illustrate the operation of the accumulators 416, intensifier 418, and the motors/pumps 430 during various stages of expansion (stages 101-106). The system 400 returns to stage 101 after stage 106 is complete.

[0179] As shown in the figures, the designations D, F, AI, and F2 refer to whether the accumulator or intensifier is driving (D) or filling (F), with the additional labels for the accumulators where AI refers to accumulator to intensifier—the accumulator air side attached to and driving the intensifier air side, and F2 refers to filling at twice the rate of the standard filling.

[0180] As shown in FIG. 7A the layout consists of three equally sized hydraulic-pneumatic accumulators 416a, 416b, 416c, one intensifier 418 having a hydraulic fluid side 446 with a capacity of about 1/3 of the accumulator capacity, and two hydraulic motor/pumps 430a, 430b.

[0181] FIG. 7A represents stage or time instance 101, where accumulator 416a is being driven with high pressure gas from a pressure vessel. After a specific amount of compressed gas is admitted (based on the current vessel pressure), a valve will be closed, disconnecting the pressure vessel and the high-pressure gas will continue to expand in accumulator 416a as shown in FIGS. 7B and 7C (i.e., stages 102 and 103). Accumulator 416b is empty of hydraulic fluid and its air chamber 440b is unpressurized and being vented to the atmosphere. The expansion of the gas in accumulator 416a drives the hydraulic fluid out of the accumulator 416a, thereby driving the hydraulic motor 430a, with the output of the motor 430a refilling accumulator 416b with hydraulic fluid. At the time point shown in 101, accumulator 416c is at a state where gas has already been expanding for two units of time and is continuing to drive motor 430b while filling intensifier 418. Intensifier 418, similar to accumulator 416b, is empty of hydraulic fluid and its air chamber 440 is unpressurized and being vented to the atmosphere.
Continuing to time instance 102, as shown in FIG. 7B, the air chamber 440a of accumulator 416a (accumulators as labeled in FIG. 7A) continues to expand, thereby forcing fluid out of the fluid chamber 438a and driving motor/pump 430a and filling accumulator 416b. Accumulator 416c is now empty of hydraulic fluid, but remains at mid-pressure. The air chamber 440c of accumulator 416c is now connected to the air chamber 440 of intensifier 418. Intensifier 418 is now full of hydraulic fluid and the mid-pressure gas in accumulator 416c drives the intensifier 418, which provides intensification of the mid-pressure gas to high pressure hydraulic fluid. The high-pressure hydraulic fluid drives motor/pump 430b, with the output of motor/pump 430b also connected to and filling accumulator 416b through appropriate valving. Thus, accumulator 416b is filled at twice the normal rate where a single expanding hydraulic pneumatic device (accumulator or intensifier) is providing the fluid for filling.

At time instance 103, as shown in FIG. 7C, the system 400 has returned to a state similar to stage 101, but with different accumulators at equivalent stages. Accumulator 416b is now full of hydraulic fluid and is being driven with high-pressure gas from a pressure vessel. After a specific amount of compressed gas is admitted (based on the current vessel pressure), a valve will be closed, disconnecting the pressure vessel. The high-pressure gas will continue to expand in accumulator 416b as shown in stages 104 and 105. In stage 103, accumulator 416c is empty of hydraulic fluid and the air chamber 440c is unpressurized and being vented to the atmosphere. The expansion of the gas in accumulator 416b drives the hydraulic fluid out of the accumulator, driving the hydraulic motor/pump 430b, with the output of the motor refilling intensifier 418 with hydraulic fluid via appropriate valving. At the time point shown in 105, accumulator 416b is at a state where gas has already been expanding for two units of time and is continuing to drive motor/pump 430b while filling accumulator 416b with hydraulic fluid via appropriate valving. Intensifier 418 is similar to accumulator 416a, is again empty of hydraulic fluid and the air chamber 444 is unpressurized and being vented to the atmosphere.

Continuing to time instance 104, as shown in FIG. 7D, the air chamber 440b of accumulator 416b continues to expand, thereby forcing fluid out of the fluid chamber 438b and driving motor/pump 430a and filling accumulator 416c. Accumulator 416a is now empty of hydraulic fluid, but remains at mid-pressure. The air chamber 440a of accumulator 416a is now connected to the air chamber 440 of intensifier 418. Intensifier 418 is now full of hydraulic fluid and the mid-pressure gas in accumulator 416a drives the intensifier 418, which provides intensification of the mid-pressure gas to high pressure hydraulic fluid. The high-pressure hydraulic fluid drives motor/pump 430b, with the output of motor/pump 430b also connected to and filling accumulator 416c through appropriate valving. Thus, accumulator 416c is filled at twice the normal rate (where the normal rate is the rate when a single expanding hydraulic pneumatic device, either accumulator or intensifier, is providing the fluid for filling).

At time instance 105, as shown in FIG. 7E, the system 400 has returned to a state similar to stage 103, but with different accumulators at equivalent stages. Accumulator 416c is now full of hydraulic fluid and is being driven with high pressure gas from a pressure vessel. After a specific amount of compressed gas is admitted (based on the current vessel pressure), a valve will be closed, disconnecting the pressure vessel. The high-pressure gas will continue to expand in accumulator 416c. Accumulator 416a is empty of hydraulic fluid and the air chamber 440a is unpressurized and being vented to the atmosphere. The expansion of the gas in accumulator 416c drives the hydraulic fluid out of the accumulator, driving the hydraulic motor/pump 430b, with the output of the motor refilling intensifier 418 with hydraulic fluid via appropriate valving. At the time point shown in 105, accumulator 416b is at a state where gas has already been expanding for two units of time and is continuing to drive motor/pump 430a while filling accumulator 416c with hydraulic fluid via appropriate valving. Intensifier 418 is similar to accumulator 416a, is again empty of hydraulic fluid and the air chamber 444 is unpressurized and being vented to the atmosphere.

Continuing to time instance 106, as shown in FIG. 7F, the air chamber 440c of accumulator 416c continues to expand, thereby forcing fluid out of the fluid chamber 438c and driving motor/pump 430b and filling accumulator 416b. Accumulator 416b is now empty of hydraulic fluid, but remains at mid-pressure. The air chamber 440b of accumulator 416b is now connected to the air chamber 444 of intensifier 418. Intensifier 418 is now full of hydraulic fluid and the mid-pressure gas in accumulator 416b drives the intensifier 418, which provides intensification of the mid-pressure gas to high-pressure hydraulic fluid. The high-pressure hydraulic fluid drives motor/pump 430b, with the output of motor/pump 430b also connected to and filling accumulator 416c through appropriate valving. Thus, accumulator 416c is filled at twice the normal rate (where the normal rate is the rate when a single expanding hydraulic pneumatic device, either accumulator or intensifier, is providing the fluid for filling). Following the states shown in 106, the system returns to the states shown in 101 and the cycle continues.

FIG. 8 is a table illustrating the expansion scheme described above and illustrated in FIGS. 7A-7F for a three-accumulator, one-intensifier system. It should be noted that throughout the cycle, two hydraulic-pneumatic devices (two accumulators or one intensifier plus one accumulator) are always expanding and the two motors are always being driven, but at different points in the expansion, such that the overall power remains relatively constant.

FIG. 9 depicts generally a staged hydraulic-pneumatic energy conversion system that stores and recovers electrical energy using thermally conditioned compressed fluids and incorporates various embodiments of the invention, for example, those described with respect to FIGS. 1, 4, and 7. As shown in FIG. 9, the system 900 includes five high-pressure gas/air storage tanks 902a-902e. Tanks 902d and 902e are joined in parallel via manual valves 904d, 904b, 904c, and 904f, respectively. Tanks 902c also includes a manual shut-off valve 904e. The tanks 902 are joined to a main air line 908 via pneumatic two-way (i.e., shut-off) valves 906a, 906b, 906c. The tank output lines include pressure sensors 912a, 912b, and 912c. The lines/tanks 902 could also include temperature sensors. The various sensors can be monitored by a system controller 960 via appropriate connections, as described above with respect to FIGS. 1 and 4. The main air line 908 is coupled to a pair of multi-stage (two-stage, in this example) accumulator circuits via automatically controlled pneumatic shut-off valves 907a, 907b. These valves 907a, 907b are coupled to respective accumulators 916 and 917. The air chambers 940, 941 of the accumulators 916, 917 are interconnected via automatically controlled pneumatic shut-offs 907c, 907d, to the air chambers.
944, 945 of the intensifiers 918, 919. Pneumatic shut-off valves 907e, 907f are also coupled to the air line connecting the respective accumulator and intensifier air chambers and to a respective atmospheric air vent 910a, 910b. This arrangement allows for air from the various tanks 902 to be selectively directed to either accumulator air chamber 944, 945. In addition, the various air lines and air chambers can include pressure and temperature sensors 922 924 that deliver sensor telemetry to the controller 960.

[0189] The system 900 also includes two heat-transfer subsystems 950A, 950B (in fluid communication with the air chambers 940, 941, 944, 945 of the accumulators and intensifiers 916-919 and the high-pressure storage tanks 902) that provide improved isothermal expansion and compression of the gas. A simplified schematic of one of the heat-transfer subsystems 950 is shown in greater detail in FIG. 9A. Each heat-transfer subsystem 950 includes a circulation apparatus 952, at least one heat exchanger 954, and pneumatic valves 956. One circulation apparatus 952, two heat exchangers 954, and two pneumatic valves 956 are shown in FIGS. 9 and 9A, however, the number and type of circulation apparatus 952, heat exchangers 954, and valves 956 can vary to suit a particular application. The various components and the operation of the heat-transfer subsystem 950 are described in greater detail herein below. Generally, in one embodiment, the circulation apparatus 952 is a positive-displacement pump capable of operating at pressures up to 3000 psi or more and the two heat exchangers 954 are tube-in-shell type (also known as a shell-and-tube type) heat exchangers 954 also capable of operating at pressures up to 3000 psi or more. The heat exchangers 954 are shown connected in parallel, although they could also be connected in series. The heat exchangers 954 can have the same or different heat-transfer areas. For example, where the heat exchangers 954 are connected in parallel and the first heat exchanger 954A has a heat-transfer area of X and the second heat exchanger 954B has a heat-transfer area of 2X, a control-valve arrangement can be used to selectively direct the gas flow to one or both of the heat exchangers 954 to obtain different heat-transfer areas (e.g., X, 2X, or 3X) and thus different thermal efficiencies.

[0190] The basic operation of the system 950 is described with respect to FIG. 9A. As shown, the system 950 includes the circulation apparatus 952, which can be driven by, for example, an electric motor 953 mechanically coupled thereto. Other types of and means for driving the circulation apparatus are contemplated and within the scope of the invention. For example, the circulation apparatus 952 could be a combination of accumulators, check valves, and an actuator. The circulation apparatus 952 is in fluid communication with each of the air chambers 940, 944 via a three-way, two-position pneumatic valve 956B and draws gas from either air chamber 940, 944 depending on the position of the valve 956B. The circulation apparatus 952 circulates the gas from the air chamber 940, 944 to the heat exchanger 954.

[0191] As shown in FIG. 9A, the two heat exchangers 954 are connected in parallel with a series of pneumatic shut-off valves 907G-907J, that can regulate the flow of gas to heat exchanger 954A, heat exchanger 954B, or both. Also included is a by-pass pneumatic shut-off valve 907K that can be used to bypass the heat exchangers 954 (i.e., the heat-transfer subsystem 950 can be operated without circulating gas through either heat exchanger). In use, the gas flows through a first side of the heat exchanger 954, while a constant temperature fluid source flows through a second side of the heat exchanger 954. The fluid source is controlled to maintain the gas at ambient temperature. For example, as the temperature of the gas increases during compression, the gas can be directed through the heat exchanger 954, while the fluid source (at ambient or colder temperature) counter-flows through the heat exchanger 954 to remove heat from the gas. The gas output of the heat exchanger 954 is in fluid communication with each of the air chambers 940, 944 via a three-way, two position pneumatic valve 956A that returns the thermally conditioned gas to either air chamber 940, 944, depending on the position of the valve 956A. The pneumatic valves 956 are used to control from which hydraulic cylinder the gas is being thermally conditioned.

[0192] The selection of the various components will depend on the particular application with respect to, for example, fluid flows, heat transfer requirements, and location. In addition, the pneumatic valves can be electrically, hydraulically, pneumatically, or manually operated. In addition, the heat transfer subsystem 950 can include at least one temperature sensor 922 that, in conjunction with the controller 960, controls the operation of the various valves 907, 956 and thus the operation of the heat-transfer subsystem 950.

[0193] In one exemplary embodiment, the heat transfer subsystem is used with a staged hydraulic-pneumatic energy conversion system as shown and described above, where the two heat exchangers are connected in series. The operation of the heat-transfer subsystem is described with respect to the operation of a 1.5-gallon capacity piston accumulator having a 4-inch bore. In one example, the system is capable of producing 1-1.5 kW of power during a 10 second expansion of the gas from 2900 psi to 350 psi. Two tube-in-shell heat exchange units (available from Sentry Equipment Corp., Oconomowoc, Wis.), one with a heat-transfer area of 0.11 m² and the other with a heat exchange area of 0.22 m², are in fluid communication with the air chamber of the accumulator. Except for the arrangement of the heat exchangers, the system is similar to that shown in FIG. 9A, and shut-off valves can be used to control the heat-exchange counter flow, thus providing for no heat exchange, heat exchange with a single heat exchanger (i.e., with a heat exchange area of 0.11 m² or 0.22 m²), or heat exchange with both heat exchangers (i.e., with a heat exchange area of 0.33 m²).

[0194] During operation of the systems 900, 950, high-pressure air is drawn from the accumulator 916 and circulated through the heat exchangers 954 by the circulation apparatus 952. Specifically, once the accumulator 916 is filled with hydraulic fluid and the piston is at the top of the cylinder, the gas circulation/heat exchanger sub-circuit and remaining volume on the air side of the accumulator is filled with 3,000 psi air. The shut-off valves 907G-907J are used to select which, if any, heat exchanger to use. Once this is complete, the circulation apparatus 952 is turned on as is the heat exchanger counter-flow. Additional heat-transfer subsystems are described herein below with respect to FIGS. 11-23.

[0195] During gas expansion in the accumulator 916, the three-way valves 956 are actuated as shown in FIG. 9A and the gas expands. Pressure and temperature transducers/sensors on the gas side of the accumulator 916 are monitored during the expansion, as well as temperature transducers/sensors located on the heat transfer subsystem 950. The thermodynamic efficiency of the gas expansion can be determined when the total fluid power energy output is compared
to the theoretical energy output that could have been obtained by expanding the known volume of gas in a perfectly isothermal manner.

[0196] The overall work output and thermal efficiency can be controlled by adjusting the hydraulic fluid flow rate and the heat-exchanger area. FIG. 10 depicts the relationship between power output, thermal efficiency, and heat-exchanger surface area for this exemplary embodiment of the systems 900, 950. As shown in FIG. 10, there is a trade-off between power output and efficiency. By increasing heat-exchange area (e.g., by adding heat exchangers to the heat transfer subsystem 950), greater thermal efficiency is achieved over the power output range. For this exemplary embodiment, thermal efficiencies above 90% can be achieved when using both heat exchangers 954 for average power outputs of ~1.0 kW. Increasing the gas circulation rate through the heat exchangers will also provide additional efficiencies. Based on the foregoing, the selection and sizing of the components can be accomplished to optimize system design, by balancing cost and size with power output and efficiency.

[0197] The basic operation and arrangement of the system 900 is substantially similar to that of systems 100 and 300; however, there are differences in the arrangement of the hydraulic valves, as described herein. Referring back to FIG. 9 for the remaining description of the basic staged hydraulic-pneumatic energy conversion system 900, the air chamber 940, 941 of each accumulator 916, 917 is partially bounded by a moveable piston 936, 937 having an appropriate sealing system using sealing rings and other components that are known to those of ordinary skill in the art. The piston 936, 937 moves along the accumulator housing in response to pressure differentials between the air chamber 940, 941 and an opposing fluid chamber 938, 939, respectively, on the opposite side of the accumulator housing. Likewise, the air chambers 944, 945 of the respective intensifiers 918, 919 are also partially bounded by a moveable piston assembly 942, 943. However, the piston assembly 942, 943 includes an air piston connected by a shaft, rod, or other coupling to a respective fluid piston that moves in conjunction. The differences between the piston diameters allow a lower air pressure acting upon the air piston to generate a similar pressure on the associated fluid chamber as the higher air pressure acting on the accumulator piston. In this manner, and as previously described, the system allows for at least two stages of pressure to be employed to generate similar levels of fluid pressure.

[0198] The accumulator fluid chambers 938, 939 are interconnected to a hydraulic motor/pump arrangement 930 via a hydraulic valve 928a. The hydraulic motor/pump arrangement 930 includes a first port 931 and a second port 933. The arrangement 930 also includes several optional valves, including a normally open shut-off valve 925, a pressure relief valve 927, and three check valves 929 that can further control the operation of the motor/pump arrangement 930. For example, check valves 929a, 929b may direct fluid flow from the motor/pump’s leak port to the port 931, 933 at a lower pressure. In addition, valves 925, 929c prevent the motor/pump from coming to a hard stop during an expansion cycle.

[0199] The hydraulic valve 928a is shown as a 3-position, 4-way directional valve that is electrically actuated and spring returned to a center closed position, where no flow through the valve 928a is possible in the unactuated state. The directional valve 928a controls the fluid flow from the accumulator fluid chambers 938, 939 to either the first port 931 or the second port 933 of the motor/pump arrangement 930. This arrangement allows fluid from either accumulator fluid chamber 938, 939 to drive the motor/pump 930 clockwise or counter-clockwise via a single valve.

[0200] The intensifier fluid chambers 946, 947 are also interconnected to the hydraulic motor/pump arrangement 930 via a hydraulic valve 928b. The hydraulic valve 928b is also a 3-position, 4-way directional valve that is electrically actuated and spring returned to a center closed position, where no flow through the valve 928b is possible in the unactuated state. The directional valve 928b controls the fluid flow from the intensifier fluid chambers 946, 947 to either the first port 931 or the second port 933 of the motor/pump arrangement 930. This arrangement allows fluid from either intensifier fluid chamber 946, 947 to drive the motor/pump 930 clockwise or counter-clockwise via a single valve.

[0201] The motor/pump 930 can be coupled to an electrical generator/motor and that drives, and is driven by the motor/pump 930. As discussed with respect to the previously described embodiments, the generator/motor assembly can be interconnected with a power distribution system and can be monitored for status and output/input level by the controller 960.

[0202] In addition, the fluid lines and fluid chambers can include pressure, temperature, or flow sensors and/or indicators 922, 924 (not all of which are explicitly labeled in FIG. 9) that deliver sensor telemetry to the controller 960 and/or provide visual indication of an operational state. In addition, the pistons 936, 937, 942, 943 can include position sensors 948 that report their present position to the controller 960. The position of the piston can be used to determine relative pressure and flow of both gas and fluid.

[0203] FIG. 11 is an illustrative embodiment of an isothermal-expansion hydraulic/pneumatic system in accordance with one simplified embodiment of the invention. The system consists of a cylinder 1101 containing a gas chamber or “pneumatic side” 1102 and a fluid chamber or “hydraulic side” 1104 separated by a movable (double arrow 1140) piston 1103 or other force/pressure-transmitting barrier that isolates the gas from the fluid. The cylinder 1101 can be a conventional, commercially available component, modified to receive additional ports as described below. As will also be described in further detail below, any of the embodiments described herein can be implemented as an accumulator or intensifier in the hydraulic and pneumatic circuits of the energy storage and recovery systems described above (e.g., accumulator 316, intensifier 318). The cylinder 1101 includes a primary gas port 1105, which can be closed via valve 1106 and that connects with a pneumatic circuit, or any other pneumatic source/storage system. The cylinder 1101 further includes a primary fluid port 1107 that can be closed by valve 1108. This fluid port connects with a source of fluid in the hydraulic circuit of the above-described storage system, or any other fluid reservoir.

[0204] With reference now to the heat-transfer subsystem 1150, the cylinder 1101 has one or more gas circulation output ports 1110 that are connected via piping 1111 to the gas circulator 1152. Note, as used herein the term “pipe,” “piping” and the like shall refer to one or more conduits that are rated to carry gas or other fluids between two points. Thus, the singular term should be taken to include a plurality of parallel conduits where appropriate. The gas circulator 1152 can be a conventional or customized low-head pneumatic
pump, fan, or any other device for circulating gas. The gas circulator 1152 should be sealed and rated for operation at the pressures contemplated within the gas chamber 1102. Thus, the gas circulator 1152 creates a predetermined flow (arrow 1130) of gas up the piping 1111 and therethrough. The gas circulator 1152 can be powered by electricity from a power source or by another drive mechanism, such as a fluid motor.

The mass-flow speed and on/off functions of the circulator 1152 can be controlled by a controller 1160 acting on the power source for the circulator 1152. The controller 1160 can be a software and/or hardware-based system that carries out the heat-exchange procedures described herein. The output of the circulator 1152 is connected via a pipe 1114 to the gas input 1115 of a heat exchanger 1154.

[0205] The heat exchanger 1154 of the illustrative embodiment can be any acceptable design that allows energy to be efficiently transferred to and from a high-pressure gas flow contained within a pressure conduit to another mass flow (fluid). The rate of heat exchange is based, in part on the relative flow rates of the gas and fluid, the exchange surface area between the gas and fluid and the thermal conductivity of the fluid exchange therebetween. In particular, the gas flow is heated in the heat exchanger 1154 by the fluid counterflow 1117 (arrows 1126), which enters the fluid input 1118 of the heat exchanger 1154 at ambient temperature and exits the heat exchanger 1154 at the fluid exit 1119 equal or approximately equal in temperature to the gas in piping 1114. The gas flow at gas exit 1120 of heat exchanger 1154 is at ambient or approximately ambient temperature, and returns via piping 1121 through one or more gas circulation input ports 1122 to gas chamber 1102. By “ambient” it is meant the temperature of the surrounding environment, or another desired temperature at which efficient performance of the system can be achieved. The ambient-temperature gas reentering the cylinder’s gas chamber 1102 at the circulation input ports 1122 mixes with the gas in the gas chamber 1102, thereby bringing the temperature of the fluid in the gas chamber 1102 closer to ambient temperature.

[0206] The controller 1160 manages the rate of heat exchange based, for example, on the prevailing temperature (T) of the gas contained within the gas chamber 1102 using a temperature sensor 1133C of conventional design that thermally communicates with the gas within the chamber 1102. The sensor 1133C can be placed at any location along the cylinder including a location that is at, or adjacent to, the heat exchanger gas input port 1110. The controller 1160 reads the value T from the cylinder sensor and compares it to an ambient temperature value (TA) derived from a sensor 1133C located somewhere within the system environment. When T is greater than TA, the heat-transfer subsystem 1150 is directed to move gas (by powering the circulator 1152) therethrough at a rate that can be partly dependent upon the temperature differential (so that the exchange does not overshoot or undershoot the desired setting). Additional sensors can be located at various locations within the heat exchange subsystem to provide additional telemetry that can be used by a more complex control algorithm. For example, the output gas temperature (TO) from the heat exchanger can be measured by a sensor 1113A that is placed upstream of the outlet port 1122.

[0207] The fluid circuit of the heat exchanger 1150 can be filled with water, a coolant mixture, and/or any acceptable heat-transfer medium. In alternative embodiments, a gas, such as air or refrigerant, can be used as the heat-transfer medium. In general, the fluid is routed by conduits to a large reservoir of such fluid in a closed or open loop. One example of an open loop is a well or body of water from which ambient water is drawn and the exhaust water is delivered to a different location, for example, downstream in a river. In a closed loop embodiment, a cooling tower can cycle the water through the air for return to the heat exchanger. Likewise, water can pass through a submerged or buried coil of continuous piping where a counter heat-exchange occurs to return the fluid flow to ambient before it returns to the heat exchanger for another cycle.

[0208] It should also be clear that the isothermal operation of the invention works in two directions thermodynamically. While the gas is warmed to ambient by the fluid during expansion, the gas can also be cooled to ambient by the heat exchanger during compression, as significant internal heat can build up via compression. The heat exchanger components should be rated, thus, to handle the temperature range expected to be encountered for entering gas and exiting fluid. Moreover, since the heat exchanger is external of the hydraulic/pneumatic cylinder, it can be located anywhere that is convenient and can be sized as needed to deliver a high rate of heat exchange. In addition it can be attached to the cylinder with straightforward taps or ports that are readily installed on the base end of an existing, commercially available hydraulic/pneumatic cylinder.

[0209] Reference is now made to FIG. 12, which details a second illustrative embodiment of an isothermal-expansion hydraulic/pneumatic system in accordance with one simplified embodiment of the invention. In this embodiment, the heat-exchange subsystem 1250 is similar or identical to the heat-exchange subsystems 950, 1150 described above. Thus, where like components are employed, they are given like reference numbers herein. The illustrative system in this embodiment comprises an “intensifier” consisting of a cylinder assembly 1201 containing a gas chamber 1202 and a fluid chamber 1204 separated by a piston assembly 1203. The piston assembly 1203 in this arrangement consists of a larger diameter/area pneumatic piston member 1210 tied by a shaft 1212 to a smaller diameter/area hydraulic piston 1214. The corresponding gas chamber 1202 is thus larger in cross section than the fluid chamber 1204 and is separated by a moveable (double arrow 420) piston assembly 1203. The relative dimensions of the piston assembly 1203 result in a differential pressure response on each side of the cylinder 1201. That is, the pressure in the gas chamber 1202 can be lower by some predetermined fraction relative to the pressure in the fluid chamber as a function of each piston members’ 1210, 1214 relative surface area.

[0210] As previously discussed, any of the embodiments described herein can be implemented as an accumulator or intensifier in the hydraulic and pneumatic circuits of the energy storage and recovery systems described above. For example, intensifier cylinder 1201 can be used as a stage along with the cylinder 1101 of FIG. 11, in the previously described systems. To interface with those systems or another application, the cylinder 1201 can include a primary gas port 1205 that can be closed via valve 1206 and a primary fluid port 1207 that can be closed by valve 1208.

[0211] With reference now to the heat-exchange subsystem 1250, the intensifier cylinder 1201 also has one or more gas circulation output ports 1210 that are connected via piping 1211 to a gas circulator 1252. Again, the gas circulator 1252 can be a conventional or customized low-head pneumatic pump, fan, or any other device for circulating gas. The gas
circulator 1252 should be sealed and rated for operation at the pressures contemplated within the gas chamber 1202. Thus, the gas circulator 1252 creates a predetermined flow (arrow 1230) of gas up the piping 1211 and therethrough. The gas circulator 1252 can be powered by electricity from a power source or by another drive mechanism, such as a fluid motor. The mass-flow speed and on/off functions of the circulator 1252 can be controlled by a controller 1260 acting on the power source for the circulator 1252. The controller 1260 can be a software and/or hardware-based system that carries out the heat-exchange procedures described herein. The output of the gas circulator 1252 is connected via a pipe 1214 to the gas input 1215 of a heat exchanger 1254.

[0212] Again, the gas flow is heated in the heat exchanger 1254 by the fluid counter-flow 1217 (arrows 1226), which enters the fluid input 1218 of heat exchanger 1254 at ambient temperature and exits the heat exchanger 1254 at the fluid exit 1219 equal or approximately equal in temperature to the gas in piping 1214. The gas flow at exit 1220 of heat exchanger 1254 is at approximately ambient temperature, and returns via piping 1221 through one or more gas circulation inputs 1222 to gas chamber 1202. By “ambient” is meant the temperature of the surrounding environment, or another desired temperature at which efficient performance of the system can be achieved. The ambient-temperature gas reentering the cylinder’s gas chamber 1202 at the circulation input ports 1222 mixes with the gas in the gas chamber 1202, thereby bringing the temperature of the fluid in gas chamber 1202 closer to ambient temperature. Again, the heat-transfer subsystem 1250 when used in conjunction with the intensifier of FIG. 12 may be particularly sized and arranged to accommodate the performance of the intensifier’s gas chamber 1202, which may differ thermodynamically from that of the cylinder’s gas chamber 1102 in the embodiment shown in FIG. 11. Nevertheless, it is contemplated that the basic structure and function of heat exchangers in both embodiments is generally similar. Likewise, the controller 1260 can be adapted to deal with the performance curve of the intensifier cylinder. As such, the temperature readings of the chamber sensor 1213B, ambient sensor 1213C, and exchanger output sensor 1213A are similar to those described with respect to sensors 1113 in FIG. 11. A variety of alternate sensor placements are expressly contemplated in this embodiment.

[0213] Reference is now made to FIG. 13, which shows the cylinder 1101 and heat transfer subsystem 1150 shown and described in FIG. 11, in combination with a potential circuit 1370. This embodiment illustrates the ability of the cylinder 1101 to perform work. The above-described intensifier 1201 can likewise be arranged to perform work in the manner shown in FIG. 13. In summary, as the pressurized gas in the gas chamber 1102 expands, the gas performs work on piston assembly 1103 as shown (or on piston assembly 1203 in the embodiment of FIG. 12), which performs work on fluid in fluid chamber 1104 (or fluid chamber 1204), thereby forcing fluid out of fluid chamber 1104 (1204). Fluid forced out of fluid chamber 1104 (1204) flows via piping 1371 to a hydraulic motor 1372 of conventional design, causing the hydraulic motor 1372 to drive a shaft 1373. The shaft 1373 drives an electric motor/generator 1374, generating electricity. The fluid entering the hydraulic motor 1372 exits the motor and flows into fluid receptacle 1375. In such a manner, energy released by the expansion of gas in gas chamber 1102 (1202) is converted to electric energy. The gas may be sourced from an array of high-pressure storage tanks as described above.

The heat-exchange subsystem may maintain ambient temperature in the gas chamber 1102 (1202) in the manner described above during the expansion process.

[0214] In a similar manner, electric energy can be used to compress gas, thereby storing energy. Electric energy supplied to the electric motor/generator 1374 drives the shaft 1373 that, in turn, drives the hydraulic motor 1372 in reverse. This action forces fluid from fluid receptacle 1375 into piping 1371 and further into fluid chamber 1104 (1204) of the cylinder 1101. As fluid enters fluid chamber 1104 (1204), it performs work on the piston assembly 1103, which thereby performs work on the gas in the gas chamber 1102 (1202), i.e., compresses the gas. The heat-exchange subsystem 1150 can be used to remove heat produced by the compression and maintain the temperature at ambient or near-ambient by proper reading by the controller 1160 (1260) of the sensors 1113 (1213), and throttling of the circulator 1152 (1252).

[0215] Reference is now made to FIGS. 14A, 14B, and 14C, which respectively show the ability to perform work when the cylinder or intensifier expands gas adiabatically, isothermally, or nearly isothermally. With reference first to FIG. 14A, if the gas in a gas chamber expands from an initial pressure 502 and an initial volume 504 quickly enough that there is virtually no heat input to the gas, then the gas expands adiabatically, following adiabatic curve 506a, until the gas reaches atmospheric pressure 508 and adiabatic final volume 510a. The work performed by this adiabatic expansion is shaded area 512a. Clearly, a small portion of the curve becomes shaded, indicating a smaller amount of work performed and an inefficient transfer of energy.

[0216] Conversely, as shown in FIG. 14B, if the gas in the gas chamber expands from the initial pressure 502 and the initial volume 504 slowly enough that there is perfect heat transfer into the gas, then the gas will remain at a constant temperature and will expand isothermally, following isothermal curve 506b until the gas reaches atmospheric pressure 508 and isothermal final volume 510b. The work performed by this isothermal expansion is shaded area 512b. The work 512b achieved by isothermal expansion 506b is significantly greater than the work 512a achieved by adiabatic expansion 506a. Achieving perfect isothermal expansion may be difficult in all circumstances, as the amount of time required approaches infinity. Actual gas expansion resides between isothermal and adiabatic.

[0217] The heat transfer subsystems 950, 1150, 1250 in accordance with the invention contemplate the creation of at least an approximate or near-perfect isothermal expansion as indicated by the graph of FIG. 14C. Gas in the gas chamber expands from the initial pressure 502 and the initial volume 504 following actual expansion curve 506c, until the gas reaches atmospheric pressure 508 and actual final volume 510c. The actual work performed by this expansion is shaded area 512c. If actual expansion 506c is near-isothermal, then the actual work 512c performed will be approximately equal to the isothermal work 512b (when comparing the area in FIG. 14B). The ratio of the actual work 512c divided by the perfect isothermal work 512b is the thermal efficiency of the expansion as plotted on the y-axis of FIG. 10.

[0218] The power output of the system is equal to the work done by the expansion of the gas divided by the time it takes to expand the gas. To increase the power output, the expansion time needs to be decreased. As the expansion time decreases, the heat transfer to the gas will decrease, the expansion will be more adiabatic, and the actual work output will be less, i.e.,
closer to the adiabatic work output. In embodiments of the invention described herein, heat transfer to the gas is increased by increasing the surface area over which heat transfer can occur in a circuit external to, but in fluid communication with, the primary air chamber, as well as the rate at which that gas is passed over the heat exchange surface area. This arrangement increases the heat transfer to/from the gas and allows the work output to remain constant and approximately equal to the isothermal work output even as the expansion time decreases, resulting in a greater power output. Moreover, embodiments of the systems and methods described herein enable the use of commercially available components that, because they are located externally, can be sized appropriately and positioned anywhere that is convenient within the footprint of the system.

[0219] It should be clear to those of ordinary skill that the design of the heat exchanger and flow rate of the pump can be based upon empirical calculations of the amount of heat absorbed or generated by each cylinder during a given expansion or compression cycle so that the appropriate exchange surface area and fluid flow is provided to satisfy the heat transfer demands. Likewise, an appropriately sized heat exchanger can be derived, at least in part, through experimental techniques, after measuring the necessary heat transfer and providing the appropriate surface area and flow rate.

[0220] FIG. 15 is a schematic diagram of a system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. The systems and methods previously described can be modified to improve heat transfer by replacing the single hydraulic-pneumatic accumulators with a series of long narrow piston-based accumulators 1517. The air and hydraulic fluid sides of these piston-based accumulators are tied together at the ends (e.g., by a machined metal block 1521 held in place with tie rods) to mimic a single accumulator with one air input/output 1532 and one hydraulic fluid input/output 1532. The bundle of piston-based accumulators 1517 are enclosed in a shell 1523, which can contain a fluid (e.g., water) that can be circulated past the bundle of accumulators 1517 (e.g., similar to a tube-in-shell heat exchanger) during air expansion or compression to expedite heat transfer. This entire bundle-and-shell arrangement forms the modified accumulator 1516. The fluid input 1527 and fluid output 1529 from the shell 1523 can run to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0221] Also shown in FIG. 15 is a modified intensifier 1518. The function of the intensifier 1518 is identical to that of those previously described; however, heat exchange between the air expanding (or being compressed) is expedited by the addition of a bundle of long, narrow, low-pressure piston-based accumulators 1519. This bundle of accumulators 1519 allows for expedited heat transfer to the air. The hydraulic fluid from the bundle of piston-based accumulators 1519 is low pressure (equal to the pressure of the expanding air). The pressure is intensified in a hydraulic-fluid to hydraulic-fluid intensifier (booster) 1520, thus mimicking the role of the air-to-hydraulic fluid intensifiers described above, except for the increased surface area for heat exchange during expansion/compression. Similar to modified accumulator 1516, this bundle of piston-based accumulators 1519 is enclosed in a shell 1525 and, along with the booster 1620, mimics a single intensifier with one air input/output 1531 and one hydraulic fluid input/output 1533. The shell 1525 can contain a fluid (e.g., water) that can be circulated past the bundle of accumulators 1519 during air expansion or compression to expedite heat transfer. The fluid input 1526 and fluid output 1528 from the shell 1525 can run to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0222] FIG. 16 is a schematic diagram of an alternative system and method for expedited heat transfer of gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system described in FIG. 15 is modified to reduce costs and potential issues with piston friction as the diameter of the long narrow piston-based accumulators is further reduced. In this embodiment, a series of long narrow fluid-filled (e.g., water) tubes (e.g., piston-less accumulators) 1617 is used in place of the many piston-based accumulators 1517 in FIG. 15. In this way, cost is substantially reduced, as the tubes no longer need to be honed to a high-precision diameter and no longer need to be straight for piston travel. Similar to those described in FIG. 15, these bundles of fluid-filled tubes 1617 are tied together at the ends to mimic a single tube (piston-less accumulator) with one air input/output 1630 and one hydraulic fluid input/output 1632. The bundle of tubes 1617 is enclosed in a shell 1623, which can contain a fluid (e.g., water) at low pressure, which can be circulated past the bundle of tubes 1617 during air expansion or compression to expedite heat transfer. This entire bundle-and-shell arrangement forms the modified accumulator 1616. The input 1627 and output 1629 from the shell 1623 can run to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium. In addition, a fluid (e.g., water) to hydraulic-fluid piston-based accumulator 1622 can be used to transmit the pressure from the fluid (water) in accumulator 1616 to a hydraulic fluid, eliminating worries about air in the hydraulic fluid.

[0223] Also shown in FIG. 16 is a modified intensifier 1618. The function of the intensifier 1618 is identical to that of those previously described; however, heat exchange between the air expanding (or being compressed) is expedited by the addition of a bundle of the long narrow low-pressure tubes (piston-less accumulators) 1619. This bundle of accumulators 1619 allows for expedited heat transfer to the air. The hydraulic fluid from the bundle of piston-based accumulators 1619 is low pressure (equal to the pressure of the expanding air). The pressure is intensified in a hydraulic-fluid to hydraulic-fluid intensifier (booster) 1620, thus mimicking the role of the air-to-hydraulic fluid intensifiers described above, except for the increased surface area for heat exchange during expansion/compression and with reduced cost and friction as compared with the intensifier 1518 described in FIG. 15. Similar to modified accumulator 1616, this bundle of piston-based accumulators 1619 is enclosed in a shell 1625 and, along with the booster 1620, mimics a single intensifier with one air input/output 1631 and one hydraulic fluid input/output 1633. The shell 1625 can contain a fluid (e.g., water) that can be circulated past the bundle of accumulators 1619 during air expansion or compression to expedite heat transfer. The fluid input 1626 and fluid output 1628 from the shell 1625 can run to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0224] FIG. 17 is a schematic diagram of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system of FIG. 11 is modified to eliminate dead air space and potentially
improve heat transfer by using a liquid-to-liquid heat exchanger. As shown in FIG. 11, an air circulator 1152 is connected to the air space of pneumatic-hydraulic cylinder 1101. One possible drawback of the air circulator system is that some "dead air space" is present and can reduce the energy efficiency by having some air expansion without useful work being extracted.

[0225] Similar to the cylinder 1101 shown in FIG. 11, the cylinder 1701 includes a primary gas port 1705, which can be closed via a valve and connected with a pneumatic circuit, or any other pneumatic source/storage system. The cylinder 1701 further includes a primary fluid port 1707 that can be closed by a valve. This fluid port connects with a source of fluid in the hydraulic circuit of the above-described storage systems, or any other fluid reservoir.

[0226] As shown in FIG. 17, a water circulator 1752 is attached to the pneumatic side 1702 of the hydraulic-pneumatic cylinder (accumulator or intensifier) 1701. Sufficient fluid (e.g., water) is added to the pneumatic side 1702, such that no dead space is present—e.g., the heat-transfer subsystem 1750 (i.e., circulator 1752 and heat exchanger 1754) are filled with fluid—when the piston 1701 is fully to the top (e.g., hydraulic side 1704 is filled with hydraulic fluid). Additionally, enough extra liquid is present in the pneumatic side 1702 such that liquid can be drawn out of the bottom of the cylinder 1701 when the piston is fully at the bottom (e.g., hydraulic side 1704 is empty of hydraulic fluid). As the gas is expanded (or being compressed) in the cylinder 1701, the liquid is circulated by liquid circulator 1752 through a liquid-to-liquid heat exchanger 1754, which may be a shell-and-tube type with the inlet 1722 and output 1724 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium. The liquid that is circulated by circulator 1752 (at a pressure similar to the expanding gas in the pneumatic side 1702) is sprayed back into the pneumatic side 1702 after passing through the heat exchanger 1754, thus increasing the heat exchange between the liquid and the expanding air. Overall, this method allows for dead-space volume to be filled with an incompressible liquid; thus, the heat-exchanger volume can be large and it can be located anywhere that is convenient. By removing all heat exchangers from the cylinders themselves, the overall efficiency of the energy storage system can be increased. Likewise, as liquid-to-liquid heat exchangers tend to more efficient than air-to-liquid heat exchangers, heat transfer may be improved. It should be noted that in this particular arrangement, the hydraulic/pneumatic cylinder 1701 would be oriented horizontally, so that liquid pools on the lengthwise base of the cylinder 1701 to be continually drawn into circulator 1752.

[0227] FIG. 18 is a schematic diagram of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system of FIG. 11 is again modified to eliminate dead air space and potentially improve heat transfer by using a liquid-to-liquid heat exchanger in a similar manner as described with respect to FIG. 17. Also, the cylinder 1801 can include a primary gas port 1805, which can be closed via a valve and connected with a pneumatic circuit, or any other pneumatic source/storage system, and a primary fluid port 1807 that can be closed by a valve and connected with a source of fluid in the hydraulic circuit of the above-described storage systems, or any other fluid reservoir.

[0228] The heat-exchange subsystem shown in FIG. 18, however, includes a hollow rod 1803 attached to the piston of the hydraulic-pneumatic cylinder (accumulator or intensifier) 1801 such that liquid can be sprayed throughout the entire volume of the pneumatic side 1802 of the cylinder 1801, thereby increasing the heat exchange between the liquid and the expanding air over FIG. 17, where the liquid is only sprayed from the end cap. Rod 1803 is attached to the pneumatic side 1802 of the cylinder 1801 and runs through a seal 1811, such that the liquid in a pressurized reservoir or vessel 1813 (e.g., a metal tube with an end cap attached to the cylinder 1801) can be pumped to a slightly higher pressure than the gas in the cylinder 1801.

[0229] As the gas is expanding (or being compressed) in the cylinder 1801, the liquid is circulated by circulator 1852 through a liquid-to-liquid heat exchanger 1854, which may be a shell-and-tube type with the input 1822 and output 1824 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium. Alternatively, a liquid-to-air heat exchanger could be used. The liquid is circulated by circulator 1852 through a heat exchanger 1854 and then sprayed back into the pneumatic side 1802 of the cylinder 1801 through the rod 1803, which has holes drilled along its length. Overall, this set-up allows for dead-space volume to be filled with an incompressible liquid; thus, the heat-exchanger volume can be large and it can be located anywhere. Likewise, as liquid to liquid heat exchangers tend to more efficient than air to liquid heat exchangers, heat transfer may be improved. By adding the spray rod 1803, the liquid can be sprayed throughout the entire gas volume increasing heat transfer over the set-up shown in FIG. 17.

[0230] FIG. 19 is a schematic diagram of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system is arranged to eliminate dead air space and potentially improve heat transfer by using a liquid-to-liquid heat exchanger in a similar manner as described with respect to FIG. 18. As shown in FIG. 19, however, the heat-exchange subsystem 1950 includes a separate pressure reservoir or vessel 1958 containing a liquid (e.g., water), in which the air expansion occurs. As the gas expands (or is being compressed) in the reservoir 1958, liquid is forced into a liquid to hydraulic fluid cylinder 1901. The liquid (e.g., water) in reservoir 1958 and cylinder 1901 is also circulated via a circulator 1952 through a heat exchanger 1954, and sprayed back into the vessel 1958 allowing for heat exchange between the air expanding (or being compressed) and the liquid. Overall, this embodiment allows for dead-space volume to be filled with an incompressible liquid; thus, the heat-exchanger volume can be large and it can be located anywhere. Likewise, as liquid-to-liquid heat exchangers tend to more efficient than air-to-liquid heat exchangers, heat transfer may be improved. By adding a separate, larger liquid reservoir 1958, the liquid can be sprayed throughout the entire gas volume, increasing heat transfer over the set-up shown in FIG. 17.

[0231] FIGS. 20A and 20B are schematic diagrams of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system is arranged to eliminate dead air space and use a similar type of heat transfer subsystem as described with respect to FIG. 11. Similar to the cylinder 1101 shown in FIG. 11, the
cylinder 2001 includes a primary gas port 2005, which can be closed via a valve and connected with a pneumatic circuit, or any other pneumatic source/storage system. The cylinder 2001 further includes a primary fluid port 2007 that can be closed by a valve. This fluid port connects with a source of fluid in the hydraulic circuit of the above-described storage systems, or any other fluid reservoir. In addition, as the gas is expanded (or being compressed) in the cylinder 2001, the gas is also circulated by circulator 2052 through an air-to-liquid heat exchanger 2054, which may be a shell-and-tube type with the input 2022 and output 2024 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0232] As shown in FIG. 20A, a sufficient amount of a liquid (e.g., water) is added to the pneumatic side 2002 of the cylinder 2001, such that no dead space is present (e.g., the heat transfer subsystem 2050 (i.e., the circulator 2052 and heat exchanger 2054 are filled with liquid) when the piston is fully to the top (e.g., hydraulic side 2004 is filled with hydraulic fluid). The circulator 2052 must be capable of circulating both liquid (e.g., water) and air. During the first part of the expansion, a mix of liquid and air is circulated through the heat exchanger 2054. Because the cylinder 2001 is mounted vertically, however, gravity will tend to empty circulator 2052 of liquid and mostly air will be circulated during the remainder of the expansion cycle shown in FIG. 20B. Overall, this set-up allows for dead-space volume to be filled with an incompressible liquid and thus the heat exchanger volume can be large and it can be located anywhere.

[0233] FIGS. 21A–21C are schematic diagrams of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, the system is arranged to eliminate dead air space and use a similar heat transfer subsystem as described with respect to FIG. 11. In addition, this set-up uses an auxiliary accumulator 2110 to store and recover energy from the liquid initially filling an air circulator 2152 and a heat exchanger 2154. Similar to the cylinder 2010 shown in FIG. 11, the cylinder 2101 includes a primary gas port 2105, which can be closed via a valve and connected with a pneumatic circuit, or any other pneumatic source/storage system. The cylinder 2101 further includes a primary fluid port 2107a that can be closed by a valve. This fluid port 2107a connects with a source of fluid in the hydraulic circuit of the above-described storage systems, or any other fluid reservoir. The auxiliary accumulator 2110 also includes a fluid port 2107b that can be closed by a valve and connected to a source of fluid. In addition, as the gas is expanded (or being compressed) in the cylinder 2101, the gas is also circulated by circulator 2152 through an air to liquid heat exchanger 2154, which may be a shell-and-tube type with the input 2122 and output 2124 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0234] Additionally, as opposed to the set-up shown in FIGS. 20A and 20B, the circulator 2152 circulates almost entirely air and not liquid. As shown in FIG. 21A, sufficient liquid (e.g., water) is added to the pneumatic side 2102 of cylinder 2101, such that no dead space is present—e.g., the heat transfer subsystem 2150 (i.e., the circulator 2152 and the heat exchanger 2154) are filled with liquid—when the piston is fully to the top (e.g., hydraulic side 2104 is filled with hydraulic liquid). In FIGS. 21A–21C, valves shaded black are closed and unshaded valves are open. During the first part of the expansion, liquid is driven out of the circulator 2152 and the heat exchanger 2154, as shown in FIG. 21B through the auxiliary accumulator 2110 and used to produce power. When the auxiliary accumulator 2110 is empty of liquid and full of compressed gas, valves are closed as shown in FIG. 21C and the expansion and air circulation continues as described above with respect to FIG. 11. Overall, this method allows for dead-space volume to be filled with an incompressible liquid and thus the heat exchanger volume can be large and it can be located anywhere. Likewise, useful work is extracted when the air circulator 2152 and the heat exchanger 2154 are filled with compressed gas, such that overall efficiency is increased.

[0235] FIGS. 22A and 22B are schematic diagrams of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, water is sprayed downward into a vertically oriented hydraulic-pneumatic cylinder (accumulator or intensifier) 2201, with a hydraulic side 2203 separated from a pneumatic side 2202 by a movable piston 2204. FIG. 22A depicts the cylinder 2201 in fluid communication with the heat transfer subsystem 2250 in a state prior to a cycle of compressed-air expansion. It should be noted that the air side 2202 of the cylinder 2201 is completely filled with liquid, leaving no air space (a circulator 2252 and a heat exchanger 2254 are filled with liquid as well), when the piston 2204 is fully to the top as shown in FIG. 22A.

[0236] Stored compressed gas in pressure vessels, not shown but indicated by 2220, is admitted via valve 2221 into the cylinder 2201 through air port 2205. As the compressed gas expands into the cylinder 2201, hydraulic fluid is forced out under pressure through fluid port 2207 to the remaining hydraulic system (such as a hydraulic motor as shown and described with respect to FIGS. 1 and 4) as indicated by 2211. During expansion (or compression), heat-exchange liquid (e.g., water) is drawn from a reservoir 2230 by a circulator, such as a pump 2252, through a liquid-to-liquid heat exchanger 2254, which may be a shell-and-tube type with an input 2222 and an output 2224 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0237] As shown in FIG. 22B, the liquid (e.g., water) that is circulated by pump 2252 (at a pressure similar to that of the expanding gas) is sprayed (as shown by spray lines 2262) via a spray head 2260 into the pneumatic side 2202 of the cylinder 2201. Overall, this method allows for an efficient means of heat exchange between the sprayed liquid (e.g., water) and the air being expanded (or compressed) while using pumps and liquid to liquid heat exchangers. It should be noted that in this particular arrangement, the hydraulic pneumatic cylinder 2201 would be oriented vertically, so that the heat-exchange liquid falls with gravity. At the end of the cycle, the cylinder 2201 is reset and in the process, the heat-exchange liquid added to the pneumatic side 2202 is removed via the pump 2252, thereby recharging reservoir 2230 and preparing the cylinder 2201 for a successive cycling.

[0238] FIG. 22C depicts the cylinder 2201 in greater detail with respect to the spray head 2260. In this design, the spray head 2260 is used much like a shower head in the vertically oriented cylinder. In the embodiment shown, the nozzles 2261 are evenly distributed over the face of the spray head 2260; however, the specific arrangement and size of the nozzles can vary to suit a particular application. With the nozzles 2261 of the spray head 2260 evenly distributed across
the end-cap area, the entire air volume (pneumatic side 2202) is exposed to the water spray 2262. As previously described, the heat-transfer subsystem circulates/injects the water into the pneumatic side 2202 at a pressure slightly higher than the air pressure and then removes the water at the end of the return stroke at ambient pressure.

[0239] As previously discussed, the specific operating parameters of the spray will vary to suit a particular application. For a specific pressure range, spray orientation, and spray characteristics, heat-transfer performance can be approximated through modeling. Considering an exemplary embodiment using an 8° diameter, 10 gallon cylinder with 3000 psi air expanding to 300 psi, the water spray flow rates can be calculated for various drop sizes and spray characteristics that would be necessary to achieve sufficient heat transfer to maintain an isothermal expansion. FIG. 22D represents the calculated thermal heat transfer power (in kW) per flow rate (in GPM) for each degree difference between the spray liquid and air at 300 and 3000 psi. The lines with the X marks show the relative heat transfer for a regime (Regime 1) where the spray breaks up into drops. The calculations assume conservative values for heat transfer and no recirculation of the droplets, but rather provide a conservative estimate of the heat transfer for Regime 1. The lines with no marks show the relative heat transfer for a regime (Regime 2) where the spray remains in coherent jets for the length of the cylinder. The calculations assume conservative values for heat transfer and no recirculation after impact, but a conservative estimate of the heat transfer for Regime 2. Considering that an actual spray may be in between a jet and pure droplet formation, the two regimes provide a conservative upper bound and fixed lower bound on expected experimental performance. Considering a 0.1 kW requirement per gallon per minute (GPM) per °C, drop sizes under 2 mm provide adequate heat transfer for a given flow rate and jet sizes under 0.1 mm provide adequate heat transfer.

[0240] Generally, FIG. 22D represents thermal transfer power levels (kW) achieved, normalized by flow rates required and each Celsius degree of temperature difference between liquid spray and air, at different pressures for a spray head (see FIG. 22C) and a vertically-oriented 10 gallon, 8° diameter cylinder. Higher numbers indicate a more efficient (more heat transfer for a given flow rate at a certain temperature difference) heat transfer between the liquid spray and the air. Also shown graphically is the relative number of holes required to provide a jet of a specific diameter. To minimize the number of spray holes required in the spray head requires that the spray break-up into droplets. The break-up of the spray into droplets versus a coherent jet can be estimated theoretically using simplifying assumptions on nozzle and fluid dynamics. In general, break-up occurs more predominantly at higher air pressure and higher flow rates (i.e., higher pressure drop across the nozzle). Break-up at high pressures can be analyzed experimentally with specific nozzles, geometries, fluids, and air pressures.

[0241] Generally, a nozzle size of 0.2 to 2.0 mm is appropriate for high pressure air cylinders (3000 to 300 psi). Flow rates of 0.2 to 1.0 liters/min per nozzle are sufficient in this range to provide medium to complete spray breakup into droplets using mechanically or laser-drilled cylindrical nozzle shapes. For example, a spray head with 250 nozzles of 0.9 mm hole diameter operating at 25 gpm is expected to provide over 50 kW of heat transfer to 3000 to 300 psi air expanding (or being compressed) in a 10 gallon cylinder. Pumping power for such a spray heat transfer implementation was determined to be less than 1% of the heat transfer power. Additional specific and exemplary details regarding the heat transfer subsystem utilizing the spray technology are discussed with respect to FIGS. 24A and 24B.

[0242] FIGS. 23A and 23B are schematic diagrams of another alternative system and method for expedited heat transfer to gas expanding (or being compressed) in an open-air staged hydraulic-pneumatic system. In this setup, water is sprayed radially into an arbitrarily-orientated cylinder 2301. The orientation of the cylinder 2301 is not essential to the liquid spraying but is shown as horizontal in FIGS. 23A and 23B. The hydraulic-pneumatic cylinder (accumulator or intensifier) 2301 has a hydraulic side 2303 separated from a pneumatic side 2302 by a moveable piston 2304. FIG. 23A depicts the cylinder 2301 in fluid communication with the heat-transfer subsystem 2350 in a state prior to a cycle of compressed air expansion. It should be noted that no air space is present on the pneumatic side 2302 in the cylinder 2301 (e.g., a circulator 2352 and a heat exchanger 2354 are filled with liquid) when the piston 2304 is fully retracted (i.e., the hydraulic side 2303 is filled with liquid) as shown in FIG. 23A.

[0243] Stored compressed gas in pressure vessels, not shown in FIGS. 23A, 23B but indicated by 2320, is admitted via valve 2321 into the cylinder 2301 through air port 2305. As the compressed air expands into the cylinder 2301, hydraulic fluid is forced out under pressure through fluid port 2307 to the remaining hydraulic system (such as a hydraulic motor as described with respect to FIGS. 1 and 4) as indicated by arrow 2311. During expansion (or compression), heat-exchange liquid (e.g., water) is drawn from a reservoir 2330 by a circulator, such as a pump 2352, through a liquid-to-liquid heat exchanger 2354, which may be a tube-in-shell setup with an input 2322 and an output 2324 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium. As indicated in FIG. 23B, the liquid (e.g., water) that is circulated by pump 2352 (at a pressure similar to that of the expanding gas) is sprayed (as shown by spray lines 2362) via a spray rod 2360 into the pneumatic side 2302 of the cylinder 2301. The spray rod 2360 is shown in this example as fixed in the center of the cylinder 2301 with a hollow piston rod 2308 separating the heat exchange liquid (e.g., water) from the hydraulic side 2303. As the moveable piston 2304 is moved (for example, leftward in FIG. 23B) forcing hydraulic fluid out of cylinder 2301, the hollow piston rod 2308 extends out of the cylinder 2301 exposing more of the spray rod 2360, such that the entire pneumatic side 2302 is exposed to the heat-exchange spray as indicated by spray lines 2362. Overall, this method allows for an efficient means of heat exchange between the sprayed liquid (e.g., water) and the air being expanded (or compressed) while using pumps and liquid-to-liquid heat exchangers. It should be noted that in this particular arrangement, the hydraulic-pneumatic cylinder could be oriented in any manner and does not rely on the heat-exchange liquid falling with gravity. At the end of the cycle, the cylinder 2301 is reset, and in the process, the heat exchange liquid added to the pneumatic side 2302 is removed via the pump 2352, thereby recharging reservoir 2330 and preparing the cylinder 2301 for a successive cycle.

[0244] FIG. 23C depicts the cylinder 2301 in greater detail with respect to the spray rod 2360. In this design, the spray rod 2360 (e.g., a hollow stainless steel tube with many holes)
is used to direct the water spray radially outward throughout the air volume (pneumatic side 2302) of the cylinder 2301. In the embodiment shown, the nozzles 2361 are evenly distributed along the length of the spray rod 2360; however, the specific arrangement and size of the nozzles can vary to suit a particular application. The water can be continuously removed from the bottom of the pneumatic side 2302 at pressure, or can be removed at the end of a return stroke at ambient pressure. This arrangement utilizes the common practice of center-drilling piston rods (e.g., for position sensors). As previously described, the heat-transfer subsystem 2350 (FIG. 23B) circulates/injects the water into the pneumatic side 2302 at a pressure slightly higher than the air pressure and then removes the water at the end of the return stroke at ambient pressure.

[0245] As previously discussed, the specific operating parameters of the spray will vary to suit a particular application. For a specific pressure range, spray orientation, and spray characteristics, heat transfer performance can be approximated through modeling. Again, considering an exemplary embodiment using an 8" diameter, 10 gallon cylinder with 3000 psi air expanding to 300 psi, the water spray flow rates can be calculated for various drop sizes and spray characteristics that would be necessary to achieve sufficient heat transfer to maintain an isothermal expansion. FIG. 23D represents the calculated thermal heat transfer power (in kW) per flow rate (in GPM) for each degree difference between the spray liquid and air at 300 and 3000 psi. The lines with the X marks show the relative heat transfer for Regime 4 where the spray breaks up into drops. The calculations assume conservative values for heat transfer and no recirculation of the drops, but rather provide a conservative estimate of the heat transfer for Regime 1. The lines with no marks show the relative heat transfer for Regime 2, where the spray remains in coherent jets for the length of the cylinder. The calculations assume conservative values for heat transfer and no recirculation after impact, but a conservative estimate of the heat transfer for Regime 2. Considering that an actual spray may be in between a jet and pure droplet formation, the two regimes provide a conservative upper bound and fixed lower bound on expected experimental performance. Considering a 0.1 kW requirement per gallon per minute (gpm) per °C, drop sizes under 2 mm provide adequate heat transfer for a given flow rate and jet sizes under 0.1 mm provide adequate heat transfer.

[0246] Generally, FIG. 23D represents thermal transfer power levels (kW) achieved, normalized by flow rates required and each Celsius degree of temperature difference between liquid spray and air, at different pressures for a spray rod (see FIG. 23C) and a horizontally-oriented 10 gallon, 8" diameter cylinder. Higher numbers indicate a more efficient (more heat transfer for a given flow rate at a certain temperature difference) heat transfer between the liquid spray and the air. Also shown graphically is the relative number of holes required to provide a jet of a specific diameter. To minimize the number of spray holes required in the spray rod requires that the spray break-up into droplets. The break-up of the spray into droplets versus a coherent jet can be estimated theoretically using simplifying assumptions on nozzle and liquid dynamics. In general, break-up occurs more prominently at higher air pressure and higher flow rates (i.e., higher pressure drop across the nozzle). Break-up at high pressures can be analyzed experimentally with specific nozzles, geometries, fluids, and air pressures.

[0247] As discussed above with respect to the spray head arrangement, a nozzle size of 0.2 to 2.0 mm is appropriate for high pressure air cylinders (3000 to 300 psi). Flow rates of 0.2 to 1.0 liters/min per nozzle are sufficient in this range to provide medium to complete spray breakup into droplets using mechanically or laser drilled cylindrical nozzle shapes. For example, a spray head with 250 nozzles of 0.9 mm hole diameter operating at 25 gpm is expected to provide over 50 kW of heat transfer to 3000 to 300 psi air expanding (or being compressed) in a 10 gallon cylinder. Pumping power for such a spray heat transfer implementation may be less than 1% of the heat transfer power. Additional specific and exemplary details regarding the heat transfer subsystem utilizing the spray technology are discussed with respect to FIGS. 24A and 24B.

[0248] Generally, for the arrangements shown in FIGS. 22 and 23, the liquid-spray heat transfer may be implemented using commercially-available pressure vessels, such as pneumatic and hydraulic/pneumatic cylinders with, at most, minor modifications. Likewise, the heat exchanger may be constructed from commercially-available, high-pressure components, thereby reducing the cost and complexity of the overall system. Since the primary heat exchanger area is external of the hydraulic/pneumatic vessel and dead-space volume is filled with an essentially incompressible liquid, the heat exchanger volume may be large and it may be located anywhere that is convenient. In addition, the heat exchanger may be attached to the vessel with common pipe fittings.

[0249] The basic design criteria for the spray heat-transfer subsystem include minimization of operational energy used (i.e., parasitic loss), primarily related to liquid spray pumping power, while maximizing thermal transfer. While actual heat transfer performance is determined experimentally, theoretical analysis indicates the areas where maximum heat transfer for a given pumping power and flow rate of water may occur. As heat transfer between the liquid spray and surrounding air is at least partially dependent on surface area, the analysis discussed herein utilized the two spray regimes discussed above: 1) water droplet heat transfer and 2) water jet heat transfer.

[0250] In Regime 1, the spray breaks up into droplets, providing a larger total surface area. Regime 1 can be considered an upper-bound for surface area, and thus heat transfer, for a given set of other assumptions. In Regime 2, the spray remains in a coherent jet or stream, thus providing much less surface area for a given volume of water. Regime 2 can be considered a lower-bound for surface area and thus heat transfer for a given set of other assumptions.

[0251] For Regime 1, where the spray breaks into droplets for a given set of conditions, it can be shown that drop sizes of less than 2 mm can provide sufficient heat transfer performance for an acceptably low flow rate (e.g., <10 gpm °C/kW), as shown in FIG. 24A. FIG. 24A represents the flow rates required for each Celsius degree of temperature difference between liquid spray droplets and air at different pressures to achieve one kilowatt of heat transfer. Lower numbers indicate a more efficient (lower flow rate for given amount of heat transfer at a certain temperature difference) heat transfer between the liquid spray droplets and the air. For the given set of conditions illustrated in FIG. 24A, drop diameters below about 2 mm are desirable. FIG. 24B is an enlarged portion of the graph of FIG. 24A and represents that for the given set of
conditions illustrated, drop diameters below about 0.5 mm no longer provide additional heat transfer benefit for a given flow rate.

[0252] As drop size continues to become smaller, eventually the terminal velocity of the drop becomes small enough (e.g., <100 microns) that the drops fall too slowly to cover the entire cylinder volume. Thus, for the given set of conditions illustrated here, drop sizes between about 0.1 and 2.0 mm may be considered as preferred for maximizing heat transfer while minimizing pumping power, which increases with increasing flow rate. A similar analysis can be performed for Regime 2, where liquid spray remains in a coherent jet. Higher flow rates and/or narrower diameter jets are generally needed to provide similar heat transfer performance.

[0253] FIG. 25 is a detailed schematic diagram of a cylinder design for use with any of the herein described systems for energy storage and recovery using compressed gas. In particular, the cylinder 2501 depicted in partial cross-section in FIG. 25 includes a spray head arrangement 2560 similar to that described with respect to FIG. 22, where water is sprayed downward into a vertical cylinder. As shown, the vertically oriented hydraulic-pneumatic cylinder 2501 has a hydraulic side 2503 separated from a pneumatic side 2502 by a moveable piston 2504. The cylinder 2501 also includes two end caps (e.g., machined steel blocks) 2563, 2565, mounted on either end of a honed-cylindrical tube 2561, typically attached via tie rods or other well-known mechanical means. The piston 2504 is slidable disposed in and sealingly engaged with the tube 2561 via seals 2567. End cap 2565 is machined with single or multiple ports 2585, which allow for the flow of hydraulic fluid. End cap 2563 is machined with single or multiple ports 2686, which may admit air and/or heat exchange liquid. The ports 2685, 2686 shown have threaded connections; however, other types of ports/connections are contemplated and within the scope of the invention (e.g., flanged).

[0256] A hollow piston rod 2608 is attached to the moveable piston 2604 and slides over the spray rod 2660 that is fixed to and oriented coaxially with the cylinder 2601. The spray rod 2660 extends through a machined hole 2669 in the piston 2604. The piston 2604 is configured to move freely along the length of the spray rod 2660. As the moveable piston 2604 moves towards end cap 2665, the hollow piston rod 2608 extends out of the cylinder 2601, exposing more of the spray rod 2660, such that the entire pneumatic side 2602 is exposed to heat-exchange spray (see, for example, FIG. 23B). The spray rod 2660 in this illustration is attached to the end cap 2663 and in fluid communication with a heat-exchange liquid port 2671. As shown in FIG. 26, the port 2671 is mechanically coupled to and sealed with the end cap 2663; however, the port 2671 could also be a threaded connection machined in the end cap 2663. The hollow piston rod 2608 also allows for position measurement via displacement transducer 2674 and piston damping via an external cushion 2675. As shown in FIG. 26, the piston rod 2608 moves into and out of the hydraulic side 2603 through a machined hole with rod seal 2672.

[0257] It should be noted that the heat-transfer subsystems discussed above with respect to FIGS. 9-13 and 15-23 may also be used in conjunction with the high-pressure gas storage systems (e.g., storage tanks 902) to thermally condition the pressurized gas stored therein, as shown in FIGS. 27 and 28. Generally, these systems are arranged and operate in the same manner as described above.

[0258] FIG. 27 depicts the use of a heat transfer subsystem 2750 in conjunction with a gas storage system 2701 for use with the compressed gas energy storage systems described herein, to expedite transfer of thermal energy to, for example, the compressed gas prior to and during expansion. Compressed air from the pressure vessels (2702a-2702c) is circulated through a heat exchanger 2754 using an air pump 2752 operating as a circulator. The air pump 2752 operates with a small pressure change sufficient for circulation, but within a housing that is able to withstand high pressures. The air pump 2752 circulates the high-pressure air through the heat exchanger 2754 without substantially increasing its pressure (e.g., a 50 psi increase for 3,000 psi air). In this way, the stored compressed air may be pre-heated (or pre-cooled) by opening valve 2704 with valve 2706 closed and heated during expansion or cooled during compression by closing 2704 and opening 2706 (which may also place heat-transfer subsystem 2750 in fluid communication with an energy storage and recovery system). The heat exchanger 2754 may be of any sort of standard heat-exchanger design; illustrated here is a tube-in-shell type heat exchanger with high-pressure air inlet and outlet ports 2721a and 2721b, and low-pressure shell water ports 2722a and 2722b.

[0259] FIG. 28 depicts the use of a heat-transfer subsystem 2850 in conjunction with a gas storage system 2801 for use with the compressed gas in energy storage systems described herein, to expedite transfer of thermal energy to the compressed gas prior to and during expansion. In this embodiment, thermal energy transfer to and from the stored compressed gas in pressure vessels (2802a, 2802b) is expedited
through a water circulation scheme using a water pump 2852 and heat exchanger 2854. The water pump 2852 operates with a small pressure change sufficient for circulation and spray, but within a housing that is able to withstand high pressures. The water pump 2852 circulates high-pressure water through heat exchanger 2854 and sprays the water into pressure vessels 2802a, 2802b without substantially increasing its pressure (e.g., a 100 psi increase for circulating and spraying within 3,000 psi stored compressed air). In this way, the stored compressed air may be pre-heated (or pre-cooled) using a water circulation and spraying method that also allows for active water monitoring of the pressure vessels 2802.

[0260] The spray heat exchange may occur as pre-heating prior to expansion and/or pre-cooling prior to compression in the system when valve 2806 is opened. The heat exchanger 2854 may be any sort of standard heat exchanger design; illustrated here is a tube-in-shell type heat exchanger with high-pressure water inlet and outlet ports 2821a and 2821b and low-pressure shell water ports 2822a and 2822b. As liquid-to-liquid heat exchangers tend to be more efficient than air-to-liquid heat exchangers, heat exchanger size may be reduced and/or heat transfer may be improved by use of the liquid to liquid heat exchanger. Heat exchange within the pressure vessels 2802a, 2802b is expedited by active spraying of the liquid (e.g., water) into the pressure vessels 2802.

[0261] As shown in FIG. 28, a perforated spray rod 2811a, 2811b is installed within each pressure vessel 2802a, 2802b. The water pump 2852 increases the water pressure above the vessel pressure such that water is actively circulated and sprayed out of rods 2811a and 2811b, as shown by arrows 2812a, 2812b. After spraying through the volume of the pressure vessels 2802, the water settles to the bottom of the vessels 2802a, 2802b (forming pools 2813a, 2813b) and is then removed through a drainage port 2814a, 2814b. The water may be circulated through the heat exchanger 2854 as part of the closed-loop water circulation and spray system.

[0262] Alternative systems and methods for energy storage and recovery are described with respect to FIGS. 29-44. These systems and methods are similar to the energy storage and recovery systems described above, but use a variety of mechanical means coupled to different types of cylinders. Such systems may include (a) distinct pneumatic and hydraulic free-piston cylinders, mechanically coupled to each other by a mechanical boundary mechanism, rather than a single pneumatic-hydraulic cylinder, such as an intensifier, or (b) pneumatic free-piston cylinders coupled to electrical machines by mechanical boundary mechanisms or subsystems rather than by hydraulic subsystems. Systems employing distinct pneumatic and hydraulic free-piston cylinders allow the heat-transfer subsystems for conditioning the gas being expanded (or compressed) to be separated from the hydraulic circuit. By mechanically coupling one or more pneumatic cylinders and/or one or more hydraulic cylinders so as to add (or share) forces produced by (or acting on) the cylinders, the hydraulic pressure range may be narrowed, allowing more efficient operation of the hydraulic motor/pump. Systems coupling pneumatic cylinders to electrical machines by mechanical means (e.g., coupling of cylinder rods to linear generators, coupling of cylinder rods to crankshafts that are in turn coupled to rotary electrical machines) allow the omission of hydraulic cylinders and pump/motors and efficient conversion of the elastic potential energy of compressed gas to electrical energy or the reverse.

[0263] The systems and methods described with respect to FIGS. 29-31 generally operate on the principle of transferring mechanical energy between two or more cylinder assemblies using a mechanical boundary mechanism to mechanically couple the cylinder assemblies and translate the linear motion produced by one cylinder assembly to the other cylinder assembly. In one embodiment, the linear motion of the first cylinder assembly is the result of a gas expanding in one chamber of the cylinder and moving a piston within the cylinder. The translated linear motion in the second cylinder assembly is converted into a rotary motion of a hydraulic motor, as the linear motion of the piston in the second cylinder assembly drives a fluid out of the cylinder and to the hydraulic motor. The rotary motion is converted to electricity by using a rotary electric generator.

[0264] The basic operation of a compressed-gas energy storage system for use with the cylinder assemblies described with respect to FIGS. 29-31 is as follows. The gas is expanded into a cylindrical chamber (i.e., the pneumatic cylinder assembly) containing a piston or other mechanism that separates the gas on one side of the chamber from the other, thereby preventing gas movement from one chamber to the other while allowing the transfer of force/pressure from one chamber to the other. A shaft attached to and extending from the piston is attached to an appropriately sized mechanical boundary mechanism that communicates force to the shaft of a hydraulic cylinder, also divided into two chambers by a piston. In one embodiment, the active area of the piston of the hydraulic cylinder is smaller than the area of the pneumatic piston, resulting in an intensification of pressure (i.e., the ratio of the pressure in the chamber undergoing compression in the hydraulic cylinder to the pressure in the chamber undergoing expansion in the pneumatic cylinder) proportional to the difference in piston areas. The hydraulic fluid pressurized in the hydraulic cylinder may be used to turn a hydraulic motor/pump, either fixed-displacement or variable-displacement, whose shaft may be affixed to that of a rotary electric motor/generator in order to produce electricity. Heat-transfer subsystems, such as those described above, may be combined with these compressed-gas energy storage systems to expand/compress the gas substantially isothermally to achieve maximum efficiency.

[0265] The systems and methods described with respect to FIGS. 32-44 generally operate on a similar principle of transferring mechanical energy to or from one or more pneumatic cylinder assemblies using a mechanical boundary mechanism to mechanically couple the one or more cylinder assemblies to electrical machines. In some embodiments, the linear motion produced by the one or more cylinder assemblies is translated to the mover of a linear electrical machine (motor/generator) by a suitable linkage, generating electricity. In other embodiments, the linear motion produced by the one or more cylinder assemblies is converted to rotary motion by a crankshaft assembly and may be mechanically transmitted therefrom to a rotary electrical machine (motor/generator), generating electricity. In various embodiments, energy may be transferred to, rather than from, the one or more pneumatic cylinder assemblies by suitable operation of the electrical and other components of such compressed-gas energy storage systems. Heat-transfer subsystems, such as those described above, may be combined with these compressed-gas energy storage systems to expand/compress the gas substantially isothermally to achieve maximum efficiency.
FIGS. 29A and 29B are schematic diagrams of a system for using compressed gas to operate two series-connected, double-acting pneumatic cylinders coupled to a single double-acting hydraulic cylinder to drive a hydraulic motor/generator to produce electricity (i.e., gas expansion). If the motor/generator is operated as a motor rather than as a generator, the identical mechanism may employ electricity to produce pressurized stored gas (i.e., gas compression). FIG. 29A depicts the system in a first phase of operation and FIG. 29B depicts the system in a second phase of operation, where the high- and low-pressure sides of the pneumatic cylinders are reversed and the direction of hydraulic motor shaft motion is reversed, as discussed in greater detail hereinbelow.

Generally, the expansion of the gas occurs in multiple stages, using the low- and high-pressure pneumatic cylinders. For example, in the case of two pneumatic cylinders, as shown in FIG. 29A, high-pressure gas is expanded in the high-pressure pneumatic cylinder from a maximum pressure (e.g., 3000 psi) to some mid-pressure (e.g., 300 psi); then this mid-pressure gas is further expanded (e.g., 300 psi to 30 psi) in the separate low-pressure cylinder. These two stages are coupled to the common mechanical boundary mechanism that communicates force to the shaft of the hydraulic cylinder. When each of the two pneumatic pistons reaches the limit of its range of motion, valves or other mechanisms may be adjusted to direct higher-pressure gas to, and vent lower-pressure gas from, the cylinder’s two chambers so as to produce piston motion in the opposite direction. In double-acting devices of this type, there is no withdrawal stroke or unpumped stroke, i.e., the stroke is powered in both directions.

The chambers of the hydraulic cylinder being driven by the pneumatic cylinders may be similarly adjusted by valves or other mechanisms to produce pressurized hydraulic fluid during the return stroke. Moreover, check valves or other mechanisms may be arranged so that regardless of which chamber of the hydraulic cylinder is producing pressurized fluid, a hydraulic motor/pump is driven in the same direction of rotation by that fluid. The rotating hydraulic motor/pump and electrical motor/generator in such a system do not reverse their direction of rotation when piston motion reverses, so that with the addition of a short-term-energy-storage device, such as a flywheel, the resulting system may be made to generate electricity continuously (i.e., without interruption during piston reversal).

As shown in FIG. 29A, the system 2900 consists of a first pneumatic cylinder 2901 divided into two chambers 2902, 2903 by a piston 2904. The cylinder 2901, which is shown in a horizontal orientation in this illustrative embodiment, may be arbitrarily oriented, has one or more gas circulation ports 2905 that are connected via piping 2906 and valves 2907, 2908 to a compressed-gas reservoir or storage system 2909. The pneumatic cylinder 2901 is connected via piping 2910, 2911 and valves 2912, 2913 to a second pneumatic cylinder 2914 operating at a lower pressure than the first. Both cylinders 2901, 2914 are double-acting and are attached in series (pneumatically) and in parallel (mechanically). Series attachment of the two cylinders 2901, 2914 means that gas from the lower-pressure chamber of the high-pressure cylinder 2901 is directed to the higher-pressure chamber of the low-pressure cylinder 2914.

Pressurized gas from the reservoir 2909 drives the piston 2904 of the double-acting high-pressure cylinder 2901. In the state of operation shown in FIG. 29A, intermediate-pressure gas from the lower-pressure chamber 2903 of the high-pressure cylinder 2901 is conveyed through a valve 2912 to the higher-pressure chamber 2915 of the lower-pressure cylinder 2914. Gas is conveyed from the lower-pressure chamber 2916 of the lower-pressure cylinder 2914 through a valve 2917 to a vent 2918. One function of this arrangement is to reduce the range of pressures over which the cylinders jointly operate.

The piston shafts 2919, 2920 of the two cylinders 2914, 2901 act jointly to move the mechanical boundary mechanism 2921 in the direction indicated by the arrows 2922. The mechanical boundary mechanism 2921 is also connected to the piston shaft 2923 of the hydraulic cylinder 2924. The piston 2925 of the hydraulic cylinder 2924, impelled by the mechanical boundary mechanism 2921, compresses hydraulic fluid in the chamber 2926. This pressurized hydraulic fluid is conveyed through piping 2927 to an arrangement of check valves 2928 that allows the fluid to flow in one direction (shown by the arrows) through a hydraulic motor/pump, either fixed-displacement or variable-displacement, whose shaft drives an electric motor/generator. For convenience, the combination of hydraulic pump/motor and electric motor/generator is shown as a single hydraulic power unit 2929. Hydraulic fluid at lower pressure is conducted from the output of the hydraulic motor/pump 2929 to the lower-pressure chamber 2930 of the hydraulic cylinder 2924 through piping 2933 and a hydraulic circulation port 2931.

Reference is now made to FIG. 29B, which depicts the system 2900 of FIG. 29A in a second operating state, where valves 2907, 2913, and 2932 are open and valves 2908, 2912, and 2917 are closed. In this state, gas flows from the high-pressure reservoir 2909 through valve 2907 into chamber 2903 of the high-pressure pneumatic cylinder 2901. Lower-pressure gas is vented from the other chamber 2902 via valve 2913 to chamber 2916 of the lower-pressure pneumatic cylinder 2914. The piston shafts 2919, 2920 of the two cylinders act jointly to move the mechanical boundary mechanism 2921 in the direction indicated by the arrow 2922. The mechanical boundary mechanism 2921 translates the movement of shafts 2919, 2920 to the piston shaft 2923 of the hydraulic cylinder 2924. The piston 2925 of the hydraulic cylinder 2924, impelled by the mechanical boundary mechanism 2921, compresses hydraulic fluid in the chamber 2930. This pressurized hydraulic fluid is conveyed through piping 2933 to the aforementioned arrangement of check valves 2928 and the hydraulic power unit 2929. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit 2929 to the lower-pressure chamber 2926 of the hydraulic cylinder 2924 through a hydraulic circulation port 2935.

As shown in FIGS. 29A and 29B, the stroke volumes of the two chambers of the hydraulic cylinder 2924 differ by the volume of the shaft 2923. The resulting imbalance in fluid volumes expelled from the cylinder 2924 during the two stroke directions shown in FIGS. 29A and 29B may be corrected either by a pump (not shown) or by extending the shaft 2923 through the entire length of both chambers 2926, 2930 of the cylinder 2924, so that the two stroke volumes are equal.

As previously discussed, the efficiency of the various energy storage and recovery systems described herein can be increased by using a heat-transfer subsystem. Accordingly, the system 2900 shown in FIGS. 29A and 29B may include a heat-transfer subsystem 2950 similar to those described above. Generally, the heat transfer subsystem 2950 includes a
fluid circulator 2952 and a heat exchanger 2954. The subsystem 2950 also includes two directional control valves 2956, 2958 that selectively connect the subsystem 2950 to one or more chambers of the pneumatic cylinders 2901, 2914 via pairs of gas ports on the cylinders 2901, 2914 identified as A and B. For example, the valves 2956, 2958 may be positioned to place the subsystem 2950 in fluidic communication with chamber 2903 during gas expansion therein, so as to thermally condition the gas expanding in the chamber 2903. The gas may be thermally conditioned by any of the previously described methods, for example, the gas from the selected chamber may be circulated through the heat exchanger. Alternatively, a heat-exchange liquid may be circulated through the selected gas chamber and any of the previously described spray arrangements for heat exchange may be used. During expansion (or compression), a heat-exchange liquid (e.g., water) may be drawn from a reservoir (not shown, but similar to those described above with respect to FIG. 22) by the circulator 2954, circulated through a liquid-to-liquid version of the heat exchanger 2954, which may be a shell-and-tube type with an input 2962 and an output 2960 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0275] FIGS. 30A-30D depict an alternative embodiment of the system of FIG. 29 modified to have a single pneumatic cylinder and two hydraulic cylinders. A decreased range of hydraulic pressures, with consequent increased motor/pump and motor/generator efficiencies, may be obtained by using two or more hydraulic cylinders. As shown, these two cylinders are connected to the aforementioned mechanical boundary mechanism for communicating force with the pneumatic cylinder. The chambers of the two hydraulic cylinders are attached to valves, lines, and other mechanisms in such a manner that either cylinder can, with appropriate adjustments, be set to present no resistance as its shaft is moved (i.e., compress no fluid).

[0276] FIG. 30A depicts the system in a state of operation where both hydraulic pistons are compressing hydraulic fluid. One effect of this arrangement is to decrease the range of hydraulic pressures delivered to the hydraulic motor as the force produced by the pressurized gas in the pneumatic cylinder decreases with expansion and as the pressure of the gas stored in the reservoir decreases. FIG. 30B depicts the system in a phase of operation wherein only one of the hydraulic cylinders is compressing hydraulic fluid. FIG. 30C depicts the system in a phase of operation where both high- and low-pressure sides of the hydraulic cylinders are reversed along with the direction of shafts and only the smaller-bore hydraulic cylinder is compressing hydraulic fluid. FIG. 30D depicts the system in a phase of operation similar to FIG. 30C, but with both hydraulic cylinders compressing hydraulic fluid.

[0277] The system 3000 shown in FIG. 30A is similar to system 2900 described above and includes a single double-acting pneumatic cylinder 3001 and two double-acting hydraulic cylinders 3024a, 3024b, where one hydraulic cylinder 3024a has a larger bore than the other cylinder 3024b. In the state of operation shown, pressurized gas from the reservoir 3009 enters one chamber 3002 of the pneumatic cylinder 3001 and drives a piston 3005 slidably disposed in the pneumatic cylinder 3001. Low-pressure gas from the other chamber 3003 of the pneumatic cylinder 3001 is conveyed through a valve 3007 to a vent 3008. A shaft 3019 extending from the piston 3005 disposed in the pneumatic cylinder 3001 moves a mechanically coupled mechanical boundary mechanism 3021 in the direction indicated by the arrow 3022. The mechanical boundary mechanism 3021 is also connected to the piston shafts 3023a, 3023b of the double-acting hydraulic cylinders 3024a, 3024b.

[0278] In the current state of operation shown, valves 3014a and 3014b permit fluid to flow to hydraulic power unit 3029. Pressurized fluid from both cylinders 3024a, 3024b is conducted via piping 3015 to an arrangement of check valves 3028 and a hydraulic pump/motor connected to a motor/generator, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic motor/pump to the lower-pressure chambers 3016a, 3016b of the hydraulic cylinders 3024a, 3024b. The fluid in the high-pressure chambers 3026a, 3026b of the two hydraulic cylinders 3024a, 3024b is at a single pressure, and the fluid in the low-pressure chambers 3016a, 3016b is also at a single pressure. In effect, the two cylinders 3024a, 3024b act as a single cylinder whose piston area is the sum of the piston areas of the two cylinders and whose operating pressure, for a given driving force from the pneumatic piston 3001, is proportionately lower than that of either hydraulic cylinder acting alone.

[0279] Reference is now made to FIG. 30B, which shows another state of operation of the system 3000 of FIG. 30A. The action of the pneumatic cylinder 3001 and the direction of motion of all pistons is the same as in FIG. 30A. In the state of operation shown, formerly closed valve 3033 is opened to permit fluid to flow freely between the two chambers 3016a, 3026a of the larger-bore hydraulic cylinder 3024a, thereby presenting minimal resistance to the motion of its piston 3025a. Pressurized fluid from the smaller-bore cylinder 3024b is conducted via piping 3015 to the aforementioned arrangement of check valves 3028 and the hydraulic power unit 3029, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit 3029 to the lower-pressure chamber 3016b of the smaller-bore hydraulic cylinder 3024b. In effect, the acting hydraulic cylinder 3024b, having a smaller piston area, provides a higher hydraulic pressure for a given force acting on the mechanically coupled boundary mechanism 3021 than in the state shown in FIG. 30A, where both hydraulic cylinders 3024a, 3024b were acting, with a larger effective piston area. Through valve actuators disabling one of the hydraulic cylinders, a narrowed hydraulic fluid pressure range is obtained.

[0280] Reference is now made to FIG. 30C, which shows another state of operation of the system 3000 of FIGS. 30A and 30B. In the state of operation shown, pressurized gas from the reservoir 3009 enters chamber 3003 of the pneumatic cylinder 3001, driving its piston 3005. Low-pressure gas from the other side 3002 of the pneumatic cylinder 3001 is conveyed through a valve 3035 to the vent 3008. The action of the mechanical boundary mechanism 3021 on the pistons 3023a, 3023b of the hydraulic cylinders 3024a, 3024b is in the opposite direction as that shown in FIG. 30B, as indicated by arrow 3022.

[0281] As in FIG. 30A, valves 3014a, 3014b are open and permit fluid to flow to the hydraulic power unit 3029. Pressurized fluid from both hydraulic cylinders 3024a, 3024b is conducted via piping 3015 to the aforementioned arrangement of check valves 3028 and the hydraulic power unit 3029, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit 3029 to the lower-pressure chambers 3026a, 3026b of the hydraulic cylinders 3024a, 3024b. The fluid in the high-pres-
pressure chambers 3016a, 3016b of the two hydraulic cylinders 3024a, 3024b is at a single pressure, and the fluid in the low-pressure chambers 3026a, 3026b is also at a single pressure. In effect, the two hydraulic cylinders 3024a, 3024b act as a single cylinder whose piston area is the sum of the piston areas of the two cylinders and whose operating pressure, for a given driving force from the pneumatic piston 3001, is proportionately lower than that of either hydraulic cylinder 3024a, 3024b acting alone.

Reference is now made to FIG. 30D, which shows another state of operation of the system 3000 of FIGS. 30A-30C. The action of the pneumatic cylinder 3001 and the direction of motion of all moving pistons is the same as in FIG. 30C. In the state of operation shown, formerly closed valve 3033 is opened to permit fluid to flow freely between the two chambers 3026a, 3016a of the larger bore hydraulic cylinder 3024a, thereby presenting minimal resistance to the motion of its piston 3025a. Pressurized fluid from the smaller-bore cylinder 3024b is conducted via piping 3015 to the aforementioned arrangement of check valves 3028 and the hydraulic power unit 3029, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic motor/pump to the lower-pressure chamber 3026b of the smaller-bore hydraulic cylinder 3024b. In effect, the acting hydraulic cylinder 3024b, having a smaller piston area, provides a higher hydraulic pressure for a given force than the state shown in FIG. 30C, where both cylinders were acting with a larger effective piston area. Through valve actuations disabling one of the hydraulic cylinders, a narrowed hydraulic fluid pressure range is obtained.

Additional valving may be added to cylinder 3024b such that it could be disabled to provide another effective hydraulic piston area (considering that 3024a and 3024b are not the same diameter cylinders) to somewhat further reduce the hydraulic fluid range for a given pneumatic pressure range. Likewise, additional hydraulic cylinders and valve arrangements may be added to substantially further reduce the hydraulic fluid range for a given pneumatic pressure range.

The operation of the exemplary system 3000 described above, where two or more hydraulic cylinders are driven by a single pneumatic cylinder, is as follows. Assuming that a quantity of high-pressure gas has been introduced into one chamber of that single pneumatic cylinder, as the gas begins to expand, moving the piston, force is communicated by the piston shaft and the mechanical boundary mechanism to the piston shafts of the two hydraulic cylinders. At any point during the expansion phase, the hydraulic pressure will be equal to the force divided by the acting hydraulic piston area. At the beginning of a stroke, when the gas in the pneumatic cylinder has only began to expand, it is producing a maximum force; this force (ignoring frictional losses) acts on the combined total piston area of the hydraulic cylinders, producing a certain hydraulic output pressure, HPmax.

As the gas in the pneumatic cylinder continues to expand, it exerts a decreasing force. Consequently, the pressure developed in the compression chamber of the active cylinders decreases. At a certain point in the process, the valves and other mechanisms attached to one of the hydraulic cylinders is adjusted so that fluid can flow freely between its two chambers and thus offer no resistance to the motion of the piston (again ignoring frictional losses). The effective piston area driven by the force developed by the pneumatic cylinder thus decreases from the piston area of both hydraulic cylinders to the piston area of one of the hydraulic cylinders. With this decrease of area comes an increase in output hydraulic pressure for a given force. If this switching point is chosen carefully, the hydraulic output pressure immediately after the switch returns to HPmax. For an example where two identical hydraulic cylinders are used, the switching pressure would be at the half pressure point.

As the gas in the pneumatic cylinder continues to expand, the pressure developed by the hydraulic cylinder decreases. As the pneumatic cylinder reaches the end of its stroke, the force developed is at a minimum and so is the hydraulic output pressure, HPmin. For an appropriately chosen ratio of hydraulic cylinder piston areas, the hydraulic pressure range HR=HPmax/HPmin achieved using two hydraulic cylinders will be the square root of the range HR achieved with a single hydraulic cylinder. The proof of this assertion is as follows.

Let a given output hydraulic pressure range HR, from high pressure HPmax, to low pressure HPmin, namely HR=HPmax/HPmin, be subdivided into two pressure ranges of equal magnitude HR/2. The first range is from HPmax down to some intermediate pressure HP1, and the second is from HP1 down to HPmin. Thus, HR=HR/2+HP1/HPmin. From this identity of ratios, HP1=HR/2*HPmin. Substituting for HP1 in HR=HPmax/HPmin, we obtain HR=HPmax/(HPmax+HPmin)*1/2. Since HPmax is determined (for a given maximum force developed by the pneumatic cylinder) by the combined piston areas of the two hydraulic cylinders (HA1+HA2), whereas HP1 is determined jointly by the choice of when (i.e., at what force level, as force declines) to deactivate the second cylinder and by the area of the single acting cylinder HA1, it is possible to choose the switching force point and HA1, so as to produce the desired intermediate output pressure HP1. It can be similarly shown that with appropriate cylinder sizing and choice of switching points, the addition of a third cylinder/stage will reduce the operating pressure range as the cube root, and so forth. In general, N appropriately sized cylinders may reduce an original operating pressure range HR, to HR1/N.

In addition, for a system using multiple pneumatic cylinders (i.e., dividing the air expansion into multiple stages), the hydraulic pressure range may be further reduced. For M appropriately sized pneumatic cylinders (i.e., pneumatic air stages) for a given expansion, the original pneumatic operating pressure range PR1 of a single stroke may be reduced to PR1/M. Since for a given hydraulic cylinder arrangement the output hydraulic pressure range is directly proportional to the pneumatic operating pressure range for each stroke, simultaneously combining M pneumatic cylinders with N hydraulic cylinders may realize a pressure range reduction to the 1/(N*M) power, that is, may reduce an original operating pressure range HR, to HR1/N*M.

Furthermore, the system 3000 shown in FIGS. 30A-30D may also include a heat transfer subsystem 3050 similar to those described above. Generally, the heat transfer subsystem 3050 includes a fluid circulator 3052 and a heat exchanger 3054. The subsystem 3050 also includes two directional control valves 3056, 3058 that selectively connect the subsystem 3050 to one or more chambers of the pneumatic cylinder 3001 via pairs of gas ports on the cylinder 3001 identified as A and B. For example, the valves 3056, 3058 may be positioned to place the subsystem 3050 in fluidic communication with chamber 3003 during gas expansion therein, so
as to thermally condition the gas expanding in the chamber 3003. The gas may be thermally conditioned by any of the previously described methods. For example, during expansion (or compression), a heat exchange liquid (e.g., water) may be drawn from a reservoir (not shown, but similar to those described above with respect to FIG. 22) by the circulator 3054, circulated through a liquid-to-liquid version of the heat exchanger 3054, which may be a shell and tube type with an input 3000 and an output 3062 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0291] FIGS. 31A-31C depict an alternative embodiment of the system of FIG. 30, where the two side-by-side hydraulic cylinders have been replaced by two telescoping hydraulic cylinders. The effect of this arrangement is to decrease the range of hydraulic pressures delivered to the hydraulic motor as the force produced by the pressurized gas in the pneumatic cylinder decreases with expansion and as the pressure of the gas stored in the reservoir decreases. FIG. 31A depicts the system in a phase of operation where only the outer, larger-bore hydraulic cylinder is compressing hydraulic fluid. FIG. 31B depicts the system in a phase of operation where the outer-cylinder piston has moved to its limit in the direction of motion and is no longer compressing hydraulic fluid and the inner, smaller-bore cylinder is compressing hydraulic fluid. FIG. 31C depicts the system in a phase of operation where the direction of the motion of the cylinders and motor are reversed; the inner, smaller-bore cylinder is acting as the shaft of the outer, larger-bore cylinder, and only the outer, larger-bore cylinder is compressing hydraulic fluid.

[0292] The system 3100 shown in FIG. 31A is similar to those described above and includes a single double-acting pneumatic cylinder 3101 and two double-acting hydraulic cylinders 3124a, 3124b, where one cylinder 3124b is telescopically disposed inside the other cylinder 3124a. In the state of operation shown, pressurized gas from the reservoir 3109 enters a chamber 3102 of the pneumatic cylinder 3101 and drives a piston 3105 slidably disposed with the pneumatic cylinder 3101. Low-pressure gas from the other chamber 3103 of the pneumatic cylinder 3101 is conveyed through a valve 3107 to a vent 3108. A shaft 3119 extending from the piston 3105 disposed in the pneumatic cylinder 3101 moves a mechanically coupled mechanical boundary mechanism 3121 in the direction indicated by the arrow 3122. The mechanical boundary mechanism 3121 is connected to the shaft 3123 of the hydraulic cylinder 3124a. The entire smaller bore cylinder 3124b acts as the shaft 3123 of the larger piston 3125a of the larger bore hydraulic cylinder 3124a; therefore, the mechanical boundary mechanism 3121 is coupled to hydraulic cylinder 3124a via its coupling to cylinder 3124b via shaft 3123.

[0293] In the state of operation shown, the entire smaller-bore cylinder 3124b acts as the shaft 3123 of the larger piston 3125a of the larger-bore hydraulic cylinder 3124a. The piston 3125a and smaller-bore cylinder 3124b (i.e., the shaft of the larger-bore hydraulic cylinder 3124a) are moved by the mechanical boundary mechanism 3121 in the direction indicated by the arrow 3122. Compressed hydraulic fluid from the higher-pressure chamber 3126a of the larger-bore cylinder 3124a passes through a valve 3120 to an arrangement of check valves 3128 and the hydraulic power unit 3129, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit through valve 3118 to the lower-pressure chamber 3116a of the hydraulic cylinder 3124a. In this state of operation, the piston 3125b of the smaller-bore cylinder 3124b remains stationary with respect thereto, and no fluid flows into or out of either of its chambers 3116b, 3126b.

[0294] Reference is now made to FIG. 31B, which shows another state of operation of the system 3100 of FIG. 31A. The action of the pneumatic cylinder 3101 and the direction of motion of the pistons is the same as in FIG. 31A. In FIG. 31B, the piston 3125a and smaller-bore cylinder 3124b (i.e., shaft of the larger-bore hydraulic cylinder 3124a) have moved to the extreme of their ranges of motion and have stopped moving relative to the larger-bore cylinder 3124a. Valves are now opened such that the piston 3125b of the smaller-bore cylinder 3124b acts. Pressurized fluid from the higher-pressure chamber 3126b of the smaller-bore cylinder 3124b is conducted through a valve 3133 to the aforementioned arrangement of check valves 3128 and the hydraulic power unit 3129, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit through valve 3135 to the lower-pressure chamber 3116b of the smaller-bore hydraulic cylinder 3124b. In this manner, the effective piston area on the hydraulic side is changed during the pneumatic expansion, narrowing the hydraulic pressure range for a given pneumatic pressure range.

[0295] Reference is now made to FIG. 31C, which shows another state of operation of the system 3100 of FIGS. 31A and 31B. The action of the pneumatic cylinder 3101 and the direction of motion of the pistons are the reverse of those shown in FIG. 31A. As in FIG. 31A, only the larger-bore hydraulic cylinder 3124a is active. The piston 3124b of the smaller bore cylinder 3124b remains stationary, and no fluid flows into or out of either of its chambers 3116b, 3126b. Compressed hydraulic fluid from the higher-pressure chamber 3116a of the larger-bore cylinder 3124a passes through a valve 3118 to the aforementioned arrangement of check valves 3128 and the hydraulic power unit 3129, thereby producing electricity. Hydraulic fluid at a lower pressure is conducted from the output of the hydraulic power unit through valve 3120 to the lower-pressure chamber 3126a of the larger-bore hydraulic cylinder 3124a.

[0296] Additionally, in yet another state of operation of the system 3100, the piston 3125a and the smaller-bore hydraulic cylinder 3124b (i.e., the shaft of the larger-bore hydraulic cylinder 3124a) have moved as far as they can in the direction indicated in FIG. 31C. Then, as in FIG. 31B, but in the opposite direction of motion, the smaller-bore hydraulic cylinder 3124b becomes the active cylinder driving the hydraulic power unit 3129.

[0297] It should also be clear that the principle of adding cylinders operating at progressively lower pressures in series (pneumatic and/or hydraulic) and in parallel or telescopic fashion (mechanically) may be carried out to two or more cylinders on the pneumatic side, the hydraulic side, or both.

[0298] Furthermore, the system 3100 shown in FIGS. 31A-31C may also include a heat-transfer subsystem 3150 similar to those described above. Generally, the heat-transfer subsystem 3150 includes a fluid circulator 3152 and a heat exchanger 3154. The subsystem 3150 also includes two directional control valves 3156, 3158 that selectively connect the subsystem 3150 to one or more chambers of the pneumatic cylinder 3101 via pairs of gas ports on the cylinder 3101 identified as A and B. For example, the valves 3156, 3158 may be positioned to place the subsystem 3150 in fluidic commu-
ication with chamber 3103 during gas expansion therein, so as to thermally condition the gas expanding in the chamber 3103. The gas may be thermally conditioned by any of the previously described methods. For example, during expansion (or compression), a heat-exchange liquid (e.g., water) may be drawn from a reservoir (not shown, but similar to those described above with respect to FIG. 22) by the circulator 3154, circulated through a liquid-to-liquid version of the heat exchanger 3154, which may be a shell-and-tube type with an input 3162 and an output 3160 from the shell running to an environmental heat exchanger or to a source of process heat, cold water, or other external heat exchange medium.

[0299] FIG. 32 illustrates the use of pressurized stored gas to operate a double-acting pneumatic cylinder and linear motor/generator to produce electricity according to another illustrative embodiment of the invention. If the linear motor/generator is operated as a motor rather than as a generator, the identical mechanism employs electricity to produce pressurized stored gas. FIG. 32 shows the mechanism being operated to produce electricity from stored pressurized gas.

[0300] The illustrated energy storage and recovery system 3200 includes a pneumatic cylinder 3202 divided into two compartments 3204 and 3206 by a piston (or other mechanism) 3208. The cylinder 3202, which is shown in a vertical orientation in FIG. 32 but may be arbitrarily oriented, has one or more gas circulation ports 3210 (one only of which is explicitly labeled), which are connected via piping 3212 to a compressed-gas reservoir 3214 and a vent 3216.

[0301] The piping 3212 connecting the compressed-gas reservoir 3214 to compartments 3204, 3206 of the cylinder 3202 passes through valves 3218, 3220. Compartments 3204, 3206 of the cylinder 3202 are connected to vent 3216 through valves 3222, 3224. A shaft 3226 coupled to the piston 3208 is coupled to one end of a translator 3228 of a linear electric motor/generator 3230.

[0302] System 3200 is shown in two operating states, namely (a) valves 3218 and 3222 open and valves 3220 and 3224 closed (shown in FIG. 32), and (b) valves 3218 and 3222 closed and valves 3220 and 3224 open (shown in FIG. 33). In state (a), high-pressure gas flows from the high-pressure reservoir 3214 through valve 3218 into compartment 3204 (where it is represented by stipping in FIG. 32). Lower-pressure gas is vented from the other compartment 3206 via valve 3222 and vent 3216. The result of the net force exerted on the piston 3208 by the pressure difference between the two compartments 3204, 3206 is the linear movement of piston 3208, piston shaft 3226, and translator 3228 in the direction indicated by the arrow 3232, causing an EMF to be induced in the stator of the linear motor/generator 3230. Power electronics are typically connected to the motor/generator 3230, and may be software-controlled. Such power electronics are conventional and not shown in FIG. 32 or in subsequent figures.

[0303] FIG. 33 shows system 3200 in a second operating state, the above-described state (b) in which valves 3220 and 3224 are open and valves 3218 and 3222 are closed. In this state, gas flows from the high-pressure reservoir 3214 through valve 3220 into compartment 3206. Lower-pressure gas is vented from the other compartment 3204 via valve 3222 and vent 3216. The result is the linear movement of piston 3208, piston shaft 3226, and translator 3228 in the direction indicated by the arrow 3302, causing an EMF to be induced in the stator of the linear motor/generator 3230.

[0304] FIG. 34 illustrates the addition of expeditied heat transfer by a liquid spray as described above. In this illustrative embodiment, a spray of droplets of liquid (indicated by arrows 3440) is introduced into either compartment (or both compartments) of the cylinder 3402 through perforated spray heads 3442, 3444, 3446, and 3448. The arrangement of spray heads shown is illustrative only; any suitable number and disposition of spray heads inside the cylinder 3402 may be employed. Liquid may be conveyed to spray heads 3446 and 3448 on the piston 3408 by a center-drilled channel 3450 in the piston shaft 3426, and may be conveyed to spray heads 3442 and 3444 by appropriate piping (not shown). Liquid flow to the spray heads 3442, 3444, 3446, and 3448 is typically controlled by an appropriate valve system (not shown).

[0305] FIG. 34 depicts system 3400 in the first of the two above-described operating states, where valves 3420 and 3424 are open and valves 3418 and 3422 are closed. In this state, gas flows from the high-pressure reservoir 3414 through valve 3420 into compartment 3406. Liquid at a temperature higher than that of the expanding gas is sprayed (indicated by arrows 3440) into compartment 3406 from spray heads 3442, 3444, and heat flows from the droplets 3440 to the gas. With suitable liquid temperature and flow rate, this arrangement enables substantially isothermal expansion of the gas in compartment 3406.

[0306] Lower-pressure gas is vented from the other compartment 3404 via valve 3424 and vent 3416, resulting in the linear movement of piston 3408, piston shaft 3426, and translator 3428 in the downward direction (arrow 3452). Since the expansion of the gas in compartment 3406 is substantially isothermal, more mechanical work is performed on the piston 3408 by the expanding gas and more electric energy is produced by the linear motor/generator 3430 than would be produced by adiabatic expansion in system 3400 of a like quantity of gas.

[0307] FIG. 35 shows the illustrative embodiment of FIG. 34 in a second operating state, where valves 3418 and 3422 are open and valves 3420 and 3424 are closed. In this state, gas flows from the high-pressure reservoir 3414 through valve 3418 into compartment 3404. Liquid at a temperature higher than that of the expanding gas is sprayed (indicated by arrows 3440) into compartment 3404 from spray heads 3446 and 3448, and heat flows from the droplets 3440 to the gas. With suitable liquid temperature and flow rate, this arrangement enables the substantially isothermal expansion of the gas in compartment 3404. Lower-pressure gas is vented from the other compartment 3406 via valve 3422 and vent 3416. The result is the linear movement of piston 3408, piston shaft 3426, and translator 3428 in the upward direction (arrow 3452), generating electricity.

[0308] System 3400 may be operated in reverse, in which case the linear motor/generator 3430 operates as an electric motor. The droplet spray mechanism is used to cool gas undergoing compression (achieving substantially isothermal compression) for delivery to the storage reservoir rather than to warm gas undergoing expansion from the reservoir. System 3400 may thus operate as a full-cycle energy storage system with high efficiency.

[0309] Additionally, the spray-head-based heat transfer illustrated in FIGS. 34 and 35 for vertically oriented cylinders may be replaced or augmented with a spray-rod heat transfer scheme for arbitrarily oriented cylinders as described above.

[0310] FIG. 36 is a schematic of system 3600 with the addition of expeditied heat transfer by a heat-exchange sub-system that includes an external heat exchanger 3602 connected by piping through valves 3604, 3606 to chamber 3608.
of the cylinder 3610 and by piping through valves 3612, 3614 to chamber 3616 of the cylinder 3610. A circulator 3618, which is preferably capable of pumping gas at high pressure (e.g., approximately 3,000 psi), drives gas through one side of the heat exchanger 3602, either continuously or in installments. An external system, not shown, drives a fluid 3620 (e.g., air, water, or another fluid) from an independent source through the other side of the heat exchanger.

The heat-exchange subsystem, which may include the heat exchanger 3602, circulator 3618, and associated piping, valves, and ports, transfers gas from either chamber 3608, 3616 (or both chambers) of the cylinder 3610 through the heat exchanger 3602. The subsystem has two operating states, either (a) valves 3612, 3614, 3622, and 3624 closed and valves 3604, 3606, 3626, and 3628 open, or (b) valves 3612, 3614, 3622, and 3624 open and valves 3604, 3606, 3626, and 3628 closed. FIG. 36 depicts state (a), in which high-pressure gas is conveyed from the reservoir 3628 to chamber 3608 of the cylinder 3610; meanwhile, low-pressure gas is exhausted from chamber 3616 via valve 3628 to the vent 3630. High-pressure gas is also circulated from chamber 3608 through valve 3604, circulator 3618, heat exchanger 3602, and valve 3606 (in that order) back to chamber 3608. Simultaneously, fluid 3620 warmer than the gas flowing through the heat exchanger 3602 is circulated through the other side of the heat exchanger 3602. With suitable temperature and flow rate of fluid 3620 through the external side of the heat exchanger 3602 and suitable flow rate of high-pressure gas through the cylinder side of the heat exchanger 3602, this arrangement enables the substantially isothermal expansion of the gas in compartment 3608.

In FIG. 36, the piston shaft 3632 and linear motor/generator translator 3634 are moving in the direction shown by the arrow 3636. It should be clear that, like the illustrative embodiment shown in FIG. 32, the embodiment shown in FIG. 36 has a second operating state (not shown), defined by the second of the two above-described valve arrangements (“state (b)” above), in which the direction of piston/translator motion is reversed. Moreover, this identical mechanism may clearly be operated in reverse—in that mode (not shown), the linear motor/generator 3638 operates as an electric motor and the heat exchanger 3602 cools gas undergoing compression (achieving substantially isothermal compression) for delivery to the storage reservoir 3628 rather than warming gas undergoing expansion. Thus, system 3600 may operate as a full-cycle energy storage system with high efficiency.

FIG. 37 depicts a system 3700 that includes a second pneumatic cylinder 3702 operating at a pressure lower than that of a first cylinder 3704. Both cylinders 3702, 3704 are, in this embodiment, double-acting. They are connected in series (pneumatically) and in line (mechanically). Pressurized gas from the reservoir 3706 drives the piston 3708 of the double-acting high-pressure cylinder 3704. Series attachment of the two cylinders directs gas from the lower-pressure compartment 3710 of the high-pressure cylinder 3704 to the higher-pressure compartment 3712 of the low-pressure cylinder 3702. In the operating state depicted in FIG. 37, gas from the lower-pressure side 3714 of the low-pressure cylinder 3702 exits through vent 3716. Through their common piston shaft 3718, the two cylinders act jointly to move the translator 3720 of the linear motor/generator 3722. This arrangement reduces the range of pressures over which the cylinders jointly operate, as described above.

[0314] System 3700 is shown in two operating states, (a) valves 3724, 3726, and 3728 closed and valves 3730, 3732, and 3734 are open (depicted in FIG. 37), and (b) valves 3724, 3726, and 3728 open and valves 3730, 3732, and 3734 closed (depicted in FIG. 38). FIG. 37 depicts state (a), in which gas flows from the high-pressure reservoir 3706 through valve 3730 into compartment 3736 of the high-pressure cylinder 3704. Intermediate-pressure gas (indicated by stippled areas in the figure) is directed from compartment 3710 of the high-pressure cylinder 3704 by piping through valve 3732 to compartment 3712 of the low-pressure cylinder 3702. The force of this intermediate-pressure gas on the piston 3738 acts in the same direction (i.e., in the direction indicated by the arrow 3740) as that of the high-pressure gas in compartment 3736 of the high-pressure cylinder 3704. The cylinders thus act jointly to move their common piston shaft 3718 and the translator 3720 of the linear motor/generator 3722 in the direction indicated by arrow 3740, generating electricity during the stroke. Low-pressure gas is vented from the low-pressure cylinder 3702 through the vent 3716 via valve 3734.

[0315] FIG. 38 depicts state (b) of system 3700. Valves 3724, 3726, and 3728 are open and valves 3730, 3732, and 3734 are closed. In this state, gas flows from the high-pressure reservoir 3706 through valve 3724 into compartment 3710 of the high-pressure cylinder 3704. Intermediate-pressure gas is directed from the other compartment 3736 of the high-pressure cylinder 3704 by piping through valve 3726 to compartment 3714 of the low-pressure cylinder 3702. The force of this intermediate-pressure gas on the piston 3738 acts in the same direction (i.e., in direction indicated by the arrow 3742) as that of the high-pressure gas in compartment 3710 of the high-pressure cylinder 3704. The cylinders thus act jointly to move the common piston shaft 3718 and the translator 3720 of the linear motor/generator 3722 in the direction indicated by arrow 3742, generating electricity during the stroke, which is in the direction opposite to that shown in FIG. 37. Low-pressure gas is vented from the low-pressure cylinder 3702 through the vent 3716 via valve 3728.

[0316] The spray arrangement for heat exchange shown in FIGS. 35 and 38 or, alternatively (or in addition to), the external heat-exchanger arrangement shown in FIG. 36 (or another heat-exchange mechanism) may be straightforwardly adapted to the system 3700 of FIGS. 37 and 38, enabling substantially isothermal expansion of the gas in the high-pressure reservoir 3706. Moreover, system 3700 may be operated as a compressor (not shown) rather than as a generator. Finally, the principle of adding cylinders operating at progressively lower pressures in series (pneumatic) and in line (mechanically) may involve three or more cylinders rather than merely two cylinders as shown in the illustrative embodiment of FIGS. 37 and 38.

[0317] FIG. 39 depicts an energy storage and recovery system 3900 with a first pneumatic cylinder 3902 and a second pneumatic cylinder 3904 operating at a lower pressure than the first cylinder 3902. Both cylinders 3902, 3904 are double-acting. They are attached in series (pneumatically) and in parallel (mechanically). Pressurized gas from the reservoir 3906 drives the piston 3908 of the double-acting high-pressure cylinder 3902. Series pneumatic attachment of the two cylinders is as detailed above with reference to FIGS. 37 and 38. Gas from the lower-pressure side of the low-pressure cylinder 3904 is directed through valve 3932 to vent 3910. Through a common beam (mechanical boundary mechanism) 3912 coupled to the piston shafts 3914, 3916 of the cylinders.
3902, 3904, the cylinders 3902, 3904 act jointly to move the translator 3918 of the linear motor/generator 3920. This arrangement reduces the operating range of cylinder pressures as compared to a similar arrangement employing only one cylinder.

[0318] System 3900 is shown in two operating states, (a) valves 3922, 3924, and 3926 closed and valves 3928, 3930, and 3932 open (shown in FIG. 39), and (b) valves 3922, 3924, and 3926 open and valves 3928, 3930, and 3932 closed (shown in FIG. 40). FIG. 39 depicts state (a), in which gas flows from the high-pressure reservoir 3906 through valve 3928 into compartment 3934 of the high-pressure cylinder 3902. Intermediate-pressure gas (depicted by stippled areas) is directed from the other compartment 3936 of the high-pressure cylinder 3902 by piping through valve 3930 to compartment 3938 of the low-pressure cylinder 3904. The force of this intermediate-pressure gas on the piston 3940 acts in the same direction (i.e., in direction indicated by the arrow 3942) as the high-pressure gas in compartment 3934 of the high-pressure cylinder 3902. The cylinders thus act jointly to move the common beam 3912 and the translator 3918 of the linear motor/generator 3920 in the direction indicated by arrow 3942, generating electricity during the stroke. Low-pressure gas is vented from the low-pressure cylinder 3904 through the vent 3910 via valve 3932.

[0319] FIG. 40 shows the second operating state (b) of system 3900, i.e., valves 3922, 3924, and 3926 are open and valves 3928, 3930, and 3932 are closed. In this state, gas flows from the high-pressure reservoir 3906 through valve 3922 into compartment 3936 of the high-pressure cylinder 3902. Intermediate-pressure gas is directed from compartment 3934 of the high-pressure cylinder 3902 by piping through valve 3924 to compartment 3944 of the low-pressure cylinder 3904. The force of this intermediate-pressure gas on the piston 3940 acts in the same direction (i.e., in direction indicated by the arrow 3942) as that exerted on piston 3908 by the high-pressure gas in compartment 3936 of the high-pressure cylinder 3902. The cylinders 3902, 3904 thus act jointly to move the common beam 3912 and the translator 3918 of the linear motor/generator 3920 in the direction indicated, generating electricity during the stroke, which is in the direction opposite to that of the operating state shown in FIG. 39. Low-pressure gas is vented from the low-pressure cylinder 3904 through the vent 3910 via valve 3932.

[0320] The cryogenic arrangement for heat exchange shown in FIGS. 34 and 35 or, alternatively or in combination, the external heat-exchanger arrangement shown in FIG. 36 may be straightforwardly adapted to the pneumatic cylinders of system 3900, enabling substantially isothermal expansion of the gas in the high-pressure reservoir 3906. Moreover, this exemplary embodiment may be operated as a compressor (not shown) rather than a generator (shown). Finally, the principle of adding cylinders operating at progressively lower pressures in series (pneumatic) and in parallel (mechanically) may be extended to three or more cylinders.

[0321] FIG. 41 is a schematic diagram of a system 4100 for achieving substantially isothermal compression and expansion of a gas for energy storage and recovery using a pair of pneumatic cylinders (shown in partial cross-section) with integrated heat exchange. In this illustrative embodiment, the mechanism linking the cylinders converts reciprocating motion of the cylinders to rotary motion. Depicted are a pair of double-acting pneumatic cylinders with appropriate valving and mechanical linkages; however, any number of single- or double-acting pneumatic cylinders, or any number of groups of single- or double-acting pneumatic cylinders, where each group contains two or more cylinders, may be employed in such a system. Likewise, a wrist-pin connecting-rod type crankshaft arrangement is depicted in FIG. 41, but other mechanical means for converting reciprocating motion to rotary motion are contemplated and considered within the scope of the invention.

[0322] In various embodiments, the system 4100 includes a first pneumatic cylinder 4102 divided into two compartments 4104, 4106 by a piston 4108. The cylinder 4102, which is shown in a vertical orientation in this illustrative embodiment, has one or more ports 4110 (only one of which is explicitly labeled) that are connected via piping 4112 to a compressed-gas reservoir 4114.

[0323] The system 4100 as shown in FIG. 41 includes a second pneumatic cylinder 4116 operating at a lower pressure than the first cylinder 4102. The second pneumatic cylinder 4116 is divided into two compartments 4118, 4120 by a piston 4122 and includes one or more ports 4110 (only one of which is explicitly labeled). Both cylinders 4102, 4116 are double-acting in this illustrative embodiment. They are attached in series (pneumatically); thus, after expansion in one compartment of the high-pressure cylinder 4102, the mid-pressure gas (depicted by stippled areas) is directed for further expansion to a compartment of the low-pressure cylinder 4116.

[0324] In the state of operation depicted in FIG. 41, pressurized gas (e.g., approximately 3,000 psig) from the reservoir 4114 passes through a valve 4126 and drives the piston 4108 of the double-acting high-pressure cylinder 4102 in the downward direction as shown by the arrow 4128. Gas that has already expanded to a mid-pressure (e.g., approximately 250 psig) in the lower chamber 4104 of the high-pressure cylinder 4102 is directed through a valve 4130 to the lower chamber 4118 of the larger-volume, low-pressure cylinder 4116, where it is further expanded. This gas exerts an upward force on the piston 4122 with resulting upward motion of the piston 4122 and shaft 4130 as indicated by the arrow 4132. Gas within the upper chamber 4120 of cylinder 4116 has already been expanded to atmospheric pressure and is vented to the atmosphere through valve 4134 and vent 4136. One function of this two-cylinder arrangement is to reduce the range of pressures and forces over which each cylinder operates, as described earlier.

[0325] The piston shaft 4138 of the high-pressure cylinder 4102 is connected by a hinged connecting rod 4140 and crank 4146 or other suitable linkage to a crankshaft 4142. The piston shaft 4130 of the low-pressure cylinder 4116 is connected by a hinged connecting rod 4144 and crank 4148 or other suitable linkage to the same crankshaft 4142. The motion of the piston shafts 4130, 4138 is shown as rectilinear, whereas the linkages 4140, 4144 have partial rotational freedom orthogonal to the axis of the crankshaft 4142.

[0326] In the state of operation shown in FIG. 41, the piston shaft 4138 and linkage 4140 are drawing the crank 4146 in a downward direction (as indicated by arrow 4128) while the piston shaft 4130 and linkage 4144 are pushing the crank 4148 in an upward direction (as indicated by arrow 4132). The two cylinders 4102, 4116 thus act jointly to rotate the crankshaft 4142. In FIG. 41, the crankshaft 4142 is shown driving an optional transmission mechanism 4150 whose output shaft 4152 rotates at a higher rate than the crankshaft 4142. Transmission mechanism 4150 may be, e.g., a gear box or a CVT (as shown in FIG. 41). The output shaft 4152 of
transmission mechanism 4150 drives an electric motor/generator 4154 that generates electricity. In some embodiments, crankshaft 4142 is directly connected to and drives motor/generator 4154.

[0327] Power electronics may be connected to the motor/generator 4154 (and may be software-controlled), thus providing control over air expansion and/or compression rates. These power electronics are not shown, but are well-known to a person of ordinary skill in the art.

[0328] In the embodiment of the invention depicted in FIG. 41, liquid sprays may be introduced into any of the compartments of the cylinders 4102, 4116. In both cylinders 4102, 4116, the liquid spray enables expedited heat transfer to (or from) the gas being expanded (or compressed) in the cylinder, as detailed above. Sprays 4156, 4158 of droplets of liquid may be introduced into the compartments of the high-pressure cylinder 4102 through perforated spray heads 4160, 4162. The liquid spray in chamber 4106 of cylinder 4102 is indicated by dashed lines 4158, and the liquid spray in chamber 4104 of cylinder 4102 is indicated by dashed lines 4156. Water (or other appropriate heat-transfer fluid) is conveyed to the spray heads 4162 by appropriate piping (not shown). Fluid may be conveyed to spray head 4160 on the piston 4108 by various methods; in one embodiment, the fluid is conveyed through a center-drilled channel (not shown) in the piston rod 4138, as described in U.S. patent application Ser. No. 12/690,513 (the ’513 application), the disclosure of which is hereby incorporated by reference herein in its entirety. Liquid flow to both sets of spray heads is typically controlled by an appropriate valve arrangement (not shown). Liquid may be removed from the cylinders through suitable ports (not shown).

[0329] The heat-transfer liquid sprays 4156, 4158 may warm gas as it expands, enabling substantially isothermal expansion of the gas. If the gas is being compressed, the sprays may cool the gas, enabling substantial isothermal compression. A liquid spray may be introduced by similar means into the compartments of the low-pressure cylinder 4116 through perforated spray heads 4164, 4166. Liquid spray in chamber 4118 of cylinder 4116 is indicated by dashed lines 4168.

[0330] In the operating state shown in FIG. 41, liquid spray transfers heat to (or from) the gas undergoing expansion (or compression) in chambers 4104, 4106, and 4118, enabling a substantially isothermal process. Spray may be introduced in chamber 4120, but this is not shown as little or no expansion is occurring in that compartment during venting. The arrangement of spray heads shown in FIG. 41 is illustrative only, as any number and disposition of spray heads and/or spray rods inside the cylinders 4102, 4116 are contemplated as embodiments of the present invention.

[0331] FIG. 42 depicts system 4100 in a second operating state, in which the piston shafts 4130, 4138 of the two pneumatic cylinders 4102, 4116 have directions of motion opposite to those shown in FIG. 41, and the crankshaft 4142 continues to rotate in the same sense as in FIG. 41. In FIG. 42, valves 4124, 4130, and 4134 are closed and valves 4126, 4170, and 4172 are open. Gas flows from the high-pressure reservoir 4114 through valve 4126 into compartment 4104 of the high-pressure cylinder 4102, where it applies an upward force on piston 4108. Mid-pressure gas in chamber 4106 of the high-pressure cylinder 4102 is directed through valve 4170 to the upper chamber 4120 of the low-pressure cylinder 4116, where it is further expanded. The expanding gas exerts a downward force on the piston 4122 with resulting motion of the piston 4122 and shaft 4130 as indicated by the arrow 4132. Gas within the lower chamber 4118 of cylinder 4116 is already expanded to approximately atmospheric pressure and is being vented to the atmosphere through valve 4172 and vent 4136. In FIG. 42, gas expanding in chambers 4104, 4106, and 4120 exchanges heat with liquid sprays 4156, 4158, and 4174 (depicted as dashed lines), respectively, to keep the gas at approximately constant temperature.

[0332] The spray-heading heat-transfer arrangement shown in FIGS. 41 and 42 for vertically oriented cylinders may be replaced or augmented with a spray-rod heat-transfer scheme for arbitrarily oriented cylinders (as mentioned above). Additionally, the systems shown may be implemented with an external gas heat exchanger instead of (or in addition to) liquid sprays, as described above. An external gas heat exchanger also enables expedited heat transfer to or from the gas being expanded (or compressed) in the cylinders. With an external heat exchanger, the cylinders may be arbitrarily oriented.

[0333] In all operating states, the two cylinders 4102, 4116 in FIGS. 41 and 42 are preferably 180° out of phase. For example, whenever the piston 4108 of the high-pressure cylinder 4102 has reached its uppermost point of motion, the piston 4122 of the low-pressure cylinder 4116 has reached its nethermost point of motion. Similarly, whenever the piston 4122 of the low-pressure cylinder 4116 has reached its uppermost point of motion, the piston 4108 of the high-pressure cylinder 4102 has reached its nethermost point of motion. Further, when the two pistons 4108, 4122 are at the midpoints of their respective strokes, they are moving in opposite directions. This constant phase relationship is maintained by the linkage of the piston rods 4130, 4138 to the two cranks 4146, 4148, which are affixed to the crankshaft 4142 so that they lie in a single plane on opposite sides of the crankshaft 4142 (i.e., they are physically 180° apart). At the moments depicted in FIG. 41 and FIG. 42, the plane in which the two cranks 4146, 4148 lie are coincident with the planes of the figures.

[0334] Reference is now made to FIG. 43, which is a schematic depiction of a single pneumatic cylinder assembly 4300 and a mechanical linkage that may be used to connect the rod or shaft 4302 of the cylinder assembly to a crankshaft 4304. Two orthogonal views of the linkage and piston are shown in partial cross section in FIG. 43. In the illustrative embodiment, the linkage includes a crosshead 4306 mounted on the end of the rod 4302. The crosshead 4306 is slidably disposed within a distance piece 4308 that constrains the lateral motion of the crosshead 4306. The distance piece 4308 may also fix the distance between the top of the cylinder 4310 and a housing (not depicted) of the crankshaft 4304.

[0335] A connecting pin 4312 is mounted on the crosshead 4306 and is free to rotate around its own long axis. A connecting rod 4314 is attached to the connecting pin 4312. The other end of the connecting rod 4314 is attached to a collar-and-pin linkage 4316 mounted on a crank 4318 affixed to the crankshaft 4304. A collar-and-pin linkage 4314 is illustrated in FIG. 43, but other mechanisms for attaching the connecting rod 4314 to the crank 4318 are contemplated within embodiments of the invention. Moreover, either or both ends of the crankshaft 4316 may be extended to attach to further cranks (not shown) interacting with other cylinders or may be linked to a gear box (or other transmission mechanism such as a CVT), motor/generator, bywheel, brake, or other device(s).
The linkage between cylinder rod 4302 and crankshaft 4316 depicted in FIG. 43 is herein termed a “crosshead linkage,” which transforms substantially rectilinear mechanical force acting along the cylinder rod 4302 into torque or rotational force acting on the crankshaft 4316. Forces transmitted by the connecting rod 4302 and not acting along the axis of the cylinder rod 4316 (e.g., lateral forces) act on the connecting pin 4312, crosshead 4306, and distance piece 4308 but not on the cylinder rod 4302. Thus, advantageously, any gaskets or seals (not depicted) through which the cylinder rod 4302 slides while passing into cylinder 4310 are subject to reduced stress, enabling the use of less durable gaskets or seals, increasing the lifespan of the employed gaskets or seals, or both.

FIGS. 44A and 44B are schematics of a system 4400 for substantially isothermal compression and expansion of a gas for energy storage and recovery using multiple pairs 4402 of pneumatic cylinders with integrated heat exchange. Stora-ge of compressed air, venting of low-pressure air, and other components of the system 4400 are not depicted in FIGS. 44A and 44B, but are consistent with the descriptions of similar systems herein. Each rectangle in FIGS. 44A and 44B labeled PAIR 1, PAIR 2, etc. represents a pair of pneumatic cylinders (with appropriate valving and linkages, not explicitly depicted) similar to the pair of cylinders depicted in FIG. 41. Each cylinder pair 4402 is a fluidly linked pneumatic cylinders communicating with a common crankshaft 4404 by a mechanism that may resemble those shown in FIG. 41 or FIG. 43 (or may have some other form). The crankshaft 4404 may communicate (with or without an intervening transmission mechanism) with an electric motor/generator 4406 that may thus generate electricity.

In various embodiments, within each of the cylinder pairs 4402 shown in FIGS. 44A and 44B, the high-pressure cylinder (not explicitly depicted) and the low-pressure cylinder (not explicitly depicted) are 180° out of phase with each other, as depicted and described for the two cylinders 4102, 4116 in FIG. 41. For simplicity, the phase of each cylinder pair 4402 is identified herein with the phase of its high-pressure cylinder. In the embodiment depicted in FIG. 44A, which includes six cylinder pairs 4402, the phase of PAIR 1 is arbitrarily denoted 0°. The phase of PAIR 2 is 120°, the phase of PAIR 3 is 240°, the phase of PAIR 4 is 360° (equivalent to 0°), the phase of PAIR 5 is 120°, and the phase of PAIR 6 is 240°. There are thus three sets of cylinder pairs 4402 that are in phase, namely PAIR 1 and PAIR 4 (0°), PAIR 2 and PAIR 5 (120°), and PAIR 3 and PAIR 6 (240°). These phase relationships are set and maintained by the affixation to the crankshaft 4404 at appropriate angles of the cranks (not explicitly depicted) linked to each of the cylinders in the system 1300.

In the embodiment depicted in FIG. 44B, which includes four cylinder pairs 4402, the phase of PAIR 1 is also denoted 0°. The phase of PAIR 2 is then 270°, the phase of PAIR 3 is 90°, and the phase of PAIR 4 is 180°. As in FIG. 44A, these phase relationships are set and maintained by the affixation to the crankshaft 4404 at appropriate angles of the cranks linked to each of the cylinders in the system 4400.

Linking an even number of cylinder pairs 4402 to a single crankshaft 4404 advantageously balances the forces acting on the crankshaft; unbalanced forces generally tend to either require more durable parts or shorten component lifetimes. An advantage of specifying the phase differences between the cylinder pairs 4402 as shown in FIGS. 44A and 44B is minimization of fluctuations in total force applied to the crankshaft 4402. Each cylinder pair 4402 applies a force varying between zero and some maximum value (e.g., approximately 330,000 lb) during the course of a single stroke. The sum of all the torques applied by the multiple cylinder pairs 4402 to the crankshaft 4404 as arranged in FIGS. 44A and 44B varies by less than the torque applied by a single cylinder pair 4402, both absolutely and as a fraction of maximum torque, and is typically never zero.

Generally, the systems described herein may be operated in both an expansion mode and in the reverse compression mode as part of a full-cycle energy storage system with high efficiency. For example, the systems may be operated as both compressor and expander, storing electricity in the form of the potential energy of compressed gas and producing electricity from the potential energy of compressed gas. Alternatively, the systems may be operated independently as compressors or expanders.

In addition, the systems described above, and/or other embodiments employing liquid-spray heat exchange or external gas heat exchange (as detailed above), may draw or deliver thermal energy via their heat-exchange mechanisms to external systems (not shown) for purposes of cogeneration, as described in the ’513 application.

Having described certain embodiments of the invention, it will be apparent to those of ordinary skill in the art that other embodiments incorporating the concepts disclosed herein may be used without departing from the spirit and scope of the invention. The terms and expressions employed herein are used as terms of description and not of limitation, and there is no intention, in the use of such terms and expressions, of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the invention claimed.

What is claimed is:

1. - 20. (canceled)

21. A method of energy recovery, the method comprising: introducing compressed gas at a first pressure into a first cylinder assembly comprising a piston therewith; expanding the gas within the first cylinder assembly to a second pressure lower than the first pressure, thereby translating the piston within the first cylinder assembly; converting the translation of the piston into rotary motion of a motor/generator outside the first cylinder assembly; introducing heat-transfer fluid into the gas such that the heat-transfer fluid exchanges heat with the gas within the first cylinder assembly during expansion; controlling operation of the first cylinder assembly (i) to enforce substantially isothermal expansion of gas therein and (ii) in response to at least one system parameter associated with operation of the first cylinder assembly; and venting substantially all of the expanded gas at the second pressure from the first cylinder assembly to atmosphere.

22. The method of claim 21, wherein the translation of the piston is converted into rotary motion by a transmission mechanism.

23. The method of claim 22, wherein the transmission mechanism comprises a crankshaft.

24. The method of claim 22, wherein the transmission mechanism comprises a crankshaft and a gear box.

25. The method of claim 22, wherein the transmission mechanism comprises a crankshaft and a continuously variable transmission.
26. The method of claim 22, wherein the transmission mechanism is connected to the piston by a shaft and a cross-head linkage.

27. The method of claim 22, wherein the transmission mechanism varies torque for a given force exerted thereon.

28. The method of claim 21, wherein the at least one system parameter comprises at least one of a fluid state, a fluid flow, a temperature, or a pressure.

29. The method of claim 21, wherein the at least one system parameter comprises a position of the piston within the first cylinder assembly.

30. The method of claim 21, wherein the at least one system parameter is monitored by at least one sensor.

31. The method of claim 21, further comprising, prior to introducing gas into the first cylinder assembly, expanding gas from a third pressure higher than the first pressure to approximately the first pressure within a second cylinder assembly (i) comprising a piston therewithin and (ii) selectively fluidly connected to the first cylinder assembly.

32. The method of claim 31, further comprising, prior to expanding gas within the second cylinder assembly, transferring gas from a compressed-gas reservoir to the second cylinder assembly at approximately the third pressure.

33. The method of claim 31, wherein the piston within the first cylinder assembly and the piston within the second cylinder assembly are mechanically coupled to a crankshaft.

34. The method of claim 31, further comprising (i) after expanding gas from the third pressure to the first pressure within the second cylinder assembly, expanding one or more additional portions of gas each from a pressure less than the third pressure to the first pressure within the second cylinder assembly, and (ii) maintaining a substantially constant power output of the motor/generator during the expansions notwithstanding the different initial pressures of gas.

35. The method of claim 21, wherein gas at the first pressure is introduced into the first cylinder assembly from a compressed-gas reservoir storing gas at approximately the first pressure.

36. The method of claim 21, further comprising (i) after expanding gas from the first pressure to the second pressure within the first cylinder assembly, expanding one or more additional portions of gas each from a pressure less than the first pressure to the second pressure within the first cylinder assembly, and (ii) maintaining a substantially constant power output of the motor/generator during the expansions notwithstanding the different initial pressures of gas.

37. The method of claim 21, further comprising monitoring a temperature of the gas during expansion of the gas.

38. The method of claim 21, further comprising monitoring a pressure of the gas during expansion of the gas.

39. The method of claim 21, further comprising monitoring, during expansion of the gas, at least one of a position or a rate of movement of the piston.

40. The method of claim 21, wherein introducing heat-transfer fluid into the gas comprises spraying heat-transfer fluid into the gas.

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