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Weiland et al.

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(54) **TRAVELING-WAVE THERMOACOUSTIC ENGINES WITH INTERNAL COMBUSTION**

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(51) **Int. Cl.**[7] **F01B 29/10**

(52) **U.S. Cl.** **60/520**; 60/526; 60/721

(58) **Field of Search** 60/517, 520, 721, 60/521, 522, 526; 62/6

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,114,380 A 9/1978 Ceperley 60/721
4,355,517 A 10/1982 Ceperley 60/721
5,953,920 A 9/1999 Swift et al. 62/6
6,032,464 A 3/2000 Swift et al. 60/520
6,164,073 A 12/2000 Swift et al. 60/721
6,314,740 B1 * 11/2001 De Blok et al. 62/6
6,560,970 B1 * 5/2003 Swift 62/6
6,564,552 B1 * 5/2003 Ward et al. 60/520
6,578,364 B2 * 6/2003 Corey 62/6
6,644,028 B1 * 11/2003 Swift et al. 60/516

OTHER PUBLICATIONS

"A Pistonless Stirling Engine—The Traveling Wave Heat Engine" Ceperley; 1979.
"Gain and Efficiency of a Short Traveling Wave Heat Engine" Ceperley; 1985.
"Pulsating Combustion" Zinn; 1986; pp. 113–181.
"A Thermoacoustic–Stirling Heat Engine: Detailed Study" Backhaus, et al.; 2000.
"Experiments with a Flow–Through Thermoacoustic Refrigerator" Reid et al.; 2000.
"Thermoacoustics for Liquefaction of Natural Gas" Swift; 2002; pp. 22–26.
"Development of a Thermoacoustic Natural Gas Liquefier" Wollan, et al.; Mar. 2002; pp. 1–8.

* cited by examiner

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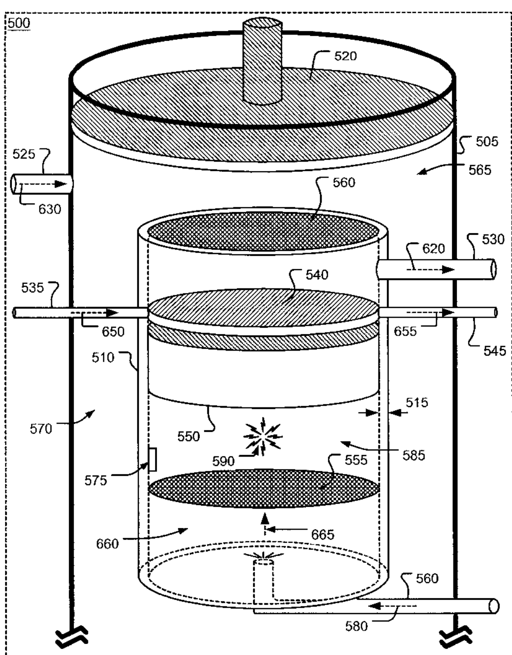
(57) **ABSTRACT**

Thermoacoustic devices are disclosed wherein, for some embodiments, a combustion zone provides heat to a regenerator using a mean flow of compressible fluid. In other embodiments, burning of a combustible mixture within the combustion zone is pulsed in phase with the acoustic pressure oscillations to increase acoustic power output. In an example embodiment, the combustion zone and the regenerator are thermally insulated from other components within the thermoacoustic device.

33 Claims, 8 Drawing Sheets



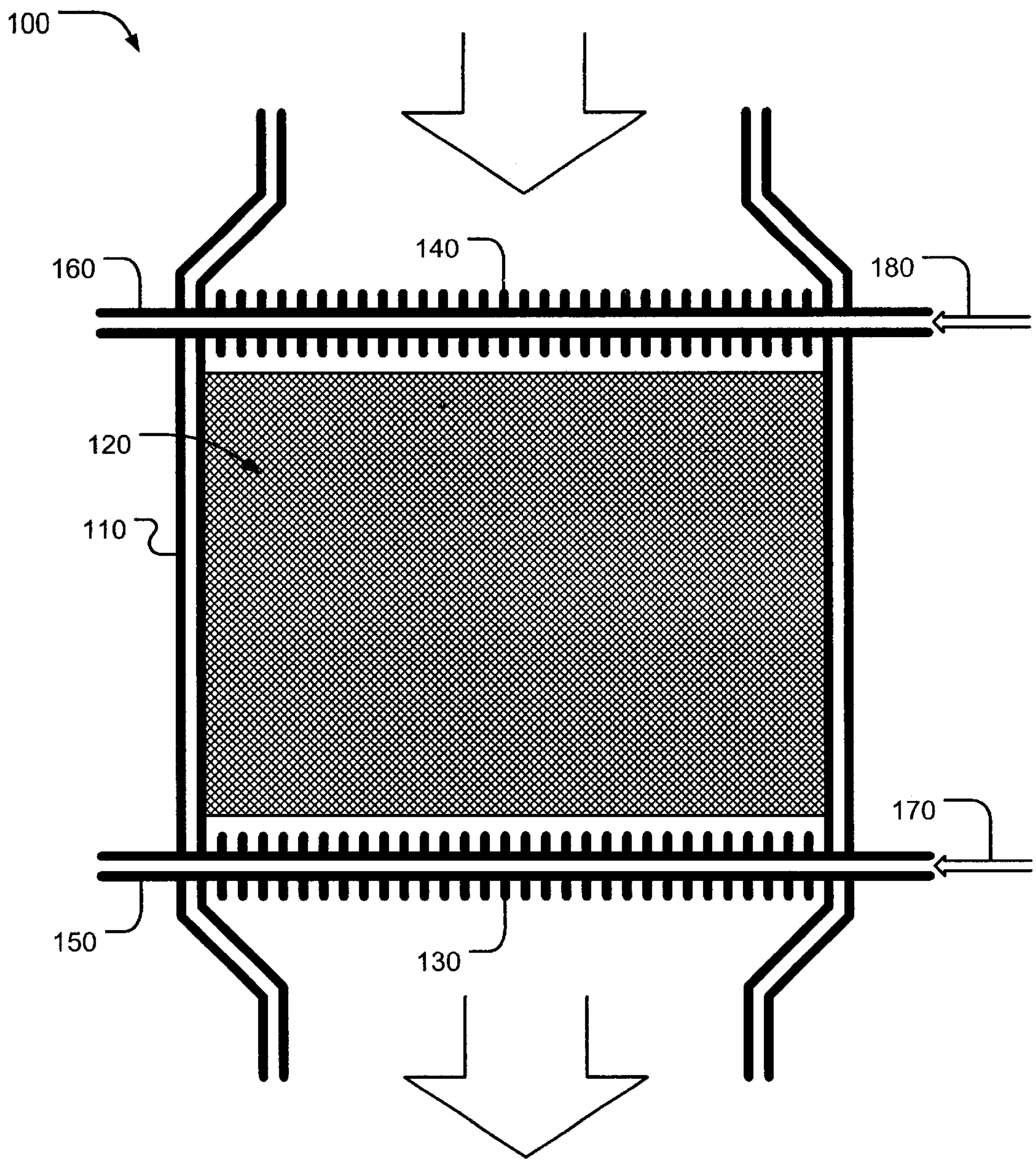


FIG. 1
PRIOR
ART

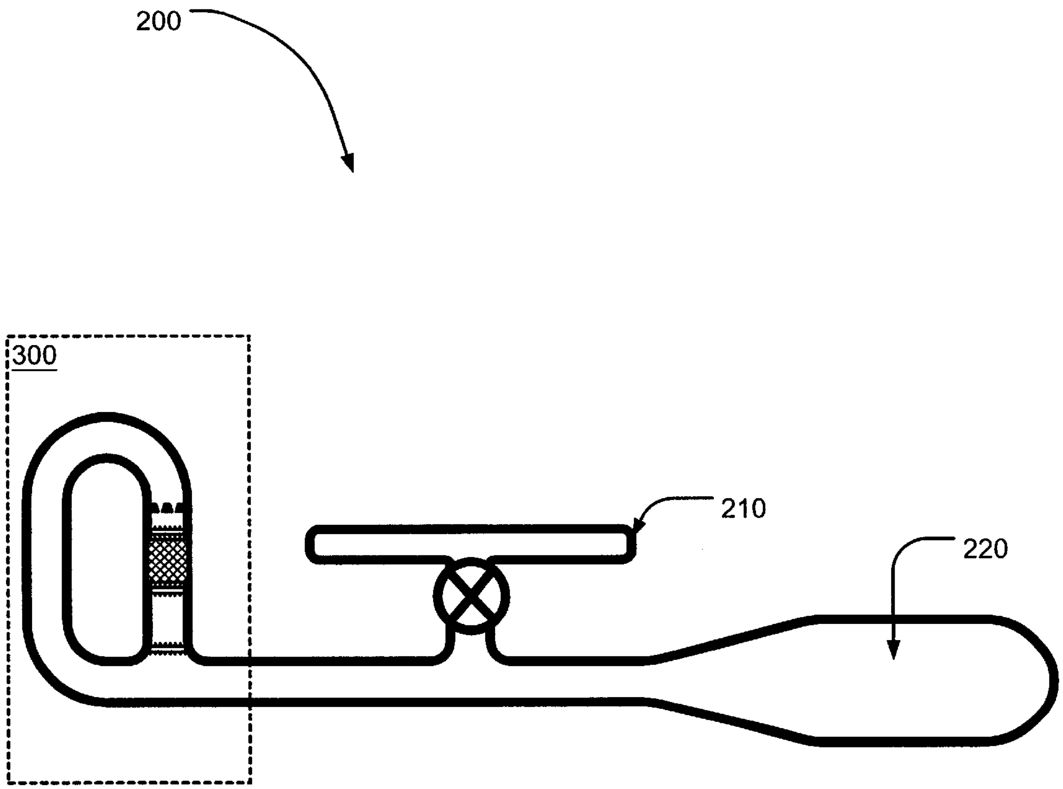


FIG. 2
PRIOR
ART

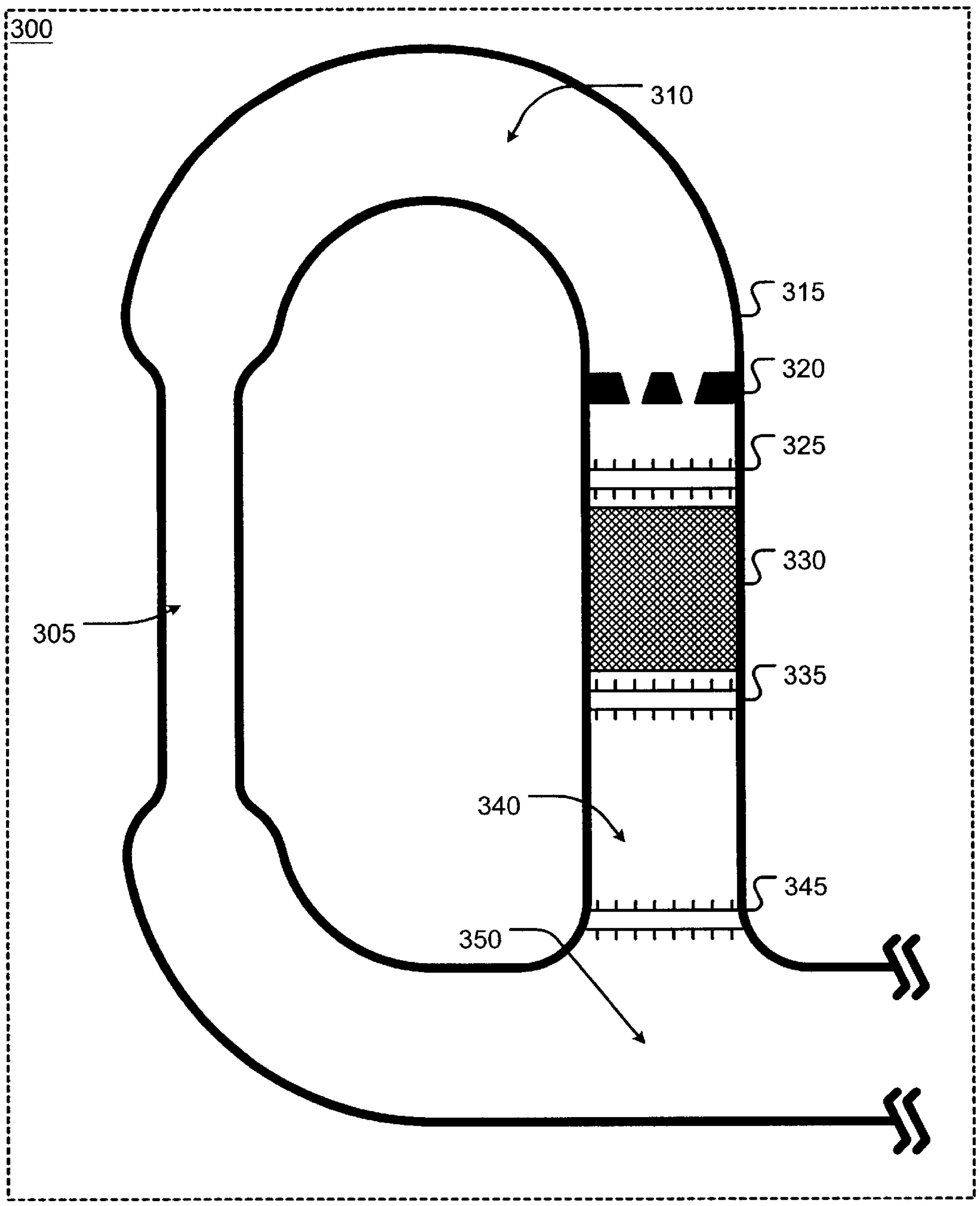


FIG. 3
PRIOR
ART

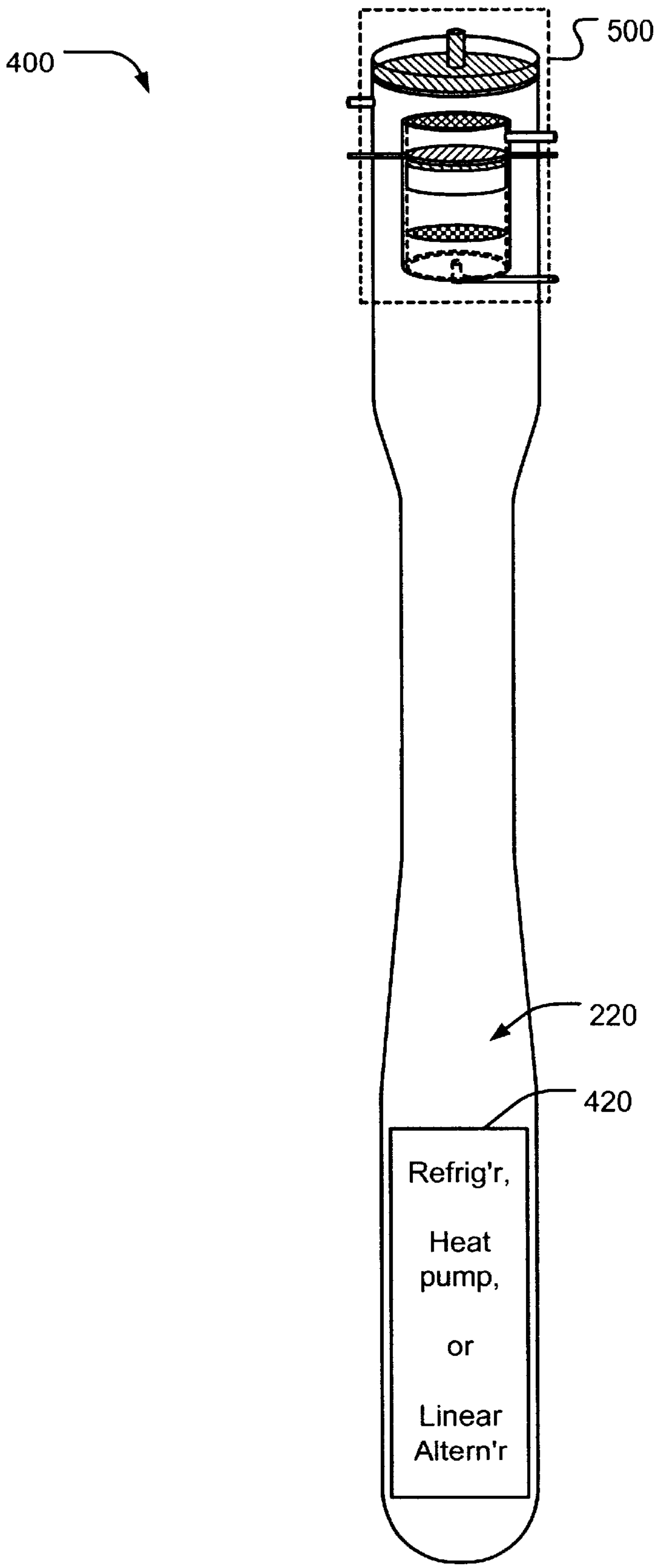


FIG. 4

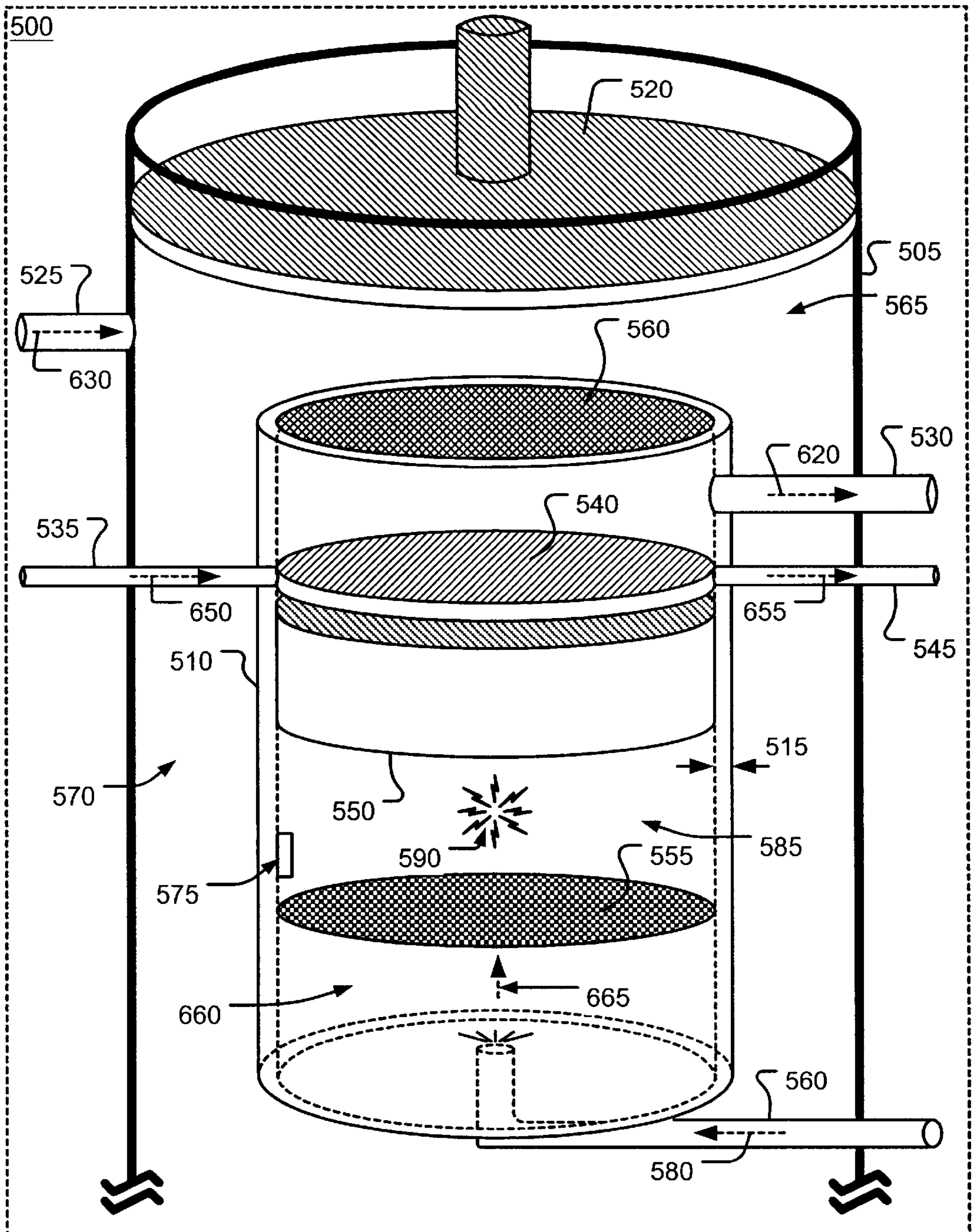

500
520
505
525
565
630
560
620
530
540
535
650
655
545
510
515
570
550
585
590
555
575
660
665
560
580

FIG. 5

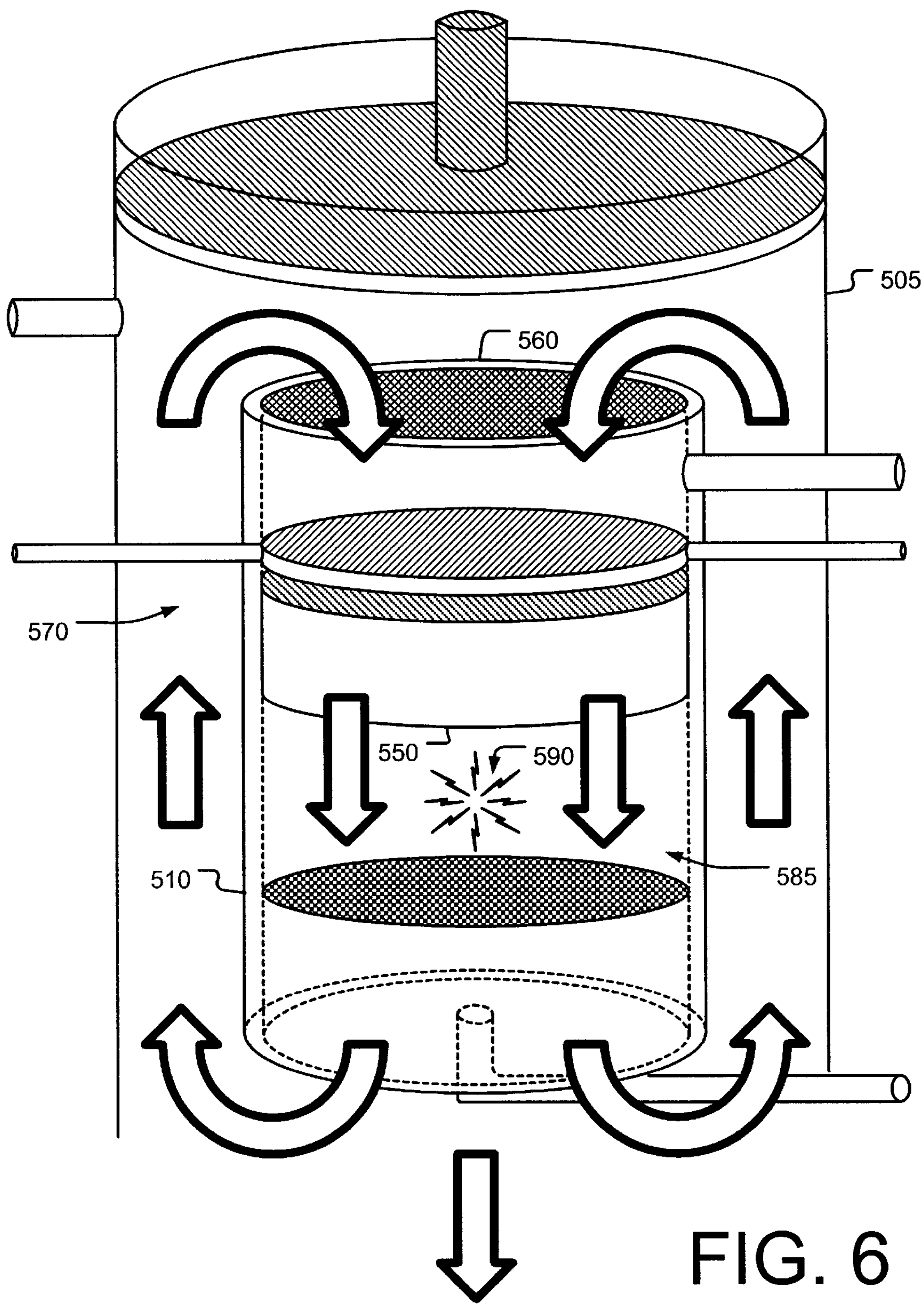


FIG. 6

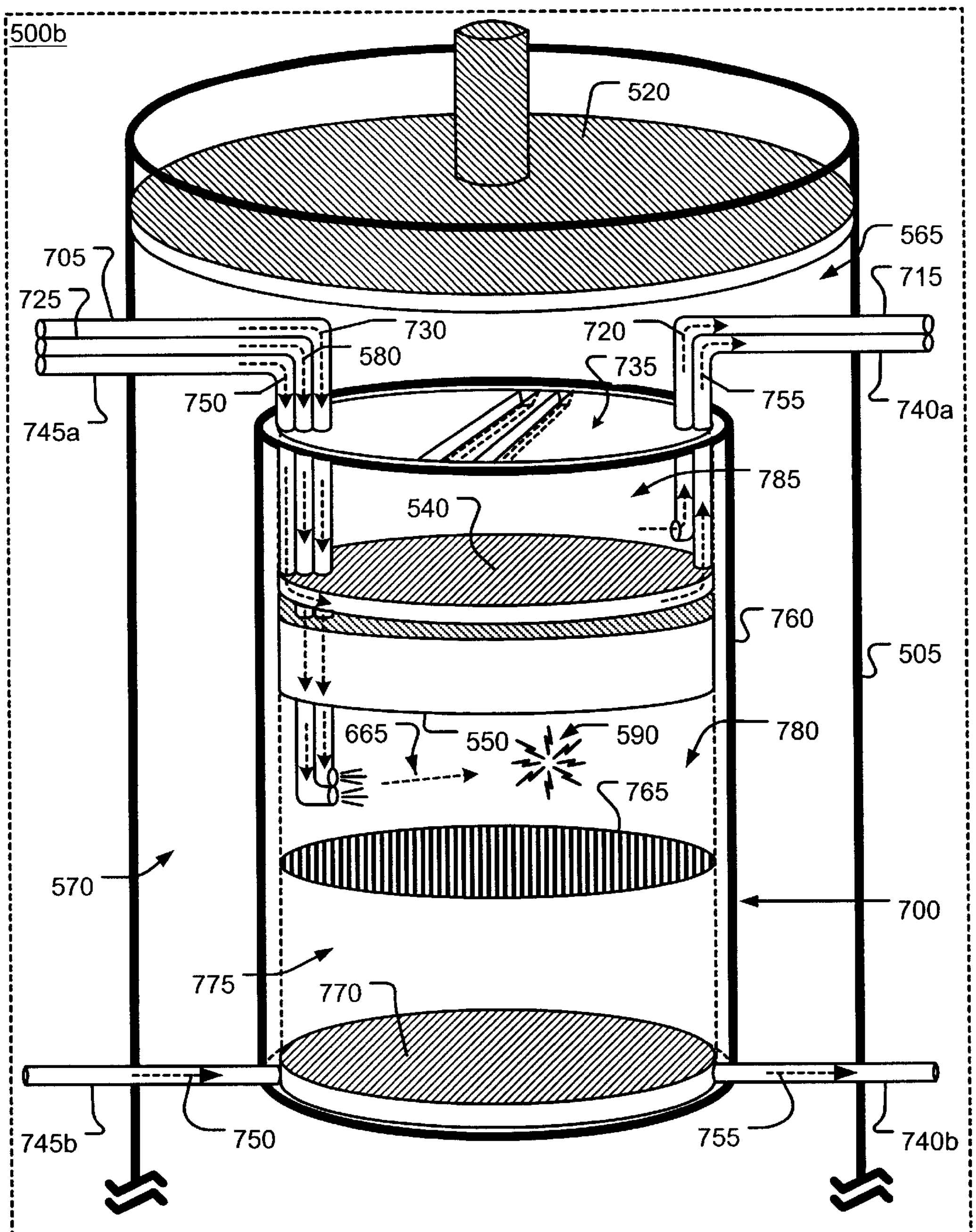

500b
520
565
715
705
725
730
720
580
735
750
755
740a
745a
785
540
760
505
665
550
590
780
765
570
700
775
770
745b
750
755
740b

FIG. 7

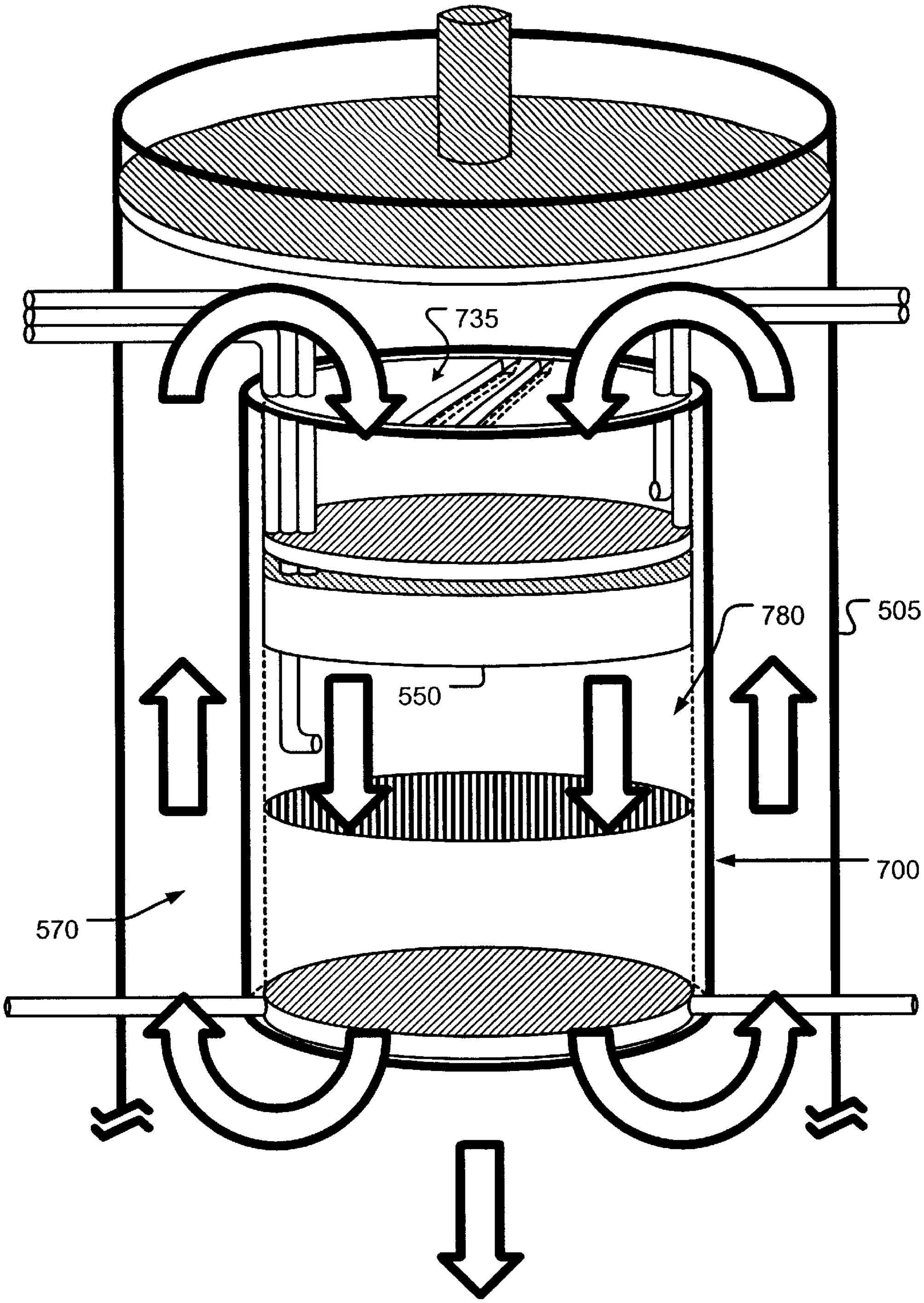


FIG. 8

TRAVELING-WAVE THERMOACOUSTIC ENGINES WITH INTERNAL COMBUSTION

CROSS REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. provisional patent application Serial No. 60/364,207, filed Mar. 13, 2002, which is incorporated herein by reference in its entirety. Also, co-pending U.S. patent application having U.S. Express Mail Mailing Label Number EV269328365US is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

The U.S. government has a paid-up license in this invention and the right in limited circumstances to require the patent owner to license others on reasonable terms as provided for by the terms of contract number F49620-99-C-0054 awarded by the National Defense Science and Engineering Graduate Fellowship, a part of the United States Air Force Office of Scientific Research.

Additionally, this invention was made at least in part with government support under Contract No. W-7405-ENG-36 awarded by the U.S. Department of Energy. The U.S. government has certain rights in the invention.

FIELD OF THE INVENTION

The present disclosure relates generally to the fields of thermoacoustics and combustion and, more particularly, to thermoacoustic devices.

BACKGROUND

Thernoacoustic devices have been used as heat engines and heat pumps. As shown in FIG. **1**, one mechanism for manipulating thermoacoustic waves is a conventional traveling wave thermoacoustic driver **100** having a hot heat exchanger **130** and a primary cold heat exchanger **140**, which are used to generate a temperature gradient across a regenerator **120**. The conventional thermoacoustic driver **100** contains a compressible fluid that is capable of sustaining acoustic oscillations. To convert thermal energy into acoustic energy, acoustic traveling waves are introduced through the top of the conventional thermoacoustic driver **100**. At substantially the same time, the primary cold heat exchanger **140** is cooled by passing an ambient temperature (or externally chilled) fluid **180** through pipe **160**, and the hot heat exchanger **130** is heated by passing externally heated fluid **170** through pipe **150**. The hot heat exchanger **130** and the primary cold heat exchanger **140** set up a temperature gradient in the regenerator **120**, which is interposed between the hot heat exchanger **130** and the primary cold heat exchanger **140**. The regenerator **120** comprises packing material that is fine enough so that the working fluid in the regenerator **120** is essentially in thermal equilibrium with the packing around it, but not so fine as to prevent the passage of acoustic waves through the regenerator **120**.

Pressure oscillations produced by the acoustic traveling wave induce the compressible fluid in the regenerator to move down towards the hot end of the temperature gradient, or up towards the cold end of the temperature gradient. Consequently, when the compressible fluid moves down, the hotter regenerator packing heats and expands the compressible fluid; when the compressible fluid moves up, the colder regenerator packing cools and contracts the compressible fluid. As the acoustic traveling wave passes through the compressible fluid, it imparts time-dependent pressure and velocity oscillations to a small volume of the fluid at the wave's location. Since traveling waves are intrinsically phased such that the peak velocity and the peak pressure occur at substantially the same time, the processes undergone by the small volume of the fluid in the regenerator mimic the thermodynamic cycle of a Stirling engine. The thermodynamic cycle, therefore, results in conversion of thermal energy into mechanical energy. In other words, the traveling wave causes the compression, expansion, and fluid movement, which adds pressure and momentum to the waves, thereby amplifying the acoustic traveling wave as it passes through the regenerator.

As is known in the art, if the direction of the acoustic traveling wave is reversed from the hot heat exchanger **130** to primary cold heat exchanger **140**, then the conventional thermoacoustic driver **100** may be used as a heat pump for refrigeration, air conditioning, or other cooling or heating applications. Since the operation of the conventional thermoacoustic driver **100** is known in the art, further discussion of the conventional thermoacoustic driver **100** is omitted here.

FIG. **2** is a diagram showing a cross-sectional view of a thermoacoustic Stirling heat engine (TASHE) **200** having a conventional thermoacoustic driver. As shown in FIG. **2**, the TASHE **200** comprises a resonator **220**, a variable acoustic load **210**, and a thermoacoustic driving section **300**. In one working example, the TASHE **200** is filled with helium at approximately thirty bars mean pressure. The use of high-pressure helium increases the acoustic power density of the TASHE **200**, which permits acoustic effects to prevail over heat conduction losses.

FIG. **3** is a diagram showing, in greater detail, the thermoacoustic driving section **300** of the TASHE **200** from FIG. **2**. The thermoacoustic driving section **300** of the TASHE **200** comprises a toroidal acoustic feedback loop (or torus) **315** having a regenerator **330** interposed between a primary cold heat exchanger **325** and a hot heat exchanger **335**. As described with reference to FIG. **1**, the primary cold heat exchanger **325**, the regenerator **330**, and the hot heat exchanger **335** are configured to amplify acoustic traveling waves that propagate clockwise through the torus **315**. At the junction **350**, a portion of the amplified acoustic energy travels to the right towards the resonator **220** and the acoustic load **210**, while the remainder is fed back, through the torus **315**, to the cold end of the regenerator **330** to be amplified within the regenerator **330**. Thus, when the acoustic traveling waves propagate clockwise through the torus **315**, the thermoacoustic driving section **300** functions as a heat engine. Conversely, a counter-clockwise propagation of acoustic traveling waves through the torus **315** attenuates the acoustic traveling waves, thereby resulting in a heat pump configuration in which heat is pumped from the primary cold heat exchanger **325** to the hot heat exchanger **335**.

Additionally, the torus **315** contains an inertance section **305** and a compliance section **310**. These sections **305**, **310**, along with the regenerator **330**, define the properties of the acoustic waves in the thermoacoustic driving section **300**. Each of these components **305**, **310** and **330**, are much shorter than an acoustic wavelength, though their specific geometries create the traveling wave acoustic phasing within the regenerator **330**. They are also geometrically configured to reduce the acoustic velocity within the regenerator **330**, thereby reducing viscous losses that would normally accompany the passage of an acoustic traveling wave through a conventional thermoacoustic driver **100**, as shown in FIG. **1**.

The thermoacoustic driving section **300** of the TASHE **200** further comprises a secondary cold heat exchanger **345**, which, in conjunction with the hot heat exchanger **335**, defines a thermal buffer tube **340**. The thermal buffer tube **340** provides thermal isolation between the hot heat exchanger **335** and the rest of the TASHE **200** beyond the cold heat exchangers **325**, **345**. Since the TASHE **200** is described in greater detail in U.S. Pat. No. 6,032,464 to Swift et al., further discussion of the TASHE **200** is omitted here.

One drawback of the TASHE **200** is that acoustic streaming in the thermoacoustic driving section **300** results in a convection current that travels clockwise around the torus **315**, carrying thermal energy away from the regenerator **330** and out the secondary cold heat exchanger **345**. Since this degrades the performance of the engine, it is desirable to eliminate or minimize any clockwise mean flow around the torus **315** and through the regenerator **330**. As a result, the thermoacoustic driving section **300** of the TASHE **200** comprises a hydrodynamic mass-flux suppressor (or jet pump) **320** that is adjustable to minimize or eliminate any net flow of the compressible fluid around the torus **315**. The operation of the mass-flux suppressor **320** relies on turbulence and the viscous dissipation of kinetic energy, so its use in suppressing the clockwise convection current is also accompanied by some dissipation of acoustic energy.

Also, in the TASHE **200**, conduction of heat through the walls of the torus **315** can result in significant energy losses. These energy losses are due to heat conduction radially through the walls into the insulation or atmosphere surrounding the torus **315**, and also due to axial heat conduction along the walls of the torus **315** between the hot heat exchanger **335** and the cold heat exchangers **325**, **345**, essentially bypassing the regenerator **330**. For higher internal gas pressures as are typically present in the TASHE **200**, greater wall thickness is required, which results in greater axial conduction losses. Additionally, cross-flow heat exchangers **325**, **335**, **345**, which are typically used due to geometric constraints, result in sub-optimal heat transfer and potentially enormous thermal stresses, especially in the hot heat exchanger **335**.

Given these inefficiencies, a need exists in the industry for more efficient traveling wave thermoacoustic devices.

SUMMARY

The present disclosure provides systems for manipulating acoustic energy.

Briefly described, some embodiments of a system comprise a thermoacoustic driver and a feedback path. In some embodiments, the thermoacoustic driver comprises an inlet conduit, a combustion zone, a regenerator, a cold heat exchanger, and an exhaust port. The inlet conduit is adapted to admit a compressible combustible mixture. The combustion zone is configured to receive the compressible combustible mixture and bum the compressible combustible mixture to generate hot compressible combustion products. The regenerator has a cold side and a hot side, which generate a temperature gradient across the regenerator. The cold side of the regenerator is coupled to the cold heat exchanger. The hot compressible combustion products are directed to the hot side of the regenerator and through the regenerator to produce cold compressible combustion products. The cold compressible combustion products are expelled by the exhaust port. This configuration permits amplification of traveling acoustic waves that propagate through the regenerator from the cold side of the regenerator to the hot side of the regenerator. The feedback path returns a portion of the acoustic energy from the hot side of the regenerator to the cold side of the regenerator for further amplification, and is thermally insulated from the regenerator and the combustion zone.

Other systems, methods, features and/or advantages will be or may become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features and/or advantages be included within this description.

BRIEF DESCRIPTION OF THE DRAWINGS

Many aspects of the disclosure can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present disclosure. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

FIG. **1** is a diagram showing a lateral cross-section of a conventional thermoacoustic driver having a hot heat exchanger and a primary cold heat exchanger, which are used to generate a temperature gradient across a regenerator, which in turn amplifies an acoustic traveling wave.

FIG. **2** is a diagram showing a cross-sectional view of a thermoacoustic Stirling heat engine (TASHE) having a conventional thermoacoustic driver.

FIG. **3** is a diagram showing, in greater detail, the thermoacoustic driving section of the TASHE engine from FIG. **2**.

FIG. **4** is a diagram of an embodiment of a thermoacoustic device having a thermoacoustic driver and a thermoacoustic refrigerator, a thermoacoustic heat pump, or a linear alternator.

FIG. **5** is a diagram showing, in greater detail, the thermoacoustic driving section from FIG. **4**.

FIG. **6** is a diagram showing the acoustic energy flow paths in the thermoacoustic driver of FIG. **5**.

FIG. **7** is a diagram showing an embodiment of a thermoacoustic driver with a feedback path that is thermally insulated from a combustion process within the thermoacoustic driver.

FIG. **8** is a diagram showing the acoustic energy flow paths in the thermoacoustic driver of FIG. **7**

DETAILED DESCRIPTION

Reference is now made in detail to the description of several embodiments as illustrated in the drawings. While the several embodiments are described in connection with these drawings, there is no intent to limit the invention to the embodiments disclosed herein. On the contrary, the intent is to cover all alternatives, modifications and/or equivalents.

The embodiments described with reference to FIGS. **4** through **8** ameliorate several of the problems associated with the TASHE **200** or other known thermoacoustic devices. Unlike the conventional thermoacoustic driver **100** or the TASHE **200**, which seek to eliminate any mean flow, the embodiments of FIGS. **4** through **8** introduce a mean flow across the regenerator. This mean flow is superimposed on the acoustic motions of the fluid and, for small mean flow velocities relative to the acoustic velocities, the mean flow and the acoustic motions can be considered to act independently of one another. The use of an applied mean flow facilitates the addition of an internal combustion process in the device, as the mean flow can supply the combustion process with fresh reactants and carry away combustion products. Adding inlet and exhaust ports to bring in combustion reactants and carry away combustion products signifies an important shift from a traditional closed cycle thermoacoustic engine such as the TASHE **200**, to an open cycle engine configuration. Thermodynamically, an open cycle thermoacoustic engine can be more efficient than a closed cycle thermoacoustic engine in converting fuel energy to acoustic energy, as the inefficiencies involved in transferring heat into a closed cycle engine are not present in an open cycle configuration.

Thus, as a result of the mean flow, the hot heat exchanger **130** may be replaced by a mean flow of hot gas, where the heat in the hot gas is obtained from a combustion zone inside the device. The absence of the hot heat exchanger **130** can drastically reduce thermal stresses that are present in the TASHE **200** and other thermoacoustic engines, particularly if the heat exchanger being replaced is a cross-flow hot heat exchanger. Additionally, by concentrically disposing a thermoacoustic driver within an outer shell, the thickness of the walls of the thermoacoustic driver may be significantly reduced. Consequently, axial heat conduction losses through these walls may be reduced as a result of the reduced wall thickness. Furthermore, radial heat transfer from the thermoacoustic driver may be used to further increase the efficiency of the thermoacoustic device.

Referring back to the drawings, FIG. **4** is a diagram showing an embodiment of a thermoacoustic device **400**. As shown in FIG. **4**, the thermoacoustic device **400** comprises a resonator **220**, a thermoacoustic driving section **500**, and a thermoacoustic refrigerator, thermoacoustic heat pump, or linear alternator **420**. The thermoacoustic device **400** is filled with compressible fluid. In an example embodiment, the thermoacoustic device **400** is filled with air and combustion products that are pressurized to increase the acoustic power density of the thermoacoustic device **400**. The increased acoustic power density reduces the impact of thermal conduction losses within the thermoacoustic device **400**. Unlike the conventional thermoacoustic driver **100** of FIG. **1** or the TASHE **200** of FIGS. **2** and **3**, the thermoacoustic device **400** of FIG. **4** manipulates acoustic energy by supplying heat to a regenerator with a mean flow of hot combustion products. Greater details of a thermoacoustic driving section **500** of FIG. **4** are shown with reference to FIG. **5**.

In some embodiments, acoustic energy generated by the thermoacoustic driving section **500** is directed through the resonator **220** to a thermoacoustic refrigerator **420**, where the acoustic energy is used for refrigeration. In some embodiments of this type, the thermoacoustic device **400** may be used to liquefy natural gas for ease of transport. A portion of the natural gas is burned to generate heat in the combustion zone of the thermoacoustic driving section **500**, and the acoustic energy that is generated in the thermoacoustic driving section **500** is used in a staged thermoacoustic refrigeration process **420** to liquefy the remainder of the natural gas. In other embodiments of this type, the thermoacoustic refrigerator **420** can be used to provide air conditioning or residential refrigeration without the use of chloro-fluoro-carbons (CFCs) or other environmentally toxic refrigerants.

In other embodiments, the acoustic energy generated by the thermoacoustic driving section **500** is directed to a thermoacoustic heat pump **420**. In embodiments of this type, the acoustic energy can be used to provide space heating or residential water heating. In still other embodiments, the acoustic energy generated by the thermoacoustic driving section **500** is directed to a linear alternator **420**, which converts the acoustic energy into electrical energy. Since the thermoacoustic device **400** contains few, if any, moving parts, an embodiment of this type may be ideal for use as a remote or portable gas-powered electric generator, where low maintenance and high reliability are desirable features.

In addition to converting acoustic energy into other forms of energy, the thermoacoustic device **400** may be used simply to amplify or generate acoustic waves at a given frequency. One application of such an acoustic-wave amplifier would be in the lumber industry, where the acoustic vibrations may assist in drying lumber in a kiln. These and other applications should be understood by those of skill in the art.

As shown in FIG. **5**, the thermoacoustic driving section **500** comprises a shell **505** and a thermoacoustic driver **510**. In an example embodiment, the shell **505** is substantially cylindrical in shape and the thermoacoustic driver **510** is located concentrically within the shell **505**. By locating the thermoacoustic driver **510** within the shell **505**, the burden of containing the high pressures inside the device is shifted from the thermoacoustic driver **510** to the shell **505**. Thus, the thickness of the walls **515** of the thermoacoustic driver **510** may be significantly reduced as compared to the TASHE **200**. Consequently, axial conduction losses may be greatly reduced due to the reduced wall thickness.

The shell **505** includes an inlet port **525** that introduces a compressible inlet fluid **630** to the interior of the shell **505**. In an example embodiment, the compressible inlet fluid **630** includes an oxidizer, such as air, which later mixes with fuel to create a combustible mixture that burns to generate heat. In other embodiments, the compressible inlet fluid **630** admitted through the inlet port **525** may include a combustible mixture so that further fuel injection and mixing is unnecessary. Furthermore, the inlet port **525** may be configured to suppress the escape of acoustic energy from the thermoacoustic device. In one such embodiment, the length of the inlet port **525** may be adjusted so that acoustic energy is reflected back to the interior of the shell **505**. In another such embodiment, the inlet port **525** can be highly pressurized, and the compressible inlet fluid **630** is admitted to the shell **505** through a choked nozzle, which will not allow acoustic waves to propagate upstream into the inlet port **525** and out of the device.

The shell **505** further comprises a compliance section **565** and an inertance section **570**, which permit the feedback of acoustic energy from the hot end of the thermoacoustic driver to the cold end, and which define properties related to the acoustic traveling wave as it propagates through the device. The thermoacoustic driving section **500** has a movable end-cap **520**, which is positioned at one end of the shell **505**. The movable end-cap **520** permits tuning of the volume of the compliance section **565** of the shell **505**, thereby permitting adjustment of the resonant properties related to the acoustic traveling wave. In addition to providing a tunable compliance, the end-cap **520** permits easy access to the thermoacoustic driver **510** in the event that maintenance is required on the thermoacoustic driver **510**. The compliance section **565**, the inertance section **570**, and the regenerator **550** are geometrically configured to set up a traveling wave acoustic phasing at the regenerator **550**, thereby constructively providing the feedback acoustic energy for amplification at the regenerator **550**. Additionally, the compliance section **565**, the inertance section **570**, and the regenerator **550** are geometrically configured to establish a region of relatively low acoustic velocity across the regenerator **550**, thereby decreasing viscous losses within the regenerator **550**.

The thermoacoustic driver **510** includes a primary cold heat exchanger **540** having a coolant inlet **535** and a coolant outlet **545**. The coolant inlet **535** introduces incoming coolant **650** to the primary cold heat exchanger **540**, while the coolant outlet **545** expels the outgoing coolant **655** from the primary cold heat exchanger **540**. In some embodiments, the coolant **650**, **655** may be cold water used to cool the primary cold heat exchanger **540**.

The thermoacoustic driver **510** also includes a regenerator **550** and a combustion zone **585**. In one such embodiment, the regenerator **550** has a cold side, which is coupled to the primary cold heat exchanger **540**, and a hot side, which is coupled to the combustion zone **585**. The coupling of the primary cold heat exchanger **540** and the combustion zone **585** to the regenerator **550** establishes a temperature gradient across the regenerator **550**. The regenerator **550** comprises packing material that is fine enough so that combustion products **620** in the regenerator **550** are essentially in thermal equilibrium with the packing around it, but not so fine as to prevent the passage of acoustic waves through the regenerator **550**. The temperature gradient across the regenerator **550** amplifies acoustic traveling waves as the combustion products **620** expand and contract within the regenerator **550** due to the pressure oscillations of the acoustic traveling wave. The combustion zone **585** is configured to burn a combustible mixture **665**, which generates heat and the combustion products **620** that are conveyed to the hot side of the regenerator **550** by the mean flow. Due to the close thermal contact between the gas and the solid within the regenerator **550**, the mean flow of combustion products **620** from the hot side of the regenerator **550** to the cold side of the regenerator **550** causes the combustion products **620** to be cooled and to exit the cold side of the regenerator **550** at approximately the same temperature as the cold side of the regenerator **550**. In some embodiments, radiative heat transfer from the combustion zone **585** to the regenerator **550** may be used to augment the transfer of heat by convective means.

In some embodiments, the combustion zone **585** may be a combustion chamber adapted to contain the burning of the combustible mixture **665**. In this regard, the device may include a fuel injector **560** that delivers fuel **580** to a mixing section **660**, in which the fuel **580** mixes with the oxidizer in the compressible inlet fluid **630** to create a combustible mixture **665**. The combustible mixture **665** is directed to the combustion zone **585** from the mixing section **660** by the mean flow.

The combustion zone **585** may also comprise an igniter **590** that initially ignites the combustible mixture **665** within the combustion zone **585**, and a flame holder **555** that is adapted to hold a flame for subsequent burning of the combustible mixture **665** after the first ignition. In some embodiments, the flame holder **555** is comprised of a wire, a wire mesh screen, or any other stationary object that can be used to anchor a flame. The flame holder **555** may also be coated with a catalyst that acts as an ignition source. In other embodiments, the igniter **590** itself may act as the flame holder **555**. In other embodiments, the fuel injector **560** may be used as the flame holder **555**, in which case the mixing section **660** is contained within the combustion zone **585**.

In other embodiments, the combustion zone **585** may include a catalyst to aid in the combustion of the combustible mixture **665**. In this regard, the combustion zone **585** may be a matrix having its surface coated with a combustion catalyst. In an example embodiment, the matrix is configured to have sufficient surface area to permit interaction of the combustible mixture **665** with the catalyst, thereby facilitating combustion of the combustible mixture **665**. Since processes related to catalytic combustion are known to those of skill in the art, further discussion of catalytic combustion is omitted here. It should, however, be appreciated that such a process may further simplify the thermoacoustic driver **510**, as the use of a catalyst in the combustion zone **585** would eliminate the need for the igniter **590** and the flame holder **555**.

In other embodiments, the burning of the combustible mixture **665** is synchronized with the pressure oscillations of the acoustic traveling wave. The synchronized combustion amplifies the pressure oscillations, thereby adding to the acoustic power output of the thermoacoustic driving section **500**. For embodiments that synchronize the combustion to the pressure oscillations, the combustion zone **585** may include a sensor **575**, which is configured to detect the pressure oscillations and convey this information to a controller (not shown) that controls the synchronized combustion. The synchronized combustion may be controlled by providing the fuel **580** at predefined time intervals that are substantially synchronous to the pressure oscillations detected by the sensor **575**. The timing of the fuel delivery may be altered to provide optimum phasing between the pulse combustion and the acoustic oscillations. In other embodiments, the controller provides timed ignition control of the igniter **590**, such that the combustible mixture **665** periodically ignites and burns in phase with the pressure oscillations.

In other embodiments, the pressure oscillations may be synchronized to the pulse combustion using a passive approach. In one such approach, the fuel **580** may be delivered to the mixing section **660** through a pressurized pipe **560**, capped with a nozzle. The rate at which the fuel **580** flows through the nozzle is approximately proportional to the square root of the pressure difference across the nozzle. Hence, during the peaks in the pressure oscillations, the pressure difference across the fuel nozzle is small and the fuel flow rate out of the nozzle is small. During troughs in the pressure oscillations, the pressure difference across the fuel nozzle is large, resulting in a higher fuel flow rate out of the nozzle. In this manner, fuel flow rate oscillations cause fluctuations in the ratio of fuel to oxidizer in the combustible mixture **665**, which can lead to combustion oscillations in the combustion zone **585**. The phase of the pulse combustion relative to the phase of the pressure oscillations may be adjusted by altering the distance between the flame holder **555** and the fuel injector **560**.

The thermoacoustic driver **510** also comprises an acoustically transparent barrier **560** that is relatively impermeable to the mean flow in the device. Additionally, the thermoacoustic driver **510** has an exhaust port **530** that expels the mean flow of combustion products **620** after the combustion products **620** have been directed through the regenerator **550** and the primary cold heat exchanger **540**. The acoustically transparent barrier **560** sustains a mean pressure difference across the acoustically transparent barrier **560**, thereby directing the mean flow in the device from the inlet port **525**, through the combustion zone **585** and the regenerator **550**, and out the exhaust port **530**. In the absence of the acoustically transparent barrier **560**, the regenerator **550** presents a large resistance to the mean flow in the device. Thus, the path of least resistance for the mean flow of compressible inlet fluid **630** is directly from the inlet port **525** to the exhaust port **530**, effectively bypassing the combustion zone **585** and the regenerator **550**. The acoustically transparent barrier **560** also attempts to prevent the re-introduction of the mean flow from the thermoacoustic driver **510** into the shell **505**, separating the combustion products **620** from the compressible inlet fluid **630** that is introduced at the inlet port **525**. Furthermore, the acoustically transparent barrier **560** must allow the passage of the feedback acoustic energy from the inertance **570** and compliance **565** to the regenerator **550** with minimal attenuation of acoustic energy. Thus, in some embodiments, the acoustically transparent barrier **560** may be a vibrating membrane that is impermeable to the mean flow in the device. In other embodiments, the acoustically transparent barrier **560** may be a hydrodynamic jet pump that may be similar to that used in the TASHE **200**, a piston, etc. Additionally, the exhaust port **530**, in an example embodiment, is configured to suppress the escape of acoustic energy from the thermoacoustic device. In this regard, the length of the exhaust port **530** may be adjusted so that acoustic energy is reflected back to the interior of the thermoacoustic driver **510**.

As seen from FIG. **5**, the combustion zone **585** in FIG. **5** replaces the hot heat exchanger **335** of FIG. **3**, thereby eliminating any thermal stresses accompanying the hot heat exchanger **335**. Additionally, the proximity of the thermoacoustic driver to the mean flow path permits radial heat transfer from the regenerator **550** to the surrounding compressible inlet fluid **630** in the inertance **570**. Similarly, the proximity of the combustion zone **585** to the mean flow path permits radial heat transfer from the combustion zone **585** to the surrounding compressible inlet fluid **630**. The radial heat transfer preheats the surrounding compressible inlet fluid **630**. In embodiments where the compressible inlet fluid comprises the combustible mixture, the combustible mixture becomes preheated and enters the combustion zone **585**. In embodiments where the compressible inlet fluid **630** comprises an oxidizer, the oxidizer is preheated and enters the mixing section **660**, where it mixes with the fuel **580**, thereby creating a preheated combustible mixture **665** that enters the combustion zone **585**. This radial heat transfer, normally a loss in a conventional thermoacoustic driver **100** or a device like the TASHE **200**, is instead recycled by effectively preheating the combustible mixture **665** before it enters the combustion zone **585**. While excessive preheating could lead to premature ignition of the combustible mixture **665** before it enters the combustion zone **585**, reasonable levels of preheating may be used to either increase the combustion temperature within the combustion zone **585**, or to reduce the consumption of fuel **580** required to reach a desired combustion temperature, either of which increases the efficiency of the device.

FIG. **6** is a diagram showing acoustic energy flow in the thermoacoustic driver section **500** of FIG. **5**. In the embodiment of FIG. **6**, acoustic energy is directed through the feedback inertance **570** established by concentrically disposing the thermoacoustic driver **510** within the shell **505**. As shown in FIG. **6**, acoustic energy passes through the acoustically transparent barrier **560** with little attenuation, and is directed down through the regenerator **550**, where it is amplified by the temperature gradient across the regenerator **550**. Then the acoustic energy passes through the combustion zone **585**, where it may be further amplified by a pulse combustion process. As the acoustic energy exits the thermoacoustic driver **510**, a portion of the acoustic energy is directed to the resonator **220** for use by a thermoacoustic refrigerator, thermoacoustic heat pump or linear alternator **420**, while the remaining portion of the acoustic energy is directed back to the regenerator **550** through the feedback inertance **570**, thus sustaining the process.

FIG. **7** is a diagram showing another embodiment of the thermoacoustic driving section **500***b*. The embodiment of FIG. **7** provides several modifications from the embodiment as shown in FIG. **5**. In this regard, the thermoacoustic driving section **500***b* of FIG. **7** comprises a shell **505**, an inlet conduit **705**, a fuel inlet **725**, coolant inlet **745***a*, a coolant outlet **740***a*, an exhaust port **715**, and a thermoacoustic driver **700** that is concentrically positioned within the shell **505**. The inlet conduit **705** and the fuel inlet **725** are adapted to admit a compressible inlet fluid **730** and fuel **580**, respectively, into the thermoacoustic driver **700**, while the exhaust port **715** is adapted to expel cold combustion products **720** that have been directed through various components in the thermoacoustic driver **700**. The coolant inlet **745***a* is adapted to introduce incoming coolant **750** to the thermoacoustic driver **700**, and the coolant outlet **740***a* expels the outgoing coolant **755** after the coolant has passed through the thermoacoustic driver **700**. In one embodiment, the coolant **750**, **755** may be cold water.

The shell **505** comprises a compliance section **565** and an inertance section **570**, which together permit the feedback of acoustic energy (e.g., an acoustic traveling wave) from one end of the thermoacoustic driver **700** to the other end of the thermoacoustic driver **700**. Additionally, these sections **565**, **570** define properties related to the acoustic traveling wave as it propagates through the device. The thermoacoustic driving section **500***b* has a movable end-cap **520**, which is positioned at one end of the shell **505**. Since the compliance section **565**, inertance section **570**, and movable end-cap **520** are discussed above with reference to FIG. **5**, further discussion of these components is omitted here.

The thermoacoustic driver **700** comprises an insulated wall **760** that thermally insulates the thermoacoustic driver **700** from the remaining portion of the interior of the shell **505**. Thus, regardless of temperature changes within the thermoacoustic driver **700**, the temperature of the remaining portion of the interior of the shell **505** remains relatively constant. This is particularly important in the inertance **570**, where temperature variations would lead to variations in the density of the compressible fluid within the inertance **570**, which may alter the properties of the acoustic traveling wave passing through the inertance **570**.

As shown in FIG. **7**, the interior of the thermoacoustic driver **700** comprises a primary cold heat exchanger **540**, a regenerator **550**, a combustion zone **780**, a flow straightener **765**, and a thermal buffer tube **775**. The primary cold heat exchanger **540** is coupled to the coolant inlet **745***a* and the coolant outlet **740***a*. The coolant inlet **745***a* introduces incoming coolant **750** to the primary cold heat exchanger **540**, while the coolant outlet **740***a* expels the outgoing coolant **755** from the primary cold heat exchanger **540**.

In one embodiment, the regenerator **550** has a cold side, which is coupled to the primary cold heat exchanger **540**, and a hot side, which is coupled to the combustion zone **780**. As described above with reference to FIG. **5**, the coupling of the primary cold heat exchanger **540** and the combustion zone **780** to the regenerator **550** establishes a temperature gradient across the regenerator **550**. The temperature gradient across the regenerator **550** amplifies acoustic traveling waves as the combustion products expand and contract within the regenerator **550** due to the pressure oscillations of the acoustic traveling wave. Since the amplification of acoustic traveling waves is described in detail with reference to FIG. **5**, further discussion of the operation of the regenerator **550** is omitted here.

The combustion zone **780** is configured to burn a combustible mixture **665**, which generates heat and the combustion products **720** that are conveyed to the hot side of the regenerator **550** by the mean flow. Due to the close thermal contact between the gas and the solid within the regenerator **550**, the mean flow of combustion products **720** from the hot side of the regenerator **550** to the cold side of the regenerator **550** causes the combustion products **720** to be cooled and to exit the cold side of the regenerator **550** at approximately the same temperature as the cold side of the regenerator **550**. In the embodiment of FIG. **7**, the combustion zone **780** is coupled to the inlet conduit **705** and the fuel inlet **725**. In this regard, if the compressible inlet fluid **730** contains an oxidizer, then the mixing of the compressible inlet fluid **730** and the fuel **580** at the combustion zone **780** results in a combustible mixture **665**. To increase the efficiency of the device, the inlet conduit **705** and the fuel inlet **725** may be configured to suppress the escape of acoustic energy from the thermoacoustic device. In one embodiment, the lengths of these inlet ports **705, 725** may be adjusted so that acoustic energy is reflected back to the interior of the thermoacoustic driver **700**. In another embodiment, the inlet ports **705, 725** can be highly pressurized, with the compressible inlet fluid **730** and the fuel **580** being admitted to the combustion zone **780** through choked nozzles, which will not allow acoustic perturbations to propagate upstream into these inlet ports **705, 725** and out of the device. While separate inlet ports **705, 725** are shown for the compressible inlet fluid **730** and the fuel **580**, it should be appreciated that, similar to FIG. **5**, the compressible inlet fluid .**730** and the fuel **580** may be supplied to the combustion zone **780** through a single inlet conduit in the form of a compressible combustible mixture **665**. Additionally, it should be appreciated that, similar to FIG. **5**, the burning of the combustible mixture may be pulsed in phase with the acoustic traveling wave such that the pulsed combustion constructively adds to the energy of the acoustic traveling wave. Since the combustion zone **780** of FIG. **7** serves a similar function to the combustion zone **585** of FIG. **5**, further discussion of the combustion zone **780** and the use of pulse combustion is omitted here.

The thermal buffer tube **775** is used to help thermally isolate the combustion zone **780** from the remaining portion of the interior of the shell **505**. The compressible fluid within the thermal buffer tube **775** sustains a mean temperature gradient from its hot side, which is coupled to the combustion zone **780**, to its cold side, which is coupled to a secondary cold heat exchanger **770**. To effectively sustain such a temperature gradient, care should be taken such that minimal net convective heat transfer effects are present in the thermal buffer tube **775**. In this manner, the compressible fluid in the thermal buffer tube **775** will remain thermally stratified along its length, and the primary method of heat transfer down the thermal buffer tube **775** is either through thermal conduction in the compressible fluid, or through axial thermal conduction in the portion of the insulated wall **760** that surrounds the thermal buffer tube **775**, depending on the thickness and axial thermal conductivity of this wall. For efficient operation, the thermal buffer tube **775** should preferably be at least twice as long as an acoustic displacement length, and may be tapered to reduce the effects of Rayleigh streaming in the thermal buffer tube **775**. Since Rayleigh streaming is known in the art and discussed in greater detail in U.S. Pat. No. 5,953,920 to Swift et al., further discussion of Rayleigh streaming is omitted here.

In some embodiments of the device, a flow straightener **765** is located between the combustion zone **780** and the thermal buffer tube **775** to preserve thermal stratification in the thermal buffer tube **775**. Since, in some embodiments, the combustion zone **780** contains a pulsed combustion process, a fairly turbulent environment may exist within the combustion zone **780** due to the pulsed combustion, which in turn may introduce undesired turbulence into the thermal buffer tube **775**. The flow straightener **765** reduces the encroachment of turbulence from the combustion zone **780** to the thermal buffer tube **775**. The flow straightener **765** may also serve a secondary role as a flashback arrestor. Through the axial acoustic motions that occur across the flow straightener **765** between the combustion zone **780** and the thermal buffer tube **775**, it is possible that the thermal buffer tube **775** may contain a quantity of unburned combustible mixture **665**. Through thermal and chemical interactions with the walls of the flow straightener **765**, the flames that burn the combustible mixture **665** in the combustion zone **780** should not be able to propagate beyond the flow straightener **765**. Thus, the combustible mixture **665** in the thermal buffer tube **775** should not explosively ignite and burn, thereby avoiding a potentially hazardous situation.

In conjunction with the primary cold heat exchanger **540** and the insulated wall **760**, the secondary cold heat exchanger **770** thermally insulates the thermal processes that occur within the thermoacoustic driver **700** from the remaining portion of the interior of the shell **505**. The secondary cold heat exchanger **770** helps generate the temperature gradient along the length of the thermal buffer tube **775**, and removes any heat that is transferred down this temperature gradient from the combustion zone **780**. The secondary cold heat exchanger **770** is coupled to a coolant inlet **745*b*** and a coolant outlet **740*b***. The coolant inlet **745*b*** introduces incoming coolant **750** to the secondary cold heat exchanger **770**, while the coolant outlet **740*b*** expels the outgoing coolant **755** from the secondary cold heat exchanger **770**. In some embodiments, the same coolant inlet **745*a*** and the same coolant outlet **740*a*** may be used for both the primary cold heat exchanger **540** and: the secondary cold heat exchanger **770**. For those embodiments, the coolant inlet **745*a*** and the coolant outlet **740*a*** are, preferably, insulated to prevent heat transfer from the regenerator **550** or the combustion zone **780** to the coolant pipes **745*a***, **740*a*** as they circulate cooling fluid to the secondary cold heat exchanger **770**.

While not shown in FIG. **7**, an additional flow straightener may be coupled to the secondary cold heat exchanger **770** at the end of the thermal buffer tube **775** to help preserve the thermal stratification in the thermal buffer tube **775**. This flow straightener would serve to suppress non-axial flow movements that may be generated due to turbulent acoustic gas motions at the junction between the inertance **570** and the lower end of the thermoacoustic driver **700**.

The thermoacoustic driver **700** also comprises an acoustically transparent barrier **735** located at one end near the exhaust port **715**. The acoustically transparent barrier **735** is relatively impermeable to the mean flow of compressible fluid and sustains a mean pressure difference across the acoustically transparent barrier **735**, thus forcing the mean flow in the device through the combustion zone **780** and the regenerator **550** before exiting the exhaust port **715**. In some embodiments, the acoustically transparent barrier **735** may be a hydrodynamic jet pump as shown in FIG. **7**. Since the acoustically transparent barrier **735** is discussed above with reference to FIG. **5**, further discussion of the acoustically transparent barrier **735** is omitted here.

Unlike FIG. **5**, the inlet conduit **705** of FIG. **7** passes through the regenerator **550** and admits the compressible inlet fluid **730** directly to the combustion zone **780** in the interior of the thermoacoustic driver **700**. This is done to preheat the compressible inlet fluid **730** before it enters the combustion zone **780**. In some embodiments, the inlet conduit **705** may be configured as an annulus that surrounds the regenerator **550** and the combustion zone **780** in order to help thermally insulate the regenerator **550** and the combustion zone **780** from the rest of the device, and to increase the amount of heat transferred to the compressible inlet fluid **730**. To further augment the preheating of the compressible inlet fluid **730**, other embodiments may include several inlet conduits that pass through the regenerator **550** and the combustion zone **780**, or in still other embodiments, fins may be added to that portion of the interior of the inlet conduit annulus that is in thermal contact with the regenerator **550** in order to enhance the rate of radial heat transfer out of the regenerator **550**. However, note that if the compressible inlet fluid **730** is comprised of a combustible mixture **665**, that the amount of preheating of the combustible mixture **665** within the inlet conduit **705** should be low enough so as to avoid premature combustion within the inlet conduit **705**.

Another difference shown in FIG. **7** is that, unlike the embodiment shown in FIG. **5**, the insulated walls **760** and the thermal buffer tube **775** suppress heat transfer between the thermoacoustic driver **700** and the remaining interior portion of the shell **505** (e.g., the inertance section **570**, the compliance section **565**, etc.). The insulation between the thermoacoustic driver **700** and the remaining portion of the interior of the shell **505** reduces temperature variations in the remaining portion of the interior of the shell. Consequently, this may result in more stable properties of the acoustic traveling wave as it passes through these components.

FIG. **8** is a diagram showing the acoustic energy flow paths in the thermoacoustic driving section **500***b* of FIG. **7**. In the embodiment of FIG. **8**, acoustic energy is directed through a feedback inertance section **570** established by concentrically disposing the thermoacoustic driver **700** within the shell **505**. As shown in FIG. **8**, acoustic energy passes through the acoustically transparent barrier **735** with minimal attenuation, and is directed down through the regenerator **550** where it is amplified by the temperature gradient across the regenerator **550**. Thereafter, the acoustic energy passes through the combustion zone **780**, where it may be further amplified by a pulse combustion process. As the acoustic energy exits the thermoacoustic driver **700**, a portion of the acoustic energy is directed to the resonator **220** for use by a thermoacoustic refrigerator, thermoacoustic heat pump or linear alternator **420**, while the remaining portion of the acoustic energy is directed back to the regenerator **550** through the feedback inertance section **570**, thus sustaining the process.

As shown, the embodiments of FIGS. **4** through **8** introduce a mean flow of compressible fluid across a regenerator. As a result of the mean flow, a hot heat exchanger in a conventional thermoacoustic device may be replaced by a combustion zone, which reduces thermal stresses that were previously present with the hot heat exchanger. Also, the concentric disposition of the thermoacoustic driver within the shell allows for the reduction of the thickness of the walls of the thermoacoustic driver, thereby reducing axial heat conduction losses in the walls and further increasing efficiency.

Although exemplary embodiments have been shown and described, it will be clear to those of ordinary skill in the art that a number of changes, modifications, or alterations to the invention as described may be made. For example, it should be appreciated that the dimensions and the shape of the shell **505** and the thermoacoustic driver **700** may be varied in order to optimize the properties of the acoustic traveling wave. Additionally, while cold water **750** is used to cool the cold heat exchangers **540** and **770**, it should be appreciated that various cooling fluid **750** may be used to cool the cold heat exchangers **540** and **770**. It should also be appreciated that the exhaust port **715** may be located between the cold heat exchanger **540** and the regenerator **550** without adversely affecting the performance of the system. Furthermore, while example embodiments show the thermoacoustic driver **700** being substantially symmetrically disposed within the shell **505**, it should be appreciated that the thermoacoustic driver **700** may be asymmetrically disposed within the shell **505**. It should also be recognized that the thermoacoustic driver **700** may be located adjacent to one side of the interior of the shell **505**. Alternatively, if one wished to only take advantage of the mean flow and combustion processes, a linear device without an acoustic feedback path could be used, similar to the conventional thermoacoustic driver **100** shown in FIG. **1**, or a toroidal device could be used, similar to the TASHE **200** shown in FIG. **2**.

All such changes, modifications, and alterations should therefore be seen as within the scope of the disclosure.

What is claimed is:

1. A thermoacoustic device comprising:

(A) a thermoacoustic driver having:

(A1) an inlet conduit adapted to admit a compressible inlet fluid, the compressible inlet fluid comprising an oxidizer;

(A2) a fuel injector adapted to provide fuel;

(A3) a mixing section adapted to receive the compressible inlet fluid from the inlet conduit, the mixing section further being adapted to receive the fuel from the fuel injector, the mixing section further being adapted to mix the fuel and the compressible inlet fluid to produce a compressible combustible mixture;

(A4) a combustion zone configured to receive the compressible combustible mixture, the combustion zone further being configured to burn the compressible combustible mixture to generate hot compressible combustion products;

(A5) a cold heat exchanger;

(A6) a regenerator coupled to the combustion zone, the regenerator having a cold side and a hot side, the cold side and the hot side being configured to generate a temperature gradient across the regenerator, the cold side of the regenerator being coupled to the cold heat exchanger, the hot compressible combustion products from the combustion zone being directed to the hot side of the regenerator, the hot compressible combustion products further being directed through the regenerator to produce cold compressible combustion products, the regenerator further being configured to amplify an acoustic traveling wave propagating from the cold side of the regenerator to the hot side through the regenerator; and

(A7) an exhaust port adapted to expel the cold compressible combustion products; and

(B) a feedback path located external to the thermoacoustic driver, the feedback path being thermally insulated from the regenerator and the combustion zone, the feedback path being configured to direct a portion of the acoustic traveling wave from the hot side of the regenerator to the cold side of the regenerator.

2. The thermoacoustic device of claim **1**, wherein the inlet conduit is an annulus surrounding the regenerator, the regenerator and the inlet conduit being in thermal contact with each other to permit heat transfer between the inlet conduit and the regenerator.

3. The thermoacoustic device of claim **1**, wherein the inlet conduit is configured to pass through the regenerator, the regenerator and the inlet conduit being in thermal contact with each other to permit heat transfer between the inlet conduit and the regenerator.

4. The thermoacoustic device of claim **1**, wherein the inlet conduit is an annulus surrounding the combustion zone, the combustion zone and the inlet conduit being in thermal contact with each other to permit heat transfer between the inlet conduit and the combustion zone.

5. The thermoacoustic device of claim **1**, wherein the inlet conduit extends through the combustion zone, the combustion zone and the inlet conduit being in thermal contact with each other to permit heat transfer between the inlet conduit and the combustion zone.

6. The thermoacoustic device of claim **1**, wherein the combustion zone is further configured employ a pulse combustion process in which the burning of the compressible combustible mixture is done in a pulsating manner, the pulsed burning of the compressible combustible mixture being synchronized to pressure oscillations of the acoustic traveling wave, the pulsed burning further being phased to the pressure oscillations of the acoustic traveling wave to amplify the pressure oscillations of the acoustic traveling wave.

7. The thermoacoustic device of claim **1**, further comprising a catalyst located within the combustion zone, the catalyst being adapted to facilitate burning of the compressible combustible mixture.

8. The thermoacoustic device of claim **1**, further comprising:

an acoustically transparent barrier adapted to direct the compressible combustible mixture to the combustion zone, the acoustically transparent barrier further being adapted to direct the compressible combustible products through the regenerator.

9. The thermoacoustic device of claim **1**, further comprising:

a compliance section located within the feedback path; and

an inertance section located within the feedback path, the inertance section being coupled to the compliance section, the inertance section together with the compliance section being configured to define properties of the acoustic traveling wave.

10. The thermoacoustic device of claim **9**, wherein the inertance section is configured as an annulus surrounding the regenerator.

11. The thermoacoustic device of claim **9**, wherein the regenerator is configured as an annulus surrounding the inertance section.

12. The thermoacoustic device of claim **9**, wherein the volume of the compliance section is adjustable to adjust the properties of the acoustic traveling wave.

13. The thermoacoustic device of claim **1**, further comprising:

a thermal buffer tube having a cold side and a hot side, the hot side of the thermal buffer tube being coupled to the combustion zone, the cold side of the thermal buffer tube being coupled to a secondary cold heat exchanger, the thermal buffer tube being configured to thermally insulate the thermoacoustic driver from the feedback path.

14. The thermoacoustic device of claim **13**, further comprising:

a flow straightener situated between the thermal buffer tube and the combustion zone, the flow straightener being adapted to prevent turbulence in the combustion zone from distributing compressible fluid in the thermal buffer tube.

15. The thermoacoustic device of claim **13**, further comprising:

a flow straightener coupled to the secondary cold heat exchanger, the flow straightener being adapted to reduce turbulence at the cold side of the thermal buffer tube.

16. A thermnoacoustic device comprising:

(A) a thermoacoustic driver having:

(A1) an inlet conduit adapted to admit a compressible combustible mixture;

(A2) a combustion zone configured to receive the compressible combustible mixture, the combustion zone further being configured to burn the compressible combustible mixture to generate hot compressible combustion products;

(A3) a cold heat exchanger;

(A4) a regenerator coupled to the combustion zone, the regenerator having a cold side and a hot side, the cold side and the hot side being configured to generate a temperature gradient across the regenerator, the cold side of the regenerator being coupled to the cold heat exchanger, the hot compressible combustion products from the combustion zone being directed to the hot side of the regenerator, the hot compressible combustion products further being directed through the regenerator to produce cold compressible combustion products, the regenerator further being configured to amplify an acoustic traveling wave propagating from the cold side of the regenerator to the hot side of the regenerator; and

(A5) an exhaust port adapted to expel the cold compressible combustion products; and

(B) a feedback path located external to the thermoacoustic driver, the feedback path being thermally insulated from the regenerator and the combustion zone, the feedback path being configured to direct a portion of the acoustic traveling wave from the hot side of the regenerator to the cold side of the regenerator.

17. The thermoacoustic device of claim **16**, wherein the inlet conduit is an annulus surrounding the regenerator, the regenerator being in thermal contact with the inlet conduit to permit heat transfer between the inlet conduit and the regenerator.

18. The thermoacoustic device of claim **16**, wherein the inlet conduit extends through the regenerator, the regenerator being in thermal contact with the inlet conduit to permit heat transfer between the inlet conduit and the regenerator.

19. The thermoacoustic device of claim **16**, wherein the inlet conduit is an annulus surrounding the combustion zone, the combustion zone being in thermal contact with the inlet conduit to permit heat transfer between the inlet conduit and the combustion zone.

20. The thermoacoustic device of claim **16**, wherein the inlet conduit extends through the combustion zone, the combustion zone being in thermal contact with the inlet conduit to permit heat transfer between the inlet conduit and the combustion zone.

21. The thermoacoustic device of claim **16**, wherein the combustion zone is further configured employ a pulse combustion process in which the burning of the compressible combustible mixture is done in a pulsating manner, the pulsed burning of the compressible combustible mixture being phased to the pressure oscillations of the acoustic traveling wave to amplify the pressure oscillations of the acoustic traveling wave.

22. The thermoacoustic device of claim **16**, further comprising a catalyst located within the combustion zone, the catalyst being adapted to facilitate burning of the compressible combustible mixture.

23. The thermoacoustic device of claim **21**, further comprising:

a sensor adapted to detect the pressure oscillations of the acoustic traveling wave; and

a controller adapted to regulate the burning of the compressible combustible mixture within the combustion zone in response to the detected pressure oscillations.

24. The thermoacoustic device of claim **16**, further comprising:

means for directing the hot compressible combustion products through the regenerator.

25. The thermoacoustic device of claim **16**, further comprising:

an acoustically transparent barrier adapted to direct the hot compressible combustion products through the regenerator.

26. The thermoacoustic device of claim **25**, wherein the acoustically transparent barrier is a hydrodynamic jet pump.

27. The thermoacoustic device of claim **16**, further comprising:

a compliance section located within the feedback path; and

an inertance section located within the feedback path, the inertance section being coupled to the compliance section, the inertance section together with the compliance section being configured to define properties of the acoustic traveling wave.

28. The thermoacoustic device of claim **27**, wherein the inertance section is configured as an annulus surrounding the regenerator.

29. The thermoacoustic device of claim **27**, wherein the regenerator is configured as an annulus surrounding the inertance section.

30. The thermoacoustic device of claim **27**, wherein the volume of the compliance section is adjustable to adjust the properties of the acoustic traveling wave.

31. The thermoacoustic device of claim **16**, further comprising:

a thermal buffer tube having a cold side and a hot side, the hot side of the thermal buffer tube being coupled to the combustion zone, the cold side of the thermal buffer tube being coupled to a secondary cold heat exchanger, the thermal buffer tube being configured to thermally insulate the thermoacoustic driver from the feedback path.

32. The thermoacoustic device of claim **31**, further comprising:

a flow straightener situated between the thermal buffer tube and the combustion zone, the flow straightener being adapted to prevent turbulence in the combustion zone from disturbing compressible fluid in the thermal buffer tube.

33. The thermoacoustic device of claim **31**, further comprising:

a flow straightener coupled to the secondary cold heat exchanger, the flow straightener being adapted to reduce turbulence at the cold side of the thermal buffer tube.

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