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Phillips et al.

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(54) **SPLIT-CYCLE AIR HYBRID V-ENGINE**

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(51) **Int. Cl.**
F02B 33/00 (2006.01)
F02M 15/00 (2006.01)

(52) **U.S. Cl.**
USPC .... **123/68**; 123/70 R; 123/542

(58) **Field of Classification Search**
USPC .... 123/68, 70 R, 542, 543, 556
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,936,653	A	11/1933	Almen
2,058,705	A	10/1936	Maniscalo
2,109,809	A	3/1938	Van Ranst
2,394,354	A	2/1946	Barr
2,772,667	A	12/1956	Nallinger
3,209,737	A	10/1965	Isao
3,774,581	A	11/1973	Lundy
3,786,792	A	1/1974	Pelizzoni et al.
3,808,818	A	5/1974	Cataldo
3,880,126	A	4/1975	Thurston et al.
3,908,701	A	9/1975	Dawawala
3,938,483	A	2/1976	Firey
3,949,964	A	4/1976	Freeman
4,133,172	A	1/1979	Cataldo

(Continued)

FOREIGN PATENT DOCUMENTS

DE	10115967	A1	10/2002
GB	2250801	A	6/1992

(Continued)

OTHER PUBLICATIONS

Meldolesi, et al. (Southwest Research Institute), Scuderi Split Cycle Fast Acting Valvetrain: Architecture and Development, SAE paper 2011-01-0404 (Jan. 18, 2011) (23 pages).

(Continued)

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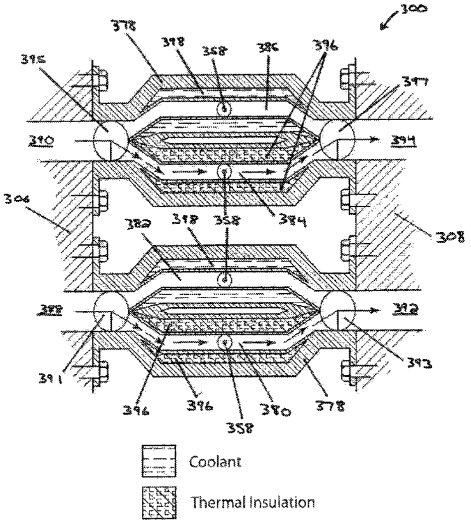
(57) **ABSTRACT**

A split-cycle air hybrid engine with improved efficiency is disclosed in which the centerline of a compression cylinder is positioned at a non-zero angle with respect to the centerline of an expansion cylinder such that the engine has a V-shaped configuration. In one embodiment, the centerlines of the respective cylinders intersect an axis parallel to, but offset from, the axis of rotation of the crankshaft. Modular crossover passages, crossover passage manifolds, and associated air reservoir valve assemblies and thermal regulation systems are also disclosed.

15 Claims, 12 Drawing Sheets



(56) References Cited

U.S. PATENT DOCUMENTS

4,224,798	A	9/1980	Brinkerhoff
4,307,687	A	12/1981	Holstein
4,344,405	A	8/1982	Zaharis
4,418,657	A	12/1983	Wishart
4,825,717	A	5/1989	Mills
4,860,716	A	8/1989	Deutschmann
4,934,652	A	6/1990	Golden
5,018,487	A	5/1991	Shinkai
5,193,495	A	3/1993	Wood, III
5,402,756	A	4/1995	Bohme et al.
5,555,861	A	9/1996	Mayr et al.
5,690,066	A	11/1997	Hampton et al.
5,713,316	A	2/1998	Sturman
5,964,087	A	10/1999	Tort-Oropeza
5,988,124	A	11/1999	Duesmann
6,152,714	A	11/2000	Mitsuya et al.
6,192,841	B1	2/2001	Vorih et al.
6,230,472	B1	5/2001	Stahlecker
6,230,742	B1	5/2001	Bircann
6,273,057	B1	8/2001	Schwoerer et al.
6,302,370	B1	10/2001	Schwoerer et al.
6,332,917	B1	12/2001	Schollkopf
6,334,435	B1	1/2002	Negre et al.
6,397,579	B1	6/2002	Negre
6,412,457	B1	7/2002	Vorih et al.
6,474,277	B1	11/2002	Vanderpoel et al.
6,510,824	B2	1/2003	Vorih et al.
6,543,225	B2	4/2003	Scuderi
6,584,885	B2	7/2003	Lou
6,609,371	B2	8/2003	Scuderi
6,647,954	B2	11/2003	Yang et al.
6,655,327	B1	12/2003	Hedman
6,874,453	B2	4/2005	Coney et al.
6,883,775	B2	4/2005	Coney et al.
6,952,923	B2	10/2005	Branyon et al.
7,140,332	B2	11/2006	Klein et al.
7,156,062	B2	1/2007	Vanderpoel
7,171,930	B2	2/2007	Keel
7,353,786	B2	4/2008	Scuderi et al.
7,481,190	B2	1/2009	Scuderi
7,513,224	B2	4/2009	Heaton
7,536,984	B2	5/2009	Lou
7,603,970	B2	10/2009	Scuderi et al.
7,628,126	B2	12/2009	Scuderi
7,637,234	B2	12/2009	Tussing et al.
7,690,337	B2	4/2010	Pirault et al.
7,810,459	B2	10/2010	Branyon et al.
7,823,547	B2	11/2010	Forner, Sr. et al.
7,963,259	B2	6/2011	Meldolesi et al.
2002/0185091	A1	12/2002	Vorih et al.
2005/0022768	A1	2/2005	Tores et al.
2005/0132987	A1	6/2005	Chang
2005/0268609	A1	12/2005	Branyon et al.
2006/0124085	A1	6/2006	Luttgeharm
2006/0273271	A1	12/2006	Yang et al.
2007/0157894	A1	7/2007	Scuderi et al.
2008/0054205	A1	3/2008	Lou
2008/0202454	A1	8/2008	Pirault
2008/0251041	A1	10/2008	Lou
2009/0038596	A1	2/2009	Pirault et al.
2009/0038598	A1	2/2009	Phillips
2009/0044778	A1	2/2009	Scuderi et al.
2009/0133648	A1	5/2009	Lou
2010/0126442	A1	5/2010	Lou
2010/0180847	A1	7/2010	Meldolesi et al.
2010/0180848	A1	7/2010	Meldolesi et al.
2010/0263646	A1	10/2010	Giannini et al.
2010/0282225	A1	11/2010	Gilbert et al.
2010/0300385	A1	12/2010	Durrett et al.

FOREIGN PATENT DOCUMENTS

GB	2340881	A	3/2000
JP	40-010860	A	4/1965
JP	10-274105	A	10/1998
JP	2004-293695	A	10/2004
WO	2006094213	A1	9/2006

OTHER PUBLICATIONS

Phillips, et al. (Southwest Research Institute), Scuderi Split Cycle Research Engine: Overview, Architecture and Operation, SAE paper 2011-01-0403 (Jan. 18, 2011) (21 pages).

Urata, et al. (Honda), A Study of Vehicle Equipped with Non-Throttling S.I. Engine with Early Intake Valve Closing Mechanism, SAE paper 930820 (Mar. 1, 1993) (13 pages).

International Search Report and Written Opinion, PCT/US2011/053802, dated Feb. 14, 2012 (13 pages).

FIG. 1
Prior Art

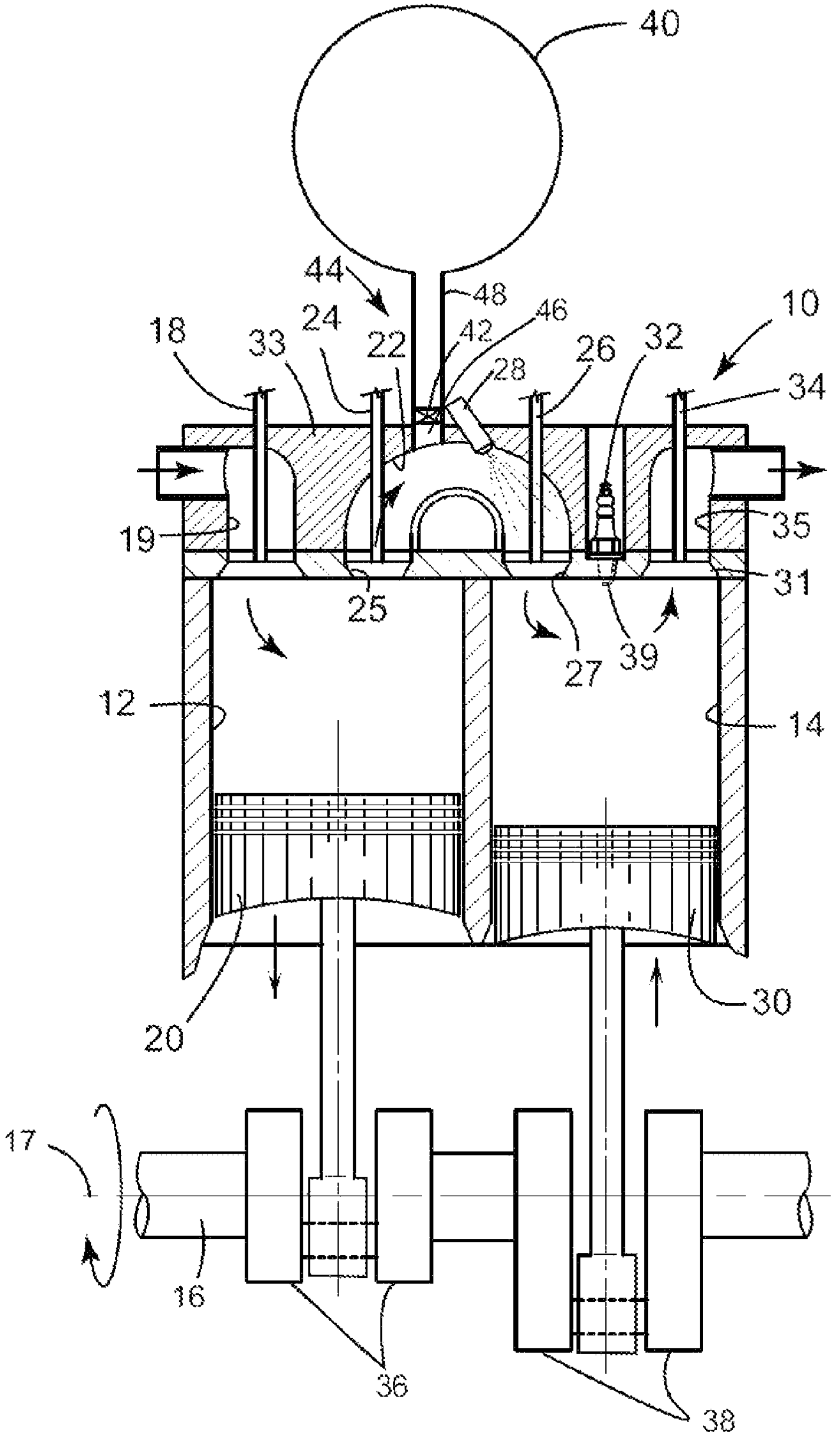


FIG. 2

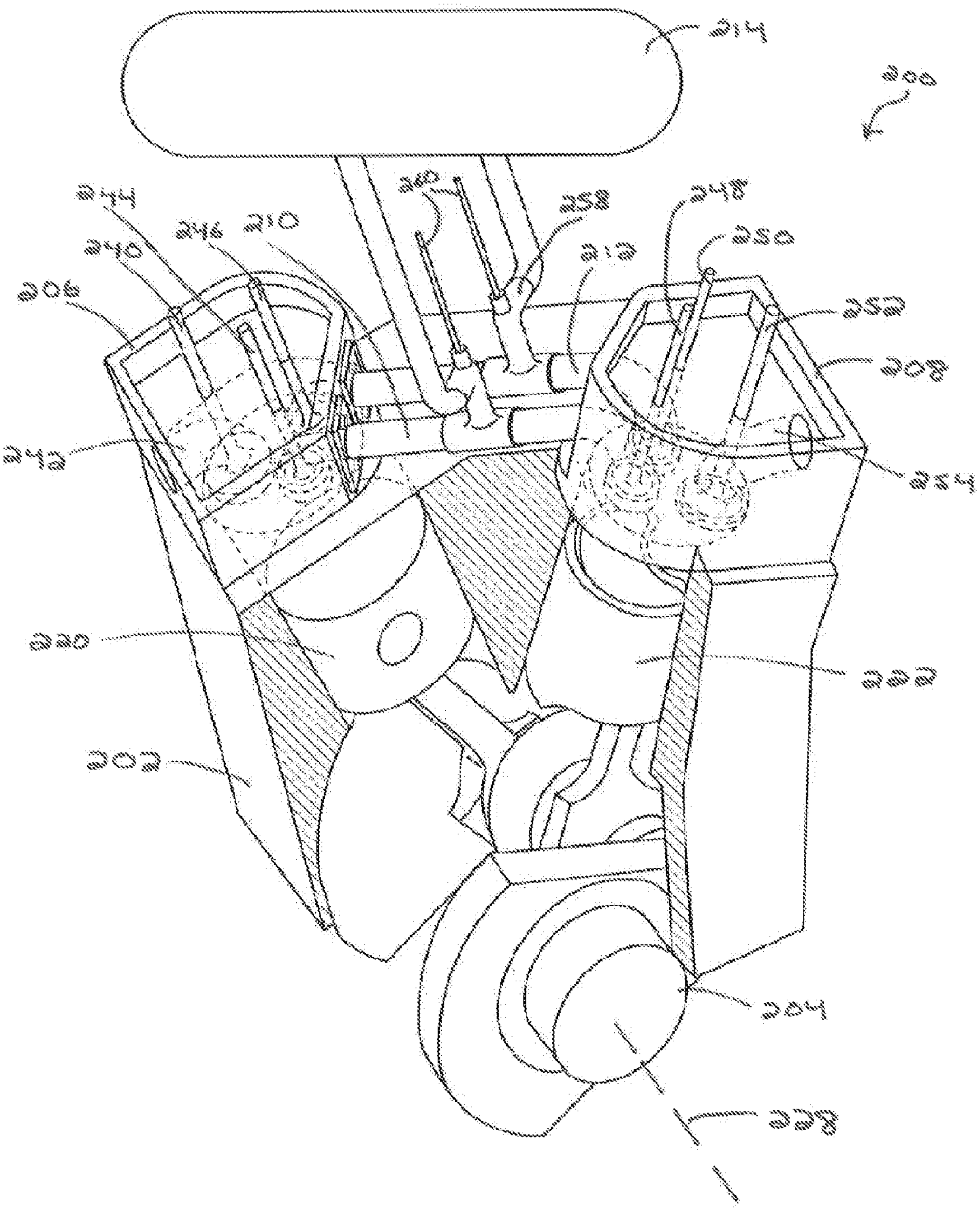

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FIG. 3

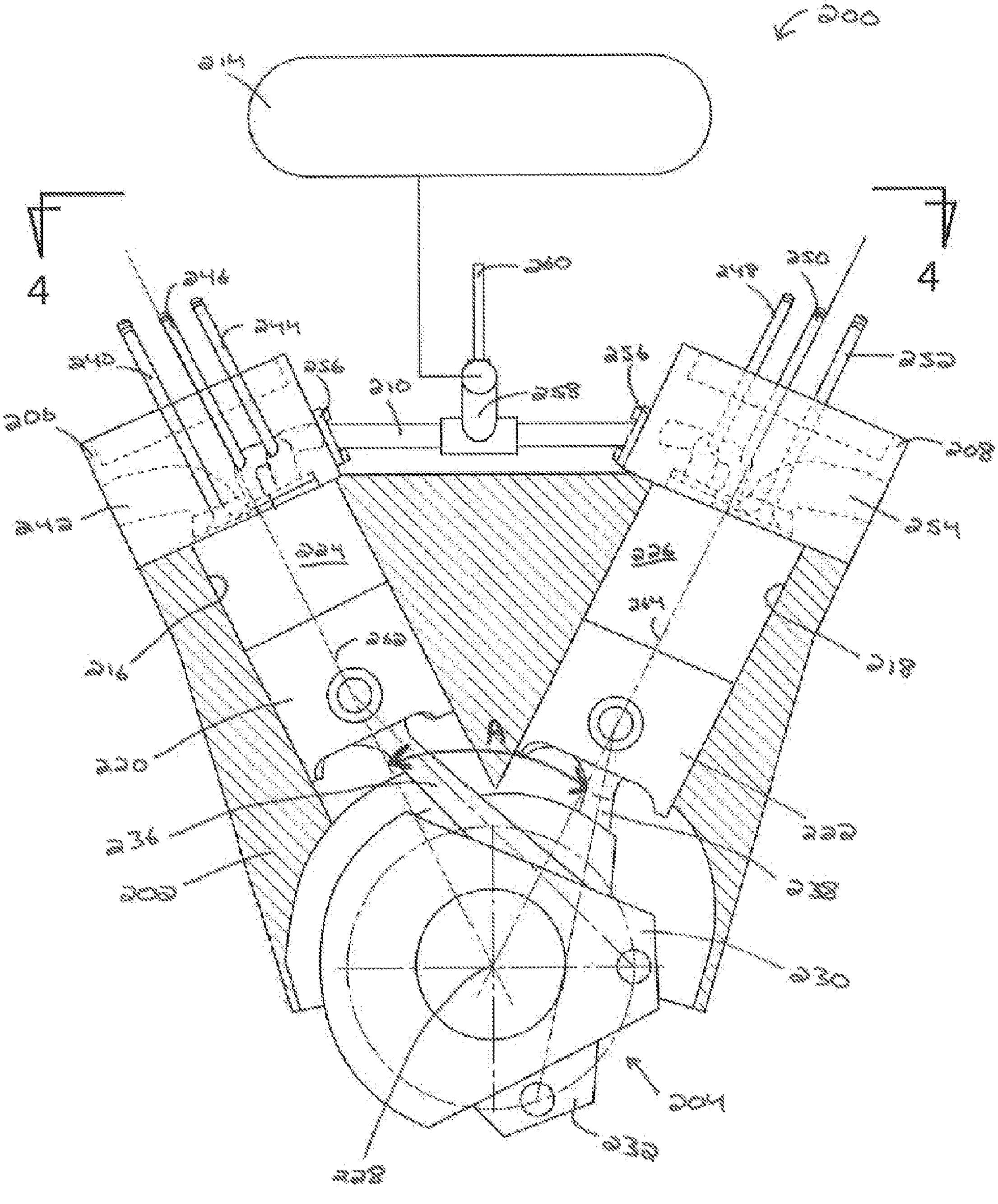
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FIG. 4

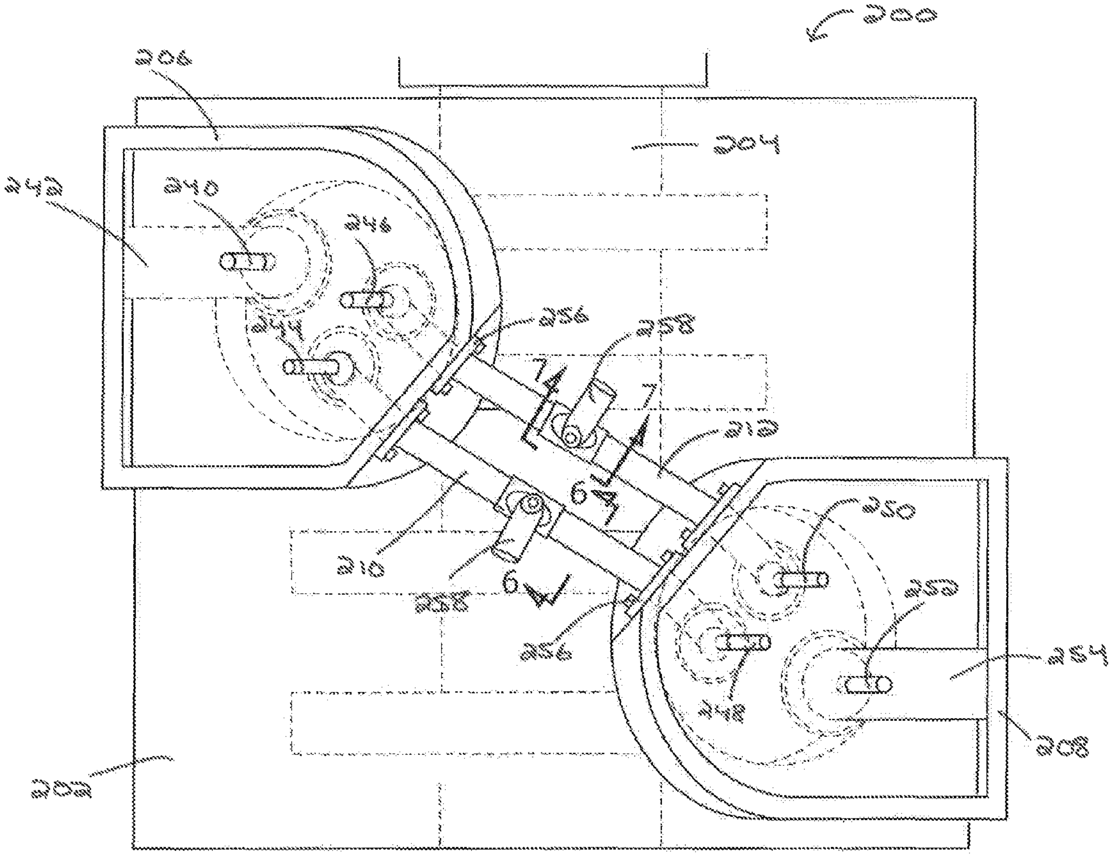
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FIG. 5

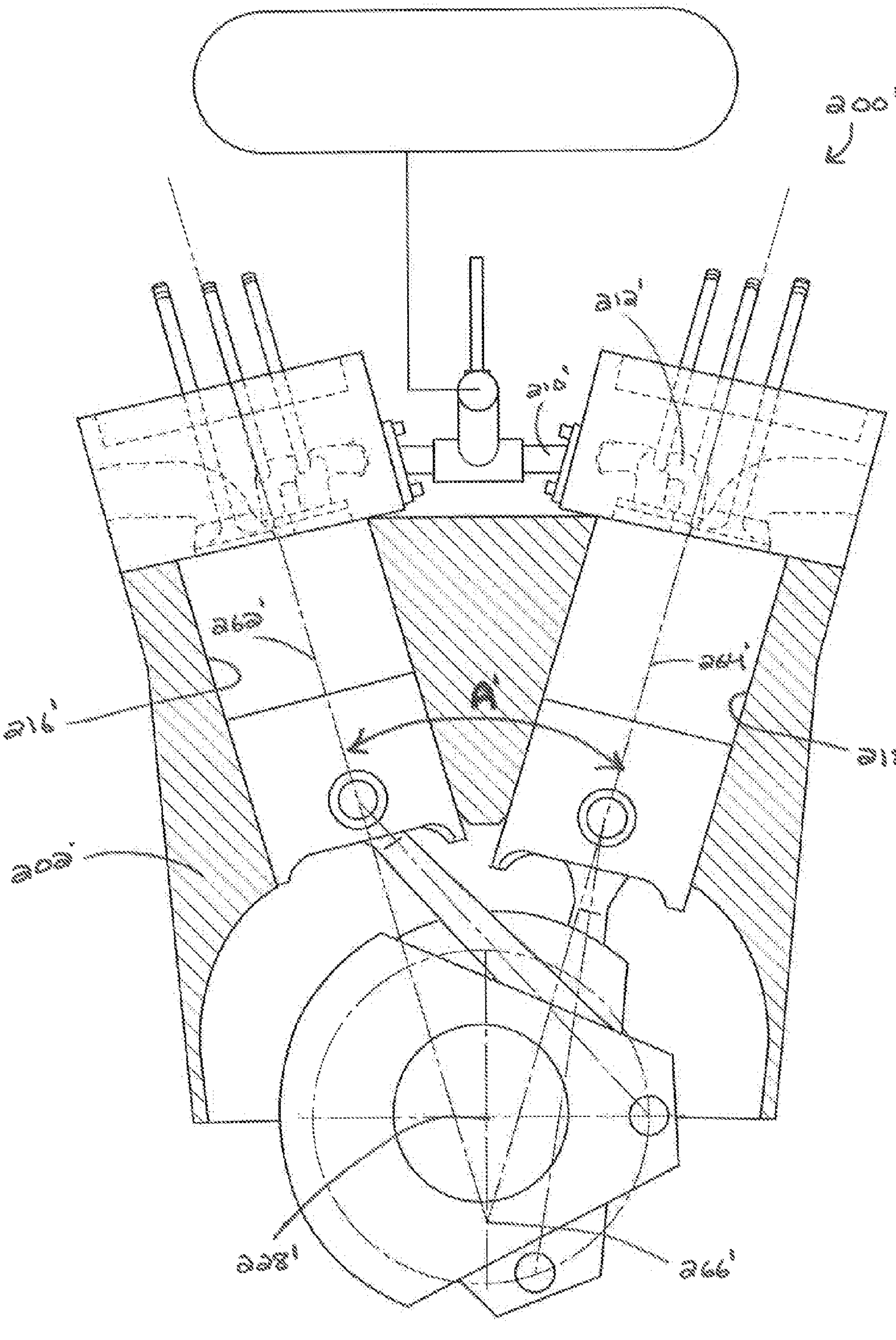


FIG. 6

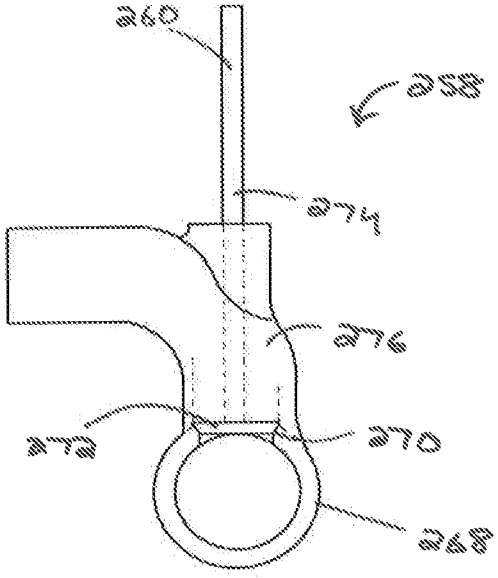


FIG. 7

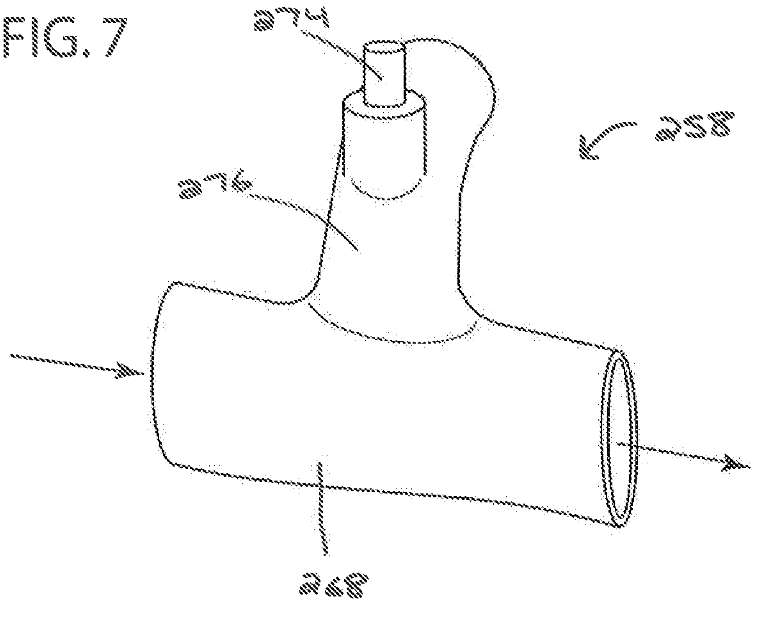


FIG. 8

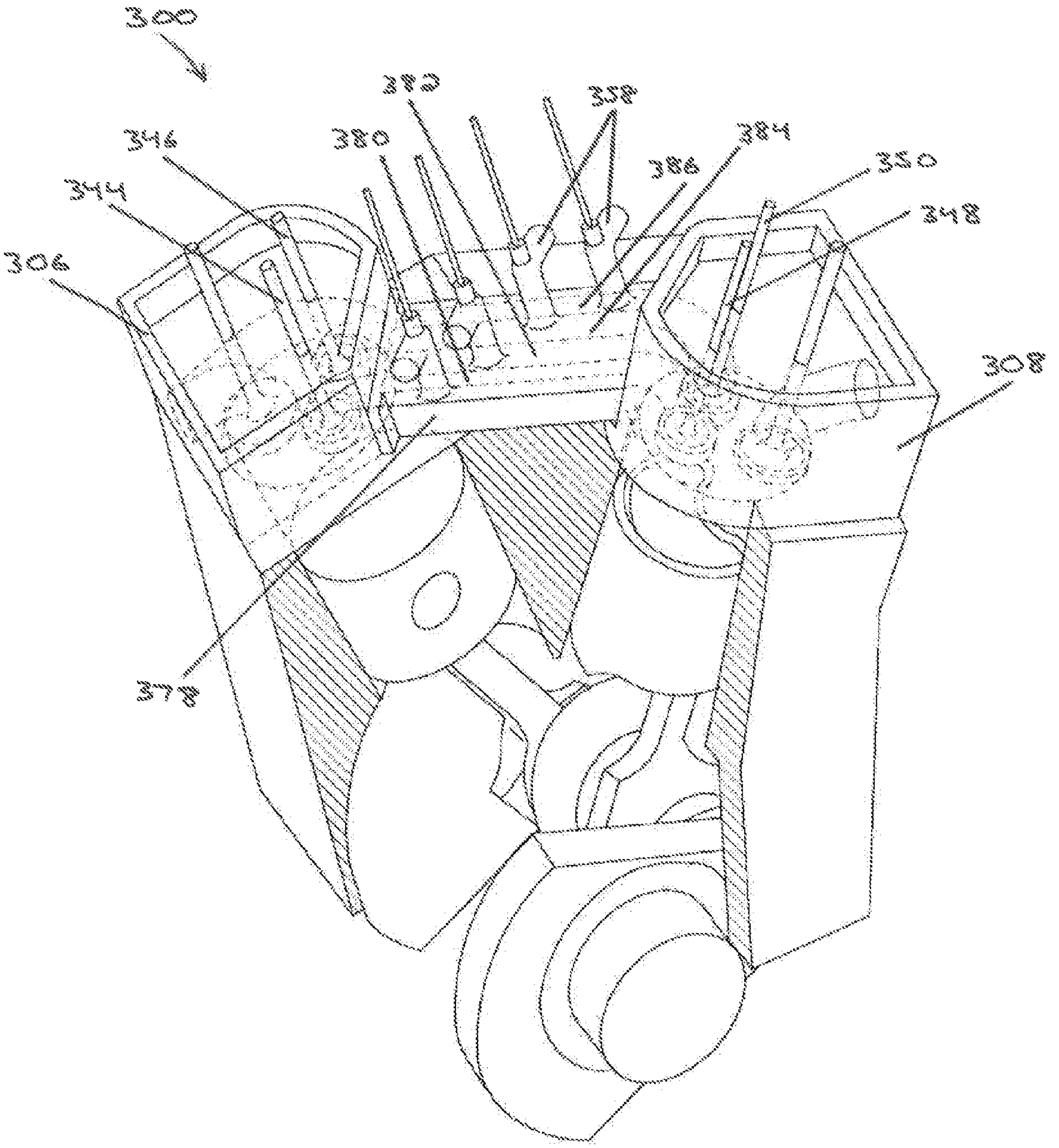
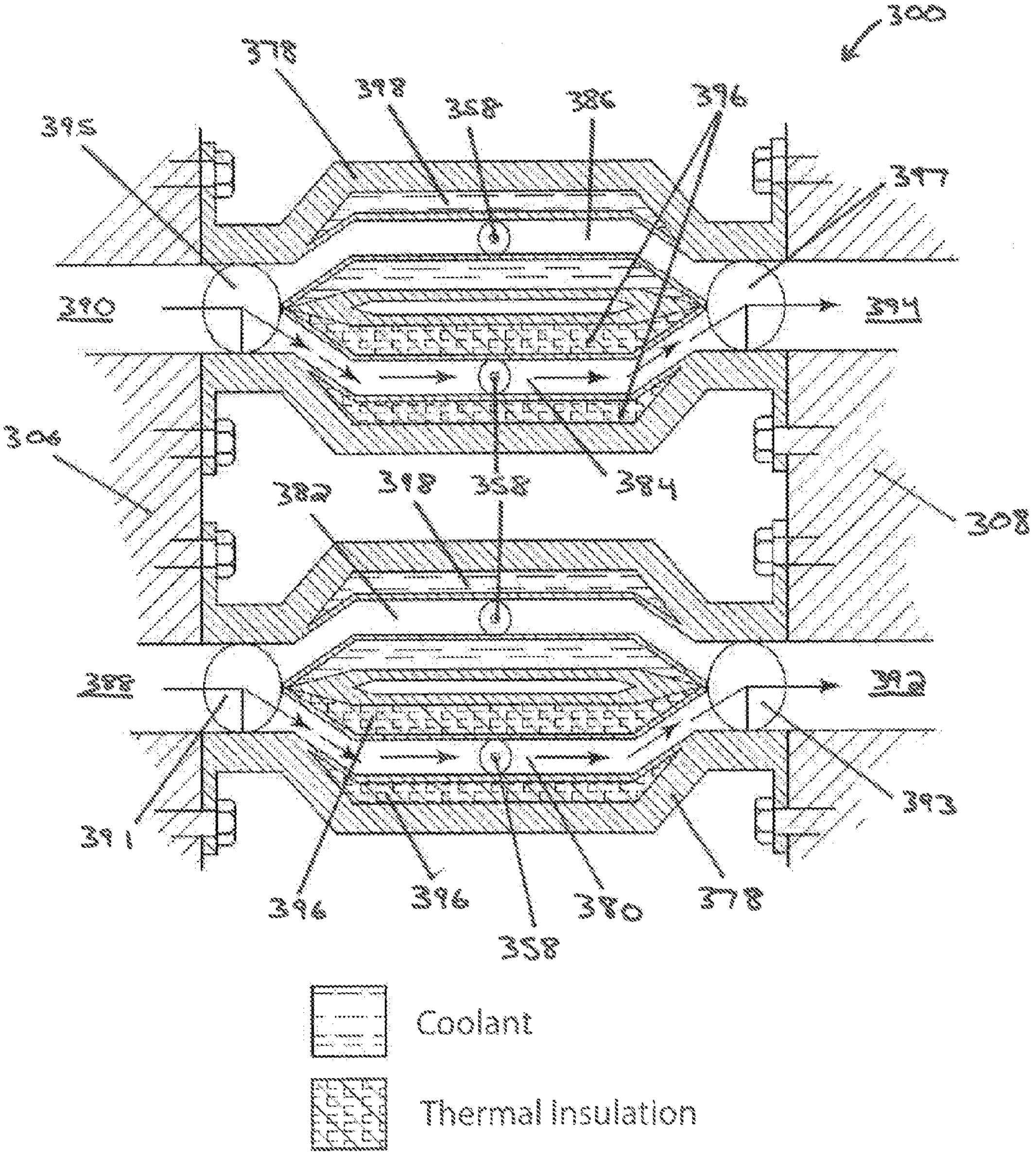


FIG. 9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Coolant
Thermal Insulation

FIG. 10

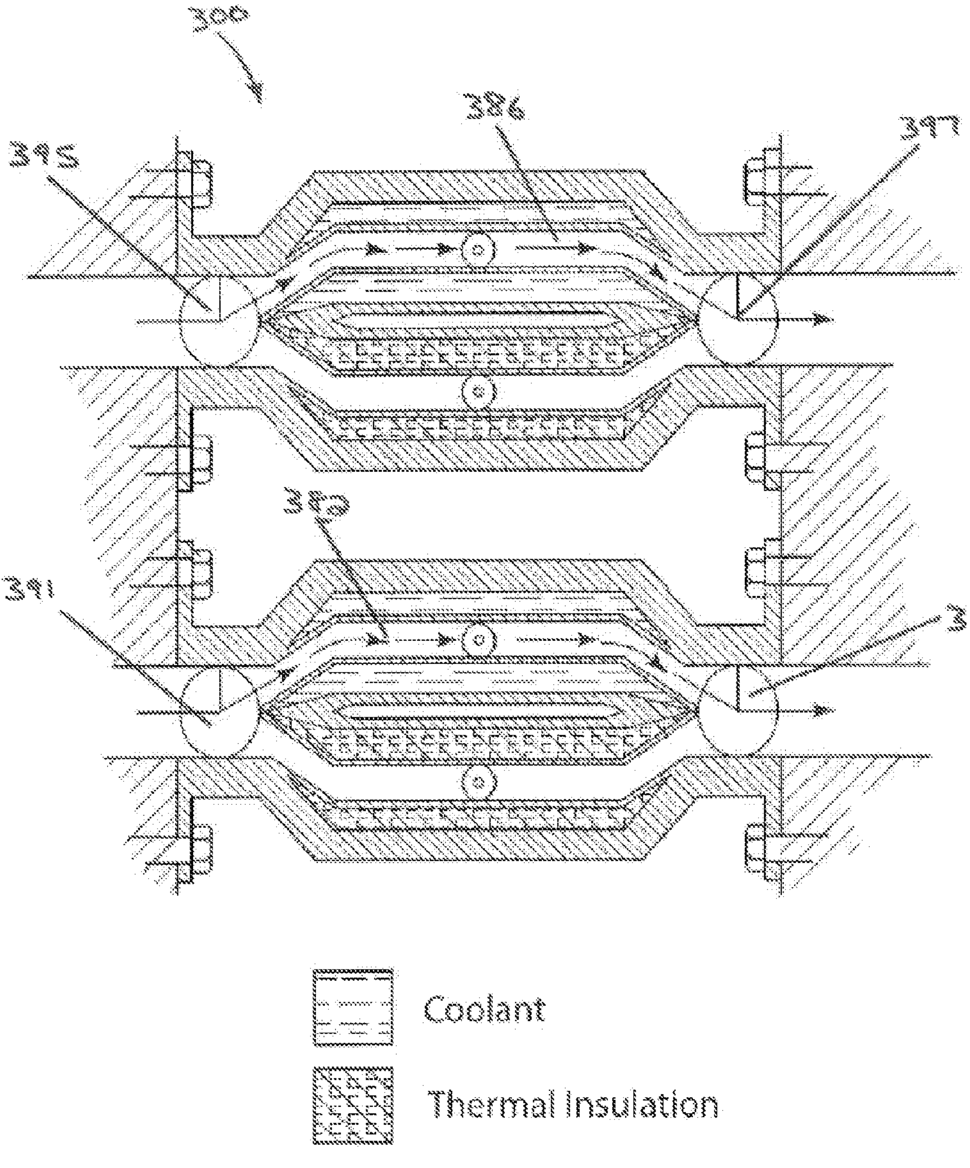


FIG. 11

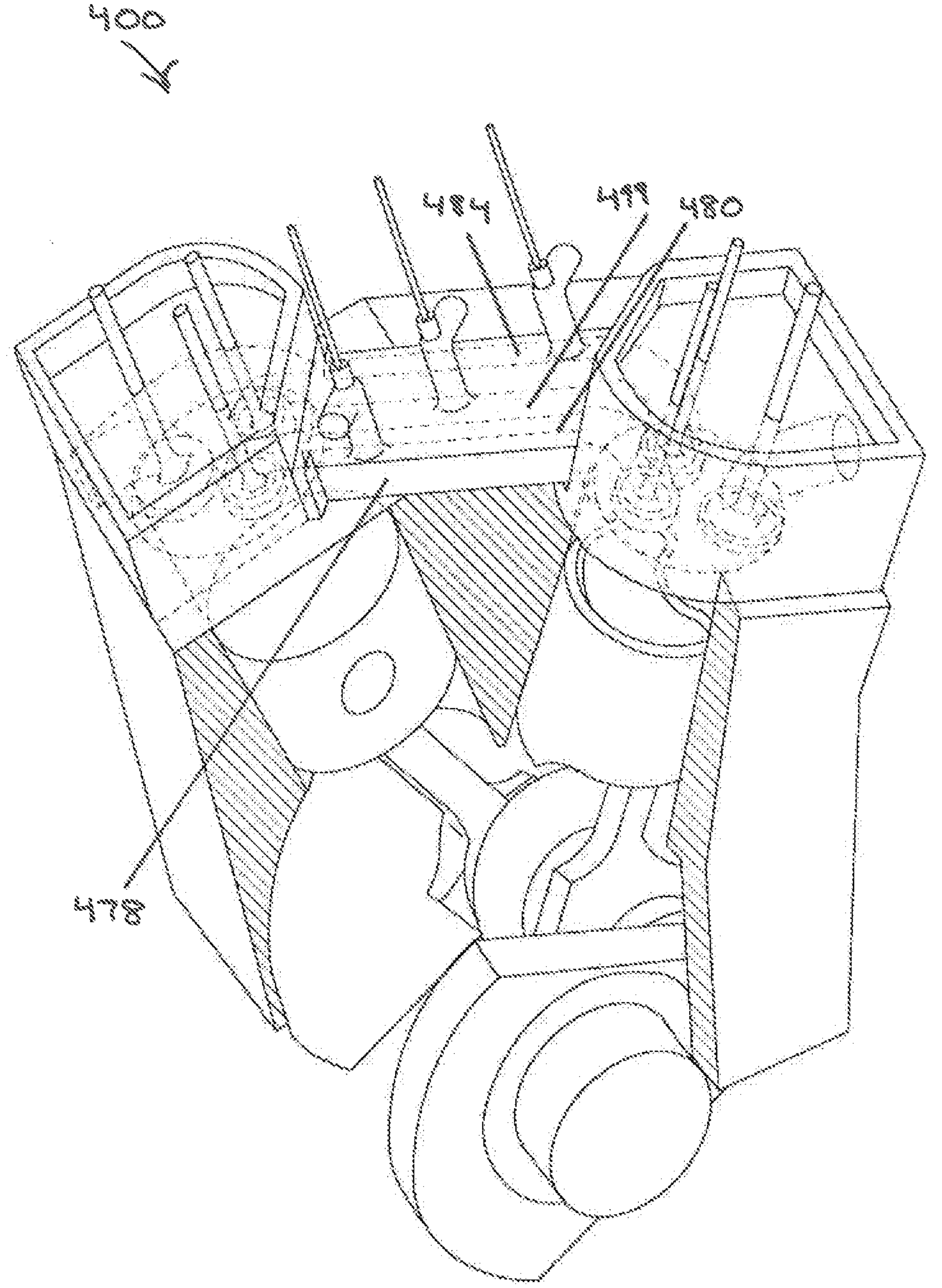
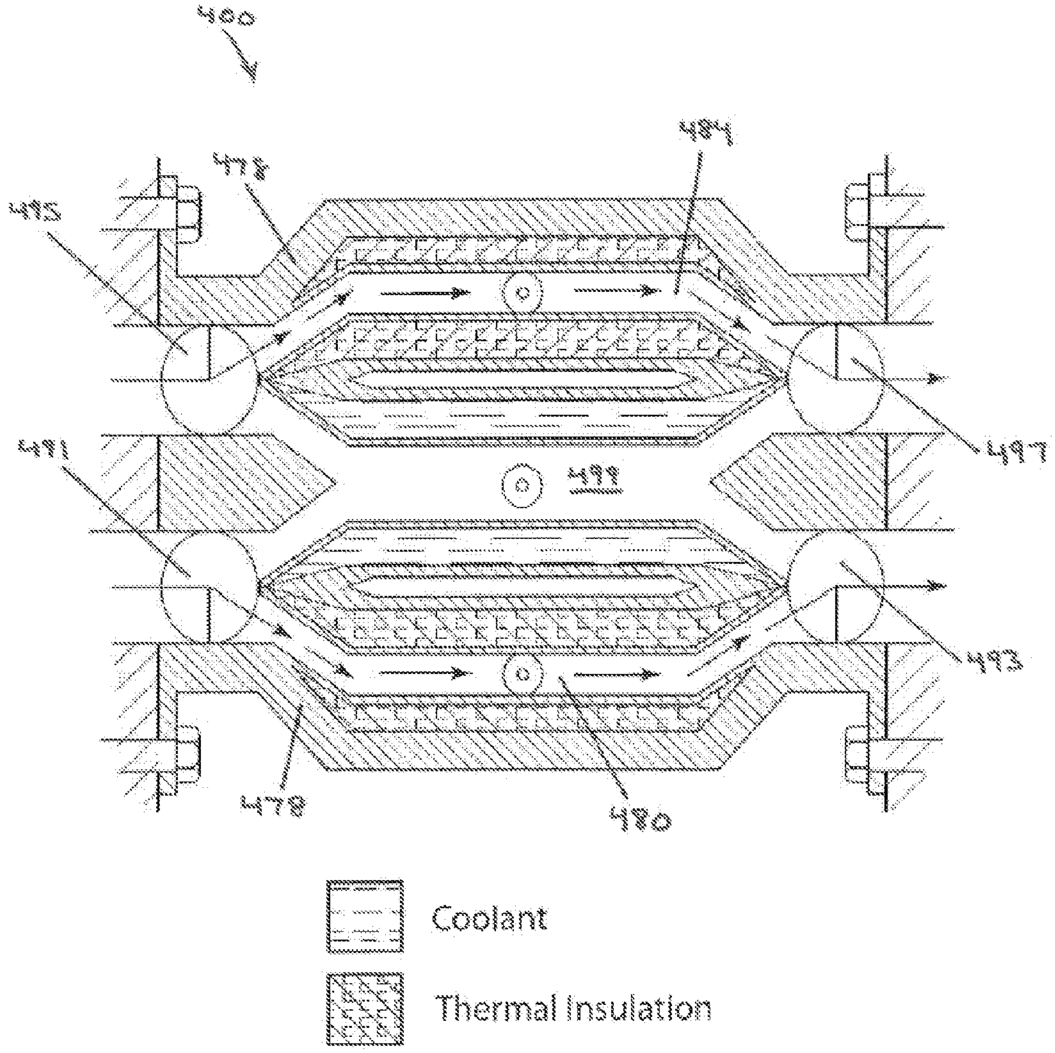


FIG. 12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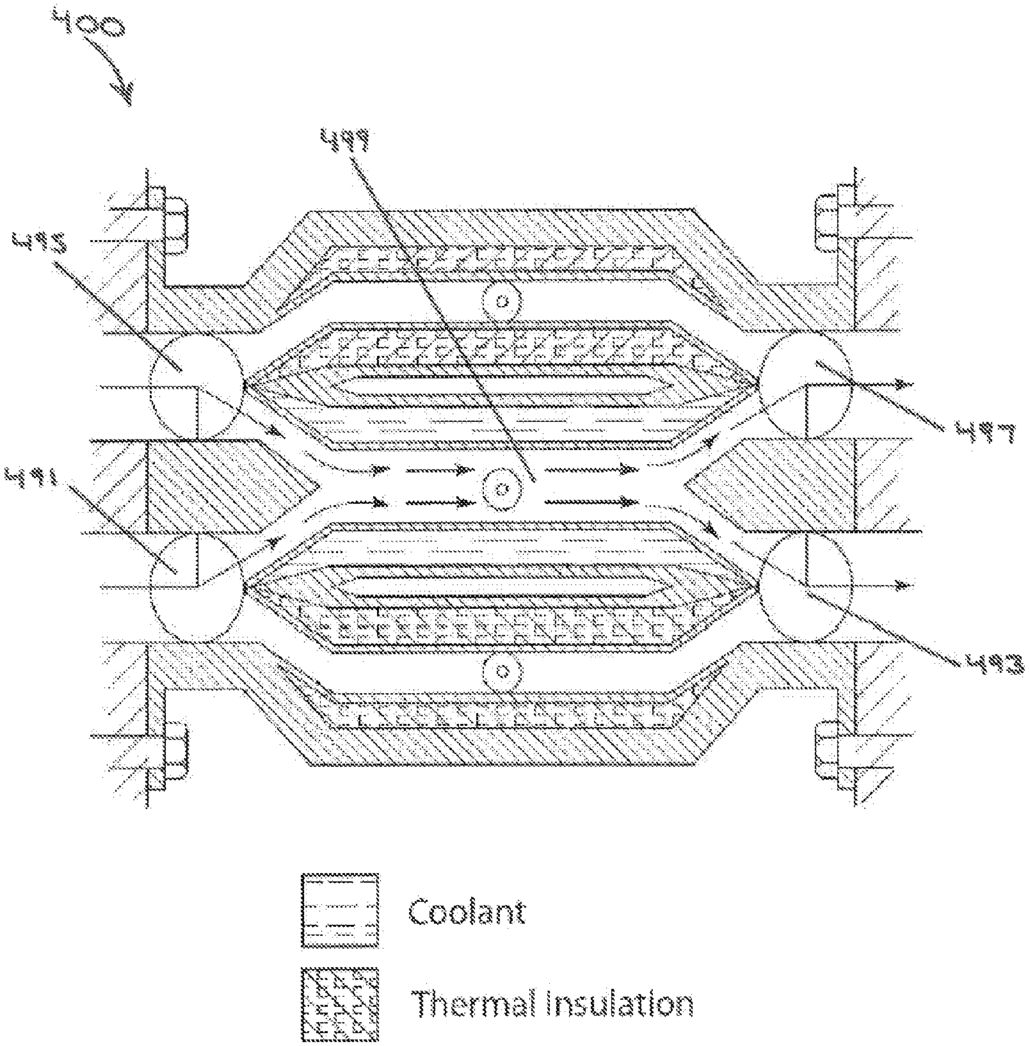
Coolant
Thermal Insulation

FIG. 13



SPLIT-CYCLE AIR HYBRID V-ENGINE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of priority of U.S. Provisional Patent Application No. 61/388,716, filed on Oct. 1, 2010, the entire contents of which are incorporated herein by reference.

FIELD

The present invention relates to split-cycle engines and in particular to split-cycle air hybrid engines having a V-shaped configuration.

BACKGROUND

For purposes of clarity, the term "conventional engine" as used in the present application refers to an internal combustion engine wherein all four strokes of the well-known Otto cycle (i.e., the intake, compression, expansion and exhaust strokes) are contained in each piston/cylinder combination of the engine. Also, for purposes of clarity, the following definition is offered for the term "split-cycle engine" as may be applied to engines disclosed in the prior art and as referred to in the present application.

A split-cycle engine as referred to herein comprises:

a crankshaft rotatable about a crankshaft axis;

a compression piston slidably received within a compression cylinder and operatively connected to the crankshaft such that the compression piston reciprocates through an intake stroke and a compression stroke during a single rotation of the crankshaft;

an expansion (power) piston slidably received within an expansion cylinder and operatively connected to the crankshaft such that the expansion piston reciprocates through an expansion stroke and an exhaust stroke during a single rotation of the crankshaft; and

a crossover passage (port) interconnecting the compression and expansion cylinders, the crossover passage including at least a crossover expansion (XovrE) valve disposed therein, but more preferably including a crossover compression (XovrC) valve and a crossover expansion (XovrE) valve defining a pressure chamber therebetween.

U.S. Pat. No. 6,543,225 granted Apr. 8, 2003 to Scuderi and U.S. Pat. No. 6,952,923 granted Oct. 11, 2005 to Branyon et al., both of which are incorporated herein by reference, contain an extensive discussion of split-cycle and similar-type engines. In addition, these patents disclose details of prior versions of an engine of which the present disclosure details further developments.

Split-cycle air hybrid engines combine a split-cycle engine with an air reservoir and various controls. This combination enables a split-cycle air hybrid engine to store energy in the form of compressed air in the air reservoir. The compressed air in the air reservoir is later used in the expansion cylinder to power the crankshaft.

A split-cycle air hybrid engine as referred to herein comprises:

a crankshaft rotatable about a crankshaft axis;

a compression piston slidably received within a compression cylinder and operatively connected to the crankshaft such that the compression piston reciprocates through an intake stroke and a compression stroke during a single rotation of the crankshaft;

an expansion (power) piston slidably received within an expansion cylinder and operatively connected to the crankshaft such that the expansion piston reciprocates through an expansion stroke and an exhaust stroke during a single rotation of the crankshaft;

a crossover passage (port) interconnecting the compression and expansion cylinders, the crossover passage including at least a crossover expansion (XovrE) valve disposed therein, but more preferably including a crossover compression (XovrC) valve and a crossover expansion (XovrE) valve defining a pressure chamber therebetween; and

an air reservoir operatively connected to the crossover passage and selectively operable to store compressed air from the compression cylinder and to deliver compressed air to the expansion cylinder.

U.S. Pat. No. 7,353,786 granted Apr. 8, 2008 to Scuderi et al., which is incorporated herein by reference, contains an extensive discussion of split-cycle air hybrid and similar-type engines. In addition, this patent discloses details of prior hybrid systems of which the present disclosure details further developments.

Referring to FIG. **1**, an exemplary prior art split-cycle air hybrid engine is shown generally by numeral **10**. The split-cycle air hybrid engine **10** replaces two adjacent cylinders of a conventional engine with a combination of one compression cylinder **12** and one expansion cylinder **14**. The four strokes of the Otto cycle are "split" over the two cylinders **12** and **14** such that the compression cylinder **12**, together with its associated compression piston **20**, perform the intake and compression strokes, and the expansion cylinder **14**, together with its associated expansion piston **30**, perform the expansion and exhaust strokes. The Otto cycle is therefore completed in these two cylinders **12**, **14** once per crankshaft **16** revolution (360 degrees CA) about crankshaft axis **17**.

During the intake stroke, intake air is drawn into the compression cylinder **12** through an intake port **19** disposed in the cylinder head **33**. An inwardly-opening (opening inward into the cylinder and toward the piston) poppet intake valve **18** controls fluid communication between the intake port **19** and the compression cylinder **12**.

During the compression stroke, the compression piston **20** pressurizes the air charge and drives the air charge into the crossover passage (or port) **22**, which is typically disposed in the cylinder head **33**. This means that the compression cylinder **12** and compression piston **20** are a source of high pressure gas to the crossover passage **22**, which acts as the intake passage for the expansion cylinder **14**. In some embodiments two or more crossover passages **22** interconnect the compression cylinder **12** and the expansion cylinder **14**.

The volumetric (or geometric) compression ratio of the compression cylinder **12** of the split-cycle engine **10** (and for split-cycle engines in general) is herein referred to as the "compression ratio" of the split-cycle engine. The volumetric (or geometric) compression ratio of the expansion cylinder **14** of the split-cycle engine **10** (and for split-cycle engines in general) is herein referred to as the "expansion ratio" of the split-cycle engine. The volumetric compression ratio of a cylinder is well known in the art as the ratio of the enclosed (or trapped) volume in the cylinder (including all recesses) when a piston reciprocating therein is at its bottom dead center (BDC) position to the enclosed volume (i.e., clearance volume) in the cylinder when said piston is at its top dead center (TDC) position. Specifically for split-cycle engines as defined herein, the compression ratio of a compression cylinder is determined when the XovrC valve is closed. Also specifically for split-cycle engines as defined herein, the expansion ratio of an expansion cylinder is determined when the XovrE valve is closed.

Due to very high volumetric compression ratios (e.g., 20 to 1, 30 to 1, 40 to 1, or greater) within the compression cylinder **12**, an outwardly-opening (opening outwardly away from the cylinder and piston) poppet crossover compression (XovrC) valve **24** at the crossover passage inlet **25** is used to control flow from the compression cylinder **12** into the crossover passage **22**. Due to very high volumetric compression ratios (e.g., 20 to 1, 30 to 1, 40 to 1, or greater) within the expansion cylinder **14**, an outwardly-opening poppet crossover expansion (XovrE) valve **26** at the outlet **27** of the crossover passage **22** controls flow from the crossover passage **22** into the expansion cylinder **14**. The actuation rates and phasing of the XovrC and XovrE valves **24**, **26** are timed to maintain pressure in the crossover passage **22** at a high minimum pressure (typically **20** bar or higher at full load) during all four strokes of the Otto cycle.

At least one fuel injector **28** injects fuel into the pressurized air at the exit end of the crossover passage **22** in correspondence with the XovrE valve **26** opening, which occurs shortly before the expansion piston **30** reaches its top dead center position. The air/fuel charge enters the expansion cylinder **14** shortly after the expansion piston **30** reaches its top dead center position. As the piston **30** begins its descent from its top dead center position, and while the XovrE valve **26** is still open, a spark plug **32**, which includes a spark plug tip **39** that protrudes into the cylinder **14**, is fired to initiate combustion in the region around the spark plug tip **39**. Combustion is initiated while the expansion piston is between **1** and **30** degrees CA past its top dead center (TDC) position. More preferably, combustion is initiated while the expansion piston is between 5 and 25 degrees CA past its top dead center (TDC) position. Most preferably, combustion is initiated while the expansion piston is between 10 and 20 degrees CA past its top dead center (TDC) position. Additionally, combustion may be initiated through other ignition devices and/or methods, such as with glow plugs, microwave ignition devices, or through compression ignition methods.

During the exhaust stroke, exhaust gases are pumped out of the expansion cylinder **14** through an exhaust port **35** disposed in the cylinder head **33**. An inwardly-opening poppet exhaust valve **34**, disposed in the inlet **31** of the exhaust port **35**, controls fluid communication between the expansion cylinder **14** and the exhaust port **35**. The exhaust valve **34** and the exhaust port **35** are separate from the crossover passage **22**. That is, the exhaust valve **34** and the exhaust port **35** do not make contact with the crossover passage **22**.

With the split-cycle engine concept, the geometric engine parameters (i.e., bore, stroke, connecting rod length, volumetric compression ratio, etc.) of the compression and expansion cylinders **12**, **14** are generally independent from one another. For example, the crank throws **36**, **38** for the compression cylinder **12** and the expansion cylinder **14**, respectively, may have different radii and may be phased apart from one another such that top dead center (TDC) of the expansion piston **30** occurs prior to TDC of the compression piston **20**. This independence enables the split-cycle engine **10** to potentially achieve higher efficiency levels and greater torques than typical four-stroke engines.

The geometric independence of engine parameters in the split-cycle engine **10** is also one of the main reasons why pressure is maintained in the crossover passage **22** as discussed earlier. Specifically, the expansion piston **30** reaches its top dead center position prior to the compression piston reaching its top dead center position by a discreet phase angle (typically between 10 and 30 crank angle degrees). This phase angle, together with proper timing of the XovrC valve **24** and the XovrE valve **26**, enables the split-cycle engine **10** to maintain pressure in the crossover passage **22** at a high minimum pressure (typically 20 bar absolute or higher during full load operation) during all four strokes of its pressure/volume cycle. That is, the split-cycle engine **10** is operable to time the XovrC valve **24** and the XovrE valve **26** such that the XovrC and XovrE valves are both open for a substantial period of time (or period of crankshaft rotation) during which the expansion piston **30** descends from its TDC position towards its BDC position and the compression piston **20** simultaneously ascends from its BDC position towards its TDC position. During the period of time (or crankshaft rotation) that the crossover valves **24**, **26** are both open, a substantially equal mass of gas is transferred (1) from the compression cylinder **12** into the crossover passage **22** and (2) from the crossover passage **22** to the expansion cylinder **14**. Accordingly, during this period, the pressure in the crossover passage is prevented from dropping below a predetermined minimum pressure (typically 20, 30, or 40 bar absolute during full load operation). Moreover, during a substantial portion of the intake and exhaust strokes (typically 90% of the entire intake and exhaust strokes or greater), the XovrC valve **24** and XovrE valve **26** are both closed to maintain the mass of trapped gas in the crossover passage **22** at a substantially constant level. As a result, the pressure in the crossover passage **22** is maintained at a predetermined minimum pressure during all four strokes of the engine's pressure/volume cycle.

For purposes herein, the method of opening the XovrC **24** and XovrE **26** valves while the expansion piston **30** is descending from TDC and the compression piston **20** is ascending toward TDC in order to simultaneously transfer a substantially equal mass of gas into and out of the crossover passage **22** is referred to herein as the Push-Pull method of gas transfer. It is the Push-Pull method that enables the pressure in the crossover passage **22** of the split-cycle engine **10** to be maintained at typically **20** bar or higher during all four strokes of the engine's cycle when the engine is operating at full load.

As discussed earlier, the exhaust valve **34** is disposed in the exhaust port **35** of the cylinder head **33** separate from the crossover passage **22**. The structural arrangement of the exhaust valve **34** not being disposed in the crossover passage **22**, and therefore the exhaust port **35** not sharing any common portion with the crossover passage **22**, is preferred in order to maintain the trapped mass of gas in the crossover passage **22** during the exhaust stroke. Accordingly, large cyclic drops in pressure, which may force the pressure in the crossover passage below the predetermined minimum pressure, are prevented.

The XovrE valve **26** opens shortly before the expansion piston **30** reaches its top dead center position. At this time, the pressure ratio of the pressure in the crossover passage **22** to the pressure in the expansion cylinder **14** is high, due to the fact that the minimum pressure in the crossover passage is typically 20 bar absolute or higher and the pressure in the expansion cylinder during the exhaust stroke is typically about one to two bar absolute. In other words, when the XovrE valve **26** opens, the pressure in the crossover passage **22** is substantially higher than the pressure in the expansion cylinder **14** (typically in the order of 20 to 1 or greater). This high pressure ratio causes initial flow of the air and/or fuel charge to flow into the expansion cylinder **14** at high speeds. These high flow speeds can reach the speed of sound, which is referred to as sonic flow. This sonic flow is particularly advantageous to the split-cycle engine **10** because it causes a rapid combustion event, which enables the split-cycle engine

10 to maintain high combustion pressures even though ignition is initiated while the expansion piston **30** is descending from its top dead center position.

The split-cycle air-hybrid engine **10** also includes an air reservoir (tank) **40**, which is operatively connected to the crossover passage **22** by an air reservoir tank valve **42**. Embodiments with two or more crossover passages **22** may include a tank valve **42** for each crossover passage **22**, which connect to a common air reservoir **40**, or alternatively each crossover passage **22** may operatively connect to separate air reservoirs **40**.

The tank valve **42** is typically disposed in an air tank port **44**, which extends from the crossover passage **22** to the air tank **40**. The air tank port **44** is divided into a first air tank port section **46** and a second air tank port section **48**. The first air tank port section **46** connects the air tank valve **42** to the crossover passage **22**, and the second air tank port section **48** connects the air tank valve **42** to the air tank **40**.

The volume of the first air tank port section **46** includes the volume of all additional recesses which connect the tank valve **42** to the crossover passage **22** when the tank valve **42** is closed. Preferably, the volume of the first air tank port section **46** is small (e.g., less than approximately 20%) relative to the volume of the crossover passage **22**. More preferably, the first air tank port section **46** is substantially nonexistent, that is, the tank valve **42** is most preferably disposed such that it is flush against the outer wall of crossover passage **22**.

The tank valve **42** may be any suitable valve device or system. For example, the tank valve **42** may be a pressure-activated check valve, or an active valve which is activated by various valve actuation devices (e.g., pneumatic, hydraulic, cam, electric or the like). Additionally, the tank valve **42** may comprise a tank valve system with two or more valves actuated with two or more actuation devices.

The air tank **40** is utilized to store energy in the form of compressed air and to later use that compressed air to power the crankshaft **16**, as described in aforementioned U.S. Pat. No. 7,353,786 to Scuderi et al. This mechanical means for storing potential energy provides numerous potential advantages over the current state of the art. For instance, the split-cycle engine **10** can potentially provide many advantages in fuel efficiency gains and NOx emissions reduction at relatively low manufacturing and waste disposal costs in relation to other technologies on the market such as diesel engines and electric-hybrid systems.

The air hybrid split-cycle engine **10** can be run in a normal operating mode (referred to as the engine firing (EF) mode or as the normal firing (NF) mode) and four basic air hybrid modes. In the EF mode, the engine **10** functions normally as previously described in detail herein, operating without the use of its air tank **40**. In the EF mode, the tank valve **42** remains closed to isolate the air tank **40** from the basic split-cycle engine **10**.

In the four hybrid modes, the engine **10** operates with the use of its air tank **40**. The four hybrid modes are:

1. Air Expander (AE) mode, which includes using compressed air energy from the air tank **40** without combustion;
2. Air Compressor (AC) mode, which includes storing compressed air energy into the air tank **40** without combustion;
3. Air Expander and Firing (AEF) mode, which includes using compressed air energy from the air tank **40** with combustion; and
4. Firing and Charging (FC) mode, which includes storing compressed air energy into the air tank **40** with combustion.

In the split-cycle engine **10**, the compression and expansion cylinders **12**, **14** are positioned in-line with each other and share a common cylinder head **33** in which the crossover passage **22** is formed. Additionally, the common head **33** must include several cooling passages (not shown) to enable engine coolant to be pumped through the head **33** to remove heat from the compression cylinder **12**, the expansion cylinder **14**, and the crossover passage **22**. Because the crossover passage **22** is formed integrally with the cylinder head **33**, it is very difficult to independently control the temperature of the crossover passage **22** (and the fluid therein) relative to the cylinders **12**, **14**.

Also, the relative lack of available space in the cylinder head **33** imposes undesirable size and shape restrictions on the crossover passage(s) **22** and the air reservoir control valve (s) **42**. For example, the crossover passage **22** or the first air tank port section **46**, which connects the valve **42** to the crossover passage **22**, may have to be curved in order to avoid breaking through or getting too close to the various cooling passages. The curved crossover passages would then be longer than necessary, which would increase heat losses therein and decrease efficiency. The curved first tank port section **46** would undesirably combine with the volume of the crossover passage to decrease pressure in the crossover passage and also decrease efficiency. Moreover, the common head may become so crowded that it may become very difficult (if not virtually impossible) to connect a tank valve **42** to the crossover passage **22** without breaking through or coming too close to some of the cooling passages.

Still further, the casting process that is typically used to form the crossover passage **22** in the cylinder head **33** leaves behind manufacturing artifacts that disrupt air flow in the crossover passage **22** and undesirably limit the shape and size of the crossover passage(s) **22**. Accordingly, there is a need for improved split-cycle engine configurations.

SUMMARY

A split-cycle air hybrid engine with improved efficiency is disclosed in which the centerline of a compression cylinder is positioned at a non-zero angle with respect to the centerline of an expansion cylinder such that the cylinders of the engine have a V-shaped configuration. The centerlines of the respective cylinders do not actually form a "V", as they do not typically intersect with each other. Rather, the centerlines are usually spaced apart from one another in the axial direction of the crankshaft (i.e., to accommodate the thickness of the respective crank throws for each cylinder). When viewed along the axis of rotation of the crankshaft, however, the centerlines have the appearance of a "V." In one embodiment, the centerlines of the respective cylinders intersect with the axis of rotation of the crankshaft such that the apex of the V is formed at the axis of rotation of the crankshaft.

In another embodiment, one or both of the compression cylinder and the expansion cylinder have a centerline that is "offset," meaning the centerline does not intersect with the axis of rotation of the crankshaft. In this embodiment, it is preferable that the centerlines of the cylinders intersect with a line (i.e., the line on which the apex of the V is formed) that is located below the axis of rotation of the crankshaft (i.e., located on the side opposite the cylinders relative to the axis of rotation of the crankshaft). The line on which the apex of the V is formed can optionally be parallel to the axis of rotation of the crankshaft. Modular crossover passages, crossover passage manifolds, thermal regulation systems, and associated air reservoir valve assemblies are also disclosed.

In one aspect of at least one embodiment of the invention, a V-shaped split-cycle air hybrid engine is provided that includes a compression cylinder having a centerline that is positioned at a non-zero angle with respect to the centerline of an expansion cylinder. In one embodiment, the non-zero angle is in a range of about 10 degrees to about 120 degrees. The non-zero angle can also be selected from the group consisting of about 30 degrees, about 45 degrees, and about 60 degrees.

In another aspect of at least one embodiment of the invention, a split-cycle engine is provided that includes a first cylinder head coupled to a compression cylinder, a second cylinder head coupled to an expansion cylinder, and at least one crossover passage formed externally to the first and second cylinder heads and configured to selectively transfer fluid between the first and second cylinder heads.

In one embodiment, the engine is an air hybrid engine and the at least one crossover passage includes an air reservoir valve for selectively placing an air reservoir in fluid communication with the first or second cylinder heads. The at least one crossover passage can include first and second crossover passages, each having an associated crossover compression valve and a crossover expansion valve. The crossover compression valves and the crossover expansion valves can be outwardly opening. In one embodiment, the air reservoir valve is outwardly opening.

In another aspect of at least one embodiment of the invention, a split-cycle air hybrid engine is provided that includes a crankshaft that rotates about a crankshaft axis and a compression cylinder having a centerline offset from the crankshaft axis that intersects an offset axis, the offset axis being parallel to the crankshaft axis and offset therefrom. The engine also includes an expansion cylinder having a centerline that intersects the offset axis, and the centerline of the compression cylinder is positioned at a non-zero angle with respect to the centerline of the expansion cylinder when viewed along the offset axis.

In another aspect of at least one embodiment of the invention, a split-cycle air hybrid engine is provided that includes a crankshaft that rotates about a crankshaft axis, a first cylinder that is offset such that a centerline of the first cylinder does not intersect the crankshaft axis, and a second cylinder having a centerline, wherein the centerline of the first cylinder is positioned at a non-zero angle with respect to the centerline of the second cylinder. The first cylinder can be a compression cylinder or the first cylinder can be an expansion cylinder. In one embodiment, the second cylinder is offset such that a centerline of the second cylinder does not intersect the crankshaft axis.

In another aspect of at least one embodiment of the invention, a split-cycle engine is provided that includes a first cylinder head coupled to a compression cylinder, a second cylinder head coupled to an expansion cylinder, and a thermally regulated crossover manifold configured to selectively transfer fluid between the first and second cylinder heads. The manifold includes at least one insulated crossover passage and at least one cooled crossover passage. In one embodiment, the manifold includes a plurality of valves configured to selectively divert fluid through either the at least one cooled crossover passage or the at least one insulated crossover passage depending on an operating condition of the engine. The engine can also include one or more fluid jackets through which engine coolant flows, the one or more fluid jackets being disposed in proximity to the at least one cooled crossover passage An insulative material can also be provided and that is disposed around the at least one insulated crossover passage. In one embodiment, the insulative material is a ceramic. The insulated crossover passage can also be heated.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will be more fully understood from the following detailed description taken in conjunction with the accompanying drawings, in which:

FIG. **1** is a schematic cross-sectional view of a prior art split-cycle air hybrid engine;

FIG. **2** is a perspective cross-sectional view of one embodiment of a split-cycle air hybrid engine according to the present invention;

FIG. **3** is a cross-sectional profile view of the split-cycle air hybrid engine of FIG. **2**;

FIG. **4** is a cross-sectional plan view of the split-cycle air hybrid engine of FIGS. **2** and **3** taken along the line **4-4** in FIG. **3**;

FIG. **5** is a cross-sectional profile view of another embodiment of a split-cycle air hybrid engine having offset cylinder centerlines according to the present invention;

FIG. **6** is a partial cross-sectional profile view of the air reservoir valve assembly of FIG. **4** taken along the line **6-6** in FIG. **4**;

FIG. **7** is a perspective view of the air reservoir valve assembly of FIG. **4** taken along the line **7-7** in FIG. **4**;

FIG. **8** is a perspective cross-sectional view of another embodiment of a split-cycle air hybrid engine having a thermally regulated crossover manifold according to the present invention;

FIG. **9** is a schematic cross-sectional view of the thermally regulated crossover manifold of the engine of FIG. **8** having crossover passages and a set of control valves in a first configuration;

FIG. **10** is a schematic cross-sectional view of the crossover manifold of the engine of FIG. **8** with the set of control valves in a second configuration;

FIG. **11** is a perspective cross-sectional view of another embodiment of a split-cycle air hybrid engine having a thermally regulated crossover manifold according to the present invention;

FIG. **12** is a schematic cross-sectional view of the thermally regulated crossover manifold of the engine of FIG. **11** having crossover passages and a set of control valves in a first configuration; and

FIG. **13** is a schematic cross-sectional view of the crossover manifold of the engine of FIG. **11** with the set of control valves in a second configuration.

DETAILED DESCRIPTION

Certain exemplary embodiments will now be described to provide an overall understanding of the principles of the structure, function, manufacture, and use of the devices and methods disclosed herein. One or more examples of these embodiments are illustrated in the accompanying drawings. Those skilled in the art will understand that the devices and methods specifically described herein and illustrated in the accompanying drawings are non-limiting exemplary embodiments and that the scope of the present invention is defined solely by the claims. The features illustrated or described in connection with one exemplary embodiment may be combined with the features of other embodiments. Such modifications and variations are intended to be included within the scope of the present invention.

FIGS. **2-4** illustrate one exemplary embodiment of a split-cycle air hybrid engine **200** according to the present invention. The engine **200** generally includes an engine block **202**, a crankshaft **204** rotating about a crankshaft axis (or axis of rotation) **228**, first and second cylinder heads **206**, **208**, first and second crossover passages **210**, **212**, and an air reservoir **214**.

As shown in FIG. **3**, the engine block **202** defines at least one compression cylinder **216** and at least one expansion cylinder **218**. As shown, the centerlines of the compression and expansion cylinders **216**, **218** are positioned at a non-zero angle A relative to each other such that the engine **200** is oriented in a V-shaped configuration when viewed along the crankshaft axis **228**. The angle A can be between about 0.1 degrees and about 180 degrees, between about 5 degrees and about 150 degrees, between about 10 degrees and about 120 degrees, between about 15 degrees and about 90 degrees, between about 30 degrees and about 60 degrees, between about 10 degrees and about 30 degrees, between about 60 degrees and about 90 degrees, and/or between about 45 degrees and about 55 degrees. For example, the angle A can be 0.1 degrees, 15 degrees, 30 degrees, 45 degrees, 60 degrees, 75 degrees, 90 degrees, 105 degrees, 120 degrees, 150 degrees, 165 degrees, or 180 degrees. In the illustrated embodiment, the compression and expansion cylinders **216**, **218** are oriented at an angle A of about 54 degrees with respect to each other.

It will be appreciated that the engine **200** can include virtually any number of compression and/or expansion cylinders, and that the number of compression cylinders need not necessarily be equal to the number of expansion cylinders. In this embodiment, the engine **200** includes one compression cylinder and one expansion cylinder. The four strokes of the Otto cycle are "split" over the compression and expansion cylinders such that the compression cylinder **216** contains the intake and compression strokes and the expansion cylinder **218** contains the expansion and exhaust strokes. The Otto cycle is therefore completed in the compression and expansion cylinders **216**, **218** once per crankshaft revolution (360 degrees CA).

Upper ends of the cylinders **216**, **218** are closed by the respective cylinder heads **206**, **208**. The compression and expansion cylinders **216**, **218** receive for reciprocation a compression piston **220** and an expansion (or "power") piston **222**, respectively. The first cylinder head **206**, the compression piston **220** and the compression cylinder **216** define a variable volume compression chamber **224** in the compression cylinder **216**. The second cylinder head **208**, the expansion piston **222** and the expansion cylinder **218** define a variable volume combustion chamber **226** in the expansion cylinder **218**.

Having separated cylinder heads **206**, **208** oriented in the V-shaped configuration allows for better access to the crossover passages **210**, **212**, which makes it easier to attach the air reservoir valve **260** thereto, thereby facilitating the construction of the air reservoir **214**.

This configuration also avoids the necessity of forming the crossover passages in the common cylinder head **33**, which, as discussed in detail below, enables independent thermal control of the crossover passages relative to the compression and expansion cylinders. The V-shaped configuration of engine **200** enables a substantial portion of the crossover passages **210**, **212** to be located outside of the first and second cylinder heads **206**, **208**, as, for example, in a separate crossover passage manifold (not shown). Accordingly, separate cooling passages can be designed for just the crossover passages, making the area around the crossover passages more open and accessible. This means that the crossover passages can be made straighter and shorter, which would cut down on heat loss and increase engine efficiency. Additionally, one or more air reservoir valves **260** can be more easily fitted to the crossover passages **210**, **212** and connected to the air reservoir **214** with little structural problems in hitting or coming too close to the cooling passages. Moreover, the connection to the air reservoir **214** can be made straight and the air reservoir valve(s) **260** can be mounted flush against the outer surface of the crossover passages **210**, **212** to further increase crossover passage pressure and engine efficiency.

The crankshaft **204** is journaled into the engine block **202** for rotation about the crankshaft axis **228** and includes axially displaced and angularly offset first and second crank throws **230**, **232**, having a phase angle therebetween. The first crank throw **230** is pivotally joined by a first connecting rod **236** to the compression piston **220** and the second crank throw **232** is pivotally joined by a second connecting rod **238** to the expansion piston **222** to reciprocate the pistons **220**, **222**, respectively, in their respective cylinders **216**, **218** in a timed relation determined by the angular offset of the crank throws **230**, **232** and the geometric relationships of the cylinders **216**, **218**, the crankshaft **204**, and the pistons **220**, **222**. Alternative mechanisms for relating the motion and timing of the pistons **220**, **222** can be utilized if desired.

The cylinder heads **206**, **208** include various passages, ports and valves suitable for accomplishing the desired purposes of the split-cycle air hybrid engine **200**. In the illustrated embodiment, a first, compression-side cylinder head **206** is provided that includes an inwardly-opening intake valve **240** for controlling fluid flow between an intake port **242** and the compression cylinder **216**. The cylinder head **206** also includes first and second outwardly-opening poppet crossover compression (XovrC) valves **244**, **246** at the inlets of the respective crossover passages **210**, **212**, respectively, for controlling fluid flow between the compression cylinder **216** and the crossover passages **210**, **212**.

During the intake stroke, intake air is drawn through the intake port **242** and into the compression cylinder **216** via the intake valve **240**. During the compression stroke, the compression piston **220** pressurizes the air charge and drives the air charge into the crossover passages **210**, **212** which act as intake passages for the expansion cylinder **218**.

The illustrated engine **200** also includes a second, expansion-side cylinder head **208**. The head **208** includes first and second outwardly-opening poppet crossover expansion (XovrE) valves **248**, **250** at the outlets of the respective crossover passages **210**, **212** which control fluid flow between the crossover passages **210**, **212** and the expansion cylinder **218**. The head **208** also includes an inwardly-opening poppet exhaust valve **252** for controlling fluid flow between the expansion cylinder **218** and an exhaust port **254**.

One or more fuel injectors (not shown) inject fuel into the pressurized air at the exit ends of the crossover passages **210**, **212** in correspondence with the opening of the XovrE valves **248**, **250** respectively. Alternatively, or in addition, fuel can be injected directly into the expansion cylinder **218** and/or directly into one or both of the crossover passages **210**, **212**. The fuel-air charge fully enters the expansion cylinder **218** shortly after the expansion piston **222** reaches its TDC position. As the piston **222** begins its descent from its TDC position, and while one or more of the XovrE valves **248**, **250** are still open, one or more spark plugs (not shown) are fired to initiate combustion (typically between 10 to 20 degrees CA after TDC of the expansion piston **222**). The spark plug(s) are mounted in the cylinder head **208** with electrodes extending into the combustion chamber **226** for igniting air fuel charges at precise times by an ignition control (not shown). It should be understood that the engine **200** can also be a diesel engine and can be operated without a spark plug. Moreover, the engine **200** can be designed to operate on any fuel suitable for reciprocating piston engines in general, such as hydrogen or natural gas.

After the spark plug is fired, the XovrE valves **248**, **250** are closed before the resulting combustion event enters the crossover passages **210**, **212**. The combustion event drives the expansion piston **222** downward in a power stroke. Exhaust gases are pumped out of the expansion cylinder **222** and through the exhaust port **254** via the exhaust valve **252** during the exhaust stroke.

The crossover passages **210**, **212** can have a variety of configurations. While the illustrated engine **200** includes two crossover passages **210**, **212**, it can also have only a single crossover passage or can have more than two crossover passages.

The illustrated crossover passages **210**, **212** generally include an elongated hollow flow tube with mounting flanges **256** formed on either end for mounting the crossover passages **210**, **212** to the cylinder heads **206**, **208**. The crossover passages **210**, **212** also include at least one air reservoir valve assembly **258** that houses at least one air reservoir valve **260** (see FIG. **3**), as discussed in further detail below. In the illustrated embodiment, the crossover passages **210**, **212** have a generally circular cross-section, although virtually any cross-sectional shape can be used without departing from the scope of the present invention. For example, the crossover passages can have an ellipsoidal cross-section. The crossover passages **210**, **212** can be generally straight as shown or can include one or more curves or bends. In one embodiment, the crossover passages are sized and shaped such that they have different internal volumes to accommodate flow for different engine load ranges. For example, the crossover passage **210** could be sized to have approximately half the volume of the crossover passage **212**. Accordingly, the smaller volume passage **210** could be used primarily for the lower third of the engine load range, the larger volume passage **212** could be used primarily for the middle third of the engine load range, and the combined passages **210**, **212** could be used primarily for the upper third of the engine load range.

The air reservoir valve assemblies **258** of the crossover passages **210**, **212** control fluid flow between the crossover passages **210**, **212** and the air reservoir **214**. The air reservoir **214** is sized to receive and store compressed air energy from a plurality of compression strokes of the compression piston **220**, and facilitates operation of the engine **200** in any of a variety of air hybrid modes, as explained below. It will be appreciated that each crossover passage **210**, **212** can be coupled to its own respective air reservoir and/or can be coupled to a single shared air reservoir **214** as shown.

The valves in the engine **200** (i.e., the intake valve **240**, the XovrC valves **244**, **246**, the XovrE valves **248**, **250**, the exhaust valve **252**, the air reservoir valves **260**, etc.) are typically actuated by camshafts (not shown) having cam lobes for respectively actuating and engaging the valves either directly or via one or more intermediate elements. Each valve can have its own cam and/or its own camshaft, or two or more valves can be actuated by common cams and/or camshafts. Alternatively, one or more of the valves can be mechanically, electronically, pneumatically, and/or hydraulically actuated variably.

The engine **200** is capable of operating in any of the aforementioned air hybrid modes (i.e., AE, AC, AEF, and FC modes).

In existing split-cycle engines, the respective centerlines of the expansion and compression cylinders are generally parallel to one another and intersect the axis of rotation of the crankshaft, as shown in FIG. **1**. In the engine **200** of FIG. **3**, the centerline **262** of the compression cylinder **216** and the centerline **264** of the expansion cylinder **218**, while not parallel to one another, do intersect with the rotational axis **228** of the crankshaft **204**. This need not always be the case, however. In other words, one or both of the compression cylinder and the expansion cylinder can be "offset," meaning that their centerlines do not intersect the axis of rotation of the crankshaft. In such embodiments, it is preferable that the centerlines of the cylinders intersect with a line (i.e., the line on which the apex of the V is formed) that is located below the axis of rotation of the crankshaft (i.e., located on the side opposite the cylinders relative to the axis of rotation of the crankshaft). The line on which the apex of the V is formed can optionally be parallel to the axis of rotation of the crankshaft. For example, FIG. **5** illustrates a split-cycle air hybrid engine **200'** in which the centerlines **262'**, **264'** of the compression and expansion cylinders **216'**, **218'** do not intersect with the crankshaft axis **228'**. Rather, the centerlines **262'**, **264'** intersect with an offset axis **266'** that is parallel to the crankshaft axis **228'** but offset therefrom. This advantageously reduces friction between the piston skirt and the cylinder wall. In addition, this allows for the angle A' of the V-shaped engine block **202'** to be reduced, which in turn allows for shorter crossover passages **210'**, **212'**. With the shorter crossover passages **210'**, **212'**, there is less pressure drop and thermal loss across the passages which increases engine efficiency. A variety of offsets (i.e., distances between the crankshaft axis **228'** and the offset axis **266'**) can be used without departing from the scope of the present invention.

FIGS. **6-7** illustrate one embodiment of an air reservoir valve assembly **258** according to the present invention. As shown, the valve assembly **258** generally includes a longitudinal tubular portion **268** configured to be placed in-line with a crossover passage (i.e., the crossover passages **210**, **212**). In one embodiment, the valve assembly **258** is formed integrally with the crossover passage. Alternatively, the crossover passage can include first and second portions, each coupled to respective ends of the longitudinal tubular portion **268** of the valve assembly **258**. The tubular portion **268** includes a valve seat **270** for forming a sealing engagement with the head **272** of an air reservoir valve **260**. In the illustrated embodiment, the air reservoir valve **260** is an outwardly-opening (i.e., opening outwardly away from the interior of the tubular portion **268**) poppet valve having a valve head **272** and a valve stem **274**. The valve stem **274** extends through a transverse portion **276** of the valve assembly **258** that extends up and away from the tubular portion **268**. Fluid communication between the interior of the transverse portion **276** and the interior of the tubular portion **268** is selectively established by actuating the air reservoir valve **260**. The end of the transverse portion **276** opposite from the tubular portion **268** is coupled to an air reservoir (not shown), either directly or via one or more intermediate structures, such as tubes, valves, etc.

The valve stem **274** extends through a sidewall of the transverse portion **276** in a slidable arrangement such that linear motion can be imparted thereto by a cam or other valve actuator disposed outside of the transverse portion **276**. A sealing feature is provided as known in the art to permit the valve stem **274** to slide with respect to the transverse portion **276** without permitting pressurized fluid in the transverse portion **276** to escape around the surface of the valve stem **274**. It will be appreciated that a variety of other valve and/or housing types can be used to selectively place the air reservoir in fluid communication with one or more crossover passages.

As noted above, forming the crossover passages external to the cylinder head advantageously permits independent thermal regulation of the crossover passages. FIG. **8** illustrates one embodiment of a split-cycle air hybrid V-shaped engine **300** in which a thermal control system is employed to regulate the temperature of the crossover passages depending on various engine operating parameters. As shown, the engine **300** includes a thermally regulated crossover passage manifold **378** in which four crossover passages **380**, **382**, **384**, **386** are formed. It will be appreciated that the use of such a crossover passage manifold is not limited to V-shaped split-cycle engines, and that the manifolds described herein can also be used with traditional inline split-cycle engines. Each passage in the manifold **378** has its own air reservoir valve assembly **358**. Again, the number of illustrated crossover passages and air reservoir valves is merely exemplary, and any number of crossover passages and/or air reservoir valves can be used without departing from the scope of the present invention. The crossover passages **380**, **382** share a common XovrC valve **344** and a common XovrE valve **348**. Likewise, the crossover passages **384**, **386** share a common XovrC valve **346** and a common XovrE valve **350**. In other embodiments, each crossover passage includes its own unique XovrC and/or XovrE valve, or a single XovrC or XovrE valve is shared by more than two crossover passages.

FIG. **9** illustrates a cross-sectional view of the crossover manifold **378**. As shown, the ends of the manifold **378** are bolted to the first and second cylinder heads **306**, **308**. The manifold **378** includes first and second XovrC inlets **388**, **390** through which fluid flow is controlled by the XovrC valves **344**, **346**, respectively. The manifold **378** also includes first and second XovrE outlets **392**, **394** through which fluid flow is controlled by the XovrE valves **348**, **350**, respectively. Adjustable ball valves **391**, **395** are disposed in the manifold inlets **388**, **390** respectively, and adjustable ball valves **393**, **397** are disposed in the manifold outlets **392**, **394**, respectively. The configurations of the ball valves **391**, **393** are adjustable to selectively direct fluid entering the inlet **388** through either the crossover passage **380** or the crossover passage **382**. Similarly, the configurations of the ball valves **395**, **397** are adjustable to selectively direct fluid entering the inlet **390** through either the crossover passage **384** or the crossover passage **386**. Any of a variety of means known in the art can be employed to change the configuration of the ball valves **391**, **393**, **395**, **397**, including mechanical, hydraulic, electromagnetic, and/or pneumatic actuators. In addition, the illustrated ball valves are only one exemplary type of valve that can be employed in the present invention, and a person having ordinary skill in the art will appreciate that any of a variety of known valve types can be used without departing from the scope of the present invention. The valves **391**, **393**, **395**, **397** can optionally be two-position valves. In one embodiment, the switch between crossover passages can occur over a plurality of engine cycles (i.e., dozens, hundreds, etc.), which means that the valves **391**, **393**, **395**, **397** need not necessarily be fast-actuating and can instead be of a slower, more durable or inexpensive variety.

The crossover passages **380**, **384** include features for generally maintaining or increasing the temperature of fluid disposed therein or passing therethrough. In the embodiment of FIG. **9**, the crossover passages **380**, **384** are encased in a thermal insulation **396** configured to maintain engine heat within the crossover passages **380**, **384**. Any of a variety of insulative materials can be used for this purpose, including without limitation ceramics, Kevlar, plastics, composites, and the like. In addition, the crossover passages **380**, **384** can be vacuum-lined (i.e., can be disposed within an outer tube in which a vacuum is generated). The engine **300** can also optionally include active heating elements. For example, high-temperature exhaust gasses can be routed through air passages formed alongside the crossover passages **380**, **384**, or can be used to heat oil or other fluid which can then be pumped through fluid jackets disposed adjacent to the crossover passages **380**, **384**. In one embodiment, the crossover passages **380**, **384** can be wrapped in an electric heating coil.

The crossover passages **382**, **386** include features for generally decreasing the temperature of fluid disposed therein or passing therethrough. As illustrated, fluid jackets **398** are formed in the manifold **378** in close proximity to the crossover passages **382**, **386**. Engine coolant or other fluid is routed through the fluid jackets **398** to cool the crossover passages **382**, **386**. The cooled crossover passages **382**, **386** can also include other cooling mechanisms, such as heat sinks or fans and can optionally be formed from materials such as aluminum that are known to dissipate heat quickly.

The engine **300** also includes a thermal control computer (not shown) and any of a variety of associated sensors, thermostats, actuators, and/or other controls to facilitate precise temperature control.

In operation, the ball valves **391**, **393**, **395**, **397** are selectively actuated such that fluid flowing from the compression cylinder to the expansion cylinder is either insulated, heated, or cooled as needed to improve the efficiency of the engine **300**. For example, when the engine **300** is first started and has not yet reached operating temperature, the valves **391**, **393**, **395**, **397** are placed in a first configuration, as shown in FIG. **9**, such that the fluid compressed in the compression cylinder is routed through the insulated crossover passages **380**, **384**, and heated and/or insulated before entering the expansion cylinder. The flow of fluid in this configuration is indicated by the illustrated arrows. This configuration is also used when the engine **300** is operating under low loads (e.g., when the engine is operating below about 70% of full load). By heating and/or insulating the incoming air charge before it reaches the expansion cylinder, crossover passage pressures are maintained at a high level, thereby improving overall efficiency.

When the engine **300** is operating at high load (e.g., when the engine is operating above about 70% of its rated load), it is desirable to cool the air charge before it enters the expansion cylinder to prevent premature combustion and to improve output power. Accordingly, the valves **391**, **393**, **395**, **397** are placed in a second configuration, as shown in FIG. **10**, to route the fluid compressed in the compression cylinder through the cooled crossover passages **382**, **386**. The flow of fluid in this configuration is indicated by the illustrated arrows. By cooling the incoming air charge before it reaches the expansion cylinder, the temperature and pressure of the air charge is reduced which advantageously prevents pre-ignition and knocking. The cooled crossover passages **382**, **386** can optionally have no air reservoir valve **358**, since it may not be desirable to operate in an air hybrid mode under the conditions in which the cooled crossover passages **382**, **386** are used.

FIG. **11** illustrates another embodiment of a split-cycle air hybrid engine **400** in which a thermal control system is employed to regulate the temperature of the crossover passages depending on various engine operating parameters. The engine **400** is substantially identical to the engine **300** discussed above with respect to FIGS. **8-10**, except that the manifold **478** of the engine **400** has only three crossover passages **480**, **484**, **499**. In other words, whereas the engine **300** includes two cooled crossover passages **382**, **386**, the engine **400** instead has a single cooled crossover passage **499**. Thus, as shown in FIG. **12**, the engine **400** includes first and second insulated crossover passages **480**, **484** and a central cooled crossover passage **499**. It will be appreciated that the engine **400** could alternatively have first and second cooled crossover passages and that the insulated crossover passages could instead be merged into a single passage.

In operation, the engine **400** operates in substantially the same way as the engine **300** described above. During low load and/or low speed operation, or during engine start-up/warm-up, a series of valves **491**, **493**, **495**, **497** are configured as shown in FIG. **12** to direct fluid from the compression cylinder through the insulated crossover passages **480**, **484** to insulate or heat the fluid before it enters the expansion cylinder. During high load and/or high speed operation, the valves **491**, **493**, **495**, **497** are configured as shown in FIG. **13** to direct fluid from the compression cylinder through the central, cooled crossover passage **499**, thereby cooling the fluid before it enters the expansion cylinder.

The engines **200**, **200'**, **300**, **400** disclosed herein are configured to operate reliably over a broad range of engine speeds. In certain embodiments, engines according to the present invention are capable of operating up to a speed of at least about 4000 rpm, and preferably at least about 5000 rpm, and more preferably at least about 7000 rpm.

Although the invention has been described by reference to specific embodiments, it should be understood that numerous changes may be made within the spirit and scope of the inventive concepts described. For example, one or more of the crossover valves or the air reservoir valves can be inwardly-opening. There can also be more than four crossover valves, and more than two crossover passages. In addition, the engines disclosed herein need not necessarily be air hybrid engines, but rather the V-shaped configuration can be applied to non-hybrid split-cycle engines as well. These changes are only exemplary, and other changes may be made without departing from the scope of the invention. Accordingly, it is intended that the invention not be limited to the described embodiments, but that it have the full scope defined by the language of the following claims.

What is claimed is:

1. A split-cycle engine comprising:

a first cylinder head coupled to a compression cylinder;

a second cylinder head coupled to an expansion cylinder;

a manifold configured to selectively transfer fluid between the first and second cylinder heads, the manifold including independent insulated and cooled crossover passages;

a first valve having a position in which the first cylinder head is in fluid communication with the insulated crossover in which the first cylinder head is in fluid communication with the cooled crossover passage; and

a second valve having position in which the second cylinder head is in fluid communication with the insulated crossover passage and a position in which the second cylinder head is in fluid communication with the cooled crossover passage.

2. The engine of claim **1**, wherein the first and second valves are configured to selectively divert fluid through either

the cooled crossover passage or the insulated crossover passage depending on an operating condition of the engine.

3. The engine of claim **1**, further comprising one or more fluid jackets through which engine coolant flows, the one or more fluid jackets being disposed in proximity to the cooled crossover passage.

4. The engine of claim **1**, further comprising an insulative material disposed around the insulated crossover passage.

5. The engine of claim **4**, wherein the insulative material is a ceramic.

6. The engine of claim **1**, wherein the at least one insulated crossover passage is heated.

7. A V-shaped split-cycle engine comprising:

a crankshaft that rotates about a crankshaft axis;

a compression cylinder having a centerline that intersects an offset axis, the offset axis being parallel to the crankshaft axis and offset therefrom; and

an expansion cylinder having a centerline that intersects the offset axis;

wherein the centerline of the compression cylinder is positioned at a non-zero angle with respect to the centerline of the expansion cylinder; and

wherein the offset axis is located opposite the compression cylinder and the expansion cylinder relative to the crankshaft axis.

8. The engine of claim **7**, wherein the engine is an air hybrid engine.

9. The engine of claim **7**, wherein the non-zero angle is in a range of about 10 degrees to about 120 degrees.

10. The engine of claim **7**, wherein the non-zero angle is selected from the group consisting of about 30 degrees, about 45 degrees, and about 60 degrees.

11. The engine of claim **7**, further comprising:

a first cylinder head coupled to the compression cylinder;

a second cylinder head coupled to the expansion cylinder; and

at least one crossover passage formed externally to the first and second cylinder heads and configured to selectively transfer fluid between the first and second cylinder heads.

12. The engine of claim **11**, wherein the engine is an air hybrid engine and the at least one crossover passage includes an air reservoir valve for selectively placing an air reservoir in fluid communication with the first or second cylinder heads.

13. The engine of claim **11**, wherein the at least one crossover passage comprises first and second crossover passages, each having an associated crossover compression valve and a crossover expansion valve.

14. The engine of claim **13**, wherein the crossover compression valves and the crossover expansion valves are outwardly opening.

15. The engine of claim **12**, wherein the air reservoir valve is outwardly opening.

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