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FUEL REFORMING SYSTEM FOR VEHICLE WITH ENGINE MOUNTED THEREON

Abstract

A fuel reforming system includes a reciprocating engine; a decomposer that decomposes a hydrocarbon fuel; and a hydrocarbon fuel supply device. The reciprocating engine includes an intake port, an exhaust port, and a third port that allows a cylinder and the decomposer to communicate and that is opened and closed by an on-off valve. The on-off valve opens in a stroke in which a combustion gas inside the cylinder is supplied to the decomposer with ascending of a piston. The on-off valve opens in a stroke in which a combustion gas, in which the carbon and the hydrogen gas has been removed, is introduced from the third port to the cylinder with descending of the piston. The hydrocarbon fuel supply device injects the hydrocarbon fuel into the third port between the on-off valve and the decomposer during a stroke in which the on-off valve is closed.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION
[0001] The present application claims priority to Japanese Application No. 2024-021533, filed in Japan on Feb. 15, 2024, the entire contents of which is incorporated by reference.
TECHNICAL FIELD
[0002] A technique disclosed herein relates to a fuel reforming system for a vehicle with an engine mounted thereon.
BACKGROUND
[0003] Patent Literature 1 describes a device that directly decomposes hydrocarbon into carbon and hydrogen. This conventional decomposition apparatus includes a reactor in which a catalyst is accommodated. When a raw material gas containing hydrocarbon is supplied to the reactor, carbon produced by a catalytic reaction adheres to the catalyst. A reactant gas containing hydrogen passes through the reactor. A hydrogen refining device downstream of the reactor refines the hydrogen in the reactant gas to increase the hydrogen concentration.
CITATION LIST
Patent Literature
[0004] [Patent Literature 1] Japanese Patent Laid-Open No. 2022-104521
SUMMARY
Problems to be Solved
[0005] In the technical field of a vehicle (for example, a four-wheel automobile), an approach for carbon neutrality has been sought. To realize carbon neutrality in a vehicle on which an engine using a hydrocarbon fuel (including gasoline and/or light oil) is mounted, a new technique of recovering carbon (C) or CO.sub.2 from the hydrocarbon fuel as well as improving the thermal efficiency and/or the exhaust emission performance of the engine is required.
[0006] In the vehicle on which the engine using the hydrocarbon fuel is mounted, when carbon or CO.sub.2 is intended to be recovered, (1) recovery of CO.sub.2 after combustion of the hydrocarbon fuel or (2) recovery of carbon by decomposing the hydrocarbon fuel into carbon and a hydrogen gas prior to combustion of the hydrocarbon fuel is conceived. Considering that the recovered CO.sub.2 or carbon is stored in the vehicle, since CO.sub.2 is heavier than carbon, (2) is more advantageous in terms of the fuel efficiency of the vehicle. Further, in (2), it is also possible to use the hydrogen gas as fuel for the engine. There is also an advantage in that combustion of the hydrogen gas generates no oxide of carbon resulted from the combustion.
[0007] Thus, mounting the aforementioned conventional decomposition apparatus on a vehicle can be conceived. The conventional decomposition apparatus includes a heating device for increasing the temperature of a catalyst. When the conventional decomposition apparatus is mounted on a vehicle, it is possible to utilize the heat of the engine for increasing the temperature of the catalyst.
[0008] However, when a hydrogen gas is intended to be used for an engine fuel, a high-concentration hydrogen gas is required. The conventional decomposition apparatus requires a hydrogen refining device using a PSA (Pressure Swing Adsorption) method for refining hydrogen from a reactant gas containing the hydrogen to obtain the high-concentration hydrogen gas. Mounting of the hydrogen refining device on a vehicle has a disadvantage in that the vehicle weight increases. The conventional decomposition apparatus is unsuitable for being mounted on a vehicle.

[0009] A technique disclosed herein provides a fuel reforming system suitable for being mounted on a vehicle.

Means for Solving the Problems

[0010] Use of a membrane reactor that concurrently performs decomposition of a hydrocarbon fuel and separation of a hydrogen gas for a fuel reforming system for a vehicle may be conceived. The membrane reactor, which is even compact, can produce a high-concentration hydrogen gas such that while a hydrocarbon fuel is decomposed into carbon and a hydrogen gas using a catalyst, a separation membrane allows only the hydrogen gas to permeate therethrough. However, for efficient production of the high-concentration hydrogen gas in the membrane reactor, the pressure of a raw material gas containing the hydrocarbon fuel to be supplied to the membrane reactor needs to be increased.

[0011] The present inventors have focused on a gas inside a cylinder being compressed with ascending of a piston in a reciprocating engine. That is, the fuel reforming system disclosed herein decomposes a hydrocarbon fuel utilizing heat of a combustion gas generated in the reciprocating engine and a pressure when the combustion gas is compressed in accordance with the ascending of the piston. A decomposition process of the hydrocarbon fuel in the fuel reforming system mounted on a vehicle is combined with operation of the reciprocating engine.

[0012] However, when a hydrocarbon fuel is decomposed using piston strokes of the reciprocating engine, a vaporization time of the hydrocarbon fuel and/or a decomposition time of the hydrocarbon fuel could not be secured sufficiently long. When a reaction available time in which vaporization and/or a decomposition reaction is available cannot be secured long, yields of carbon and a hydrogen gas in the fuel reforming system are reduced. This is because when the reaction available time is short, the carbon and the hydrogen gas obtained from the injected hydrocarbon fuel are reduced. Note that the “reaction available time” of the hydrocarbon fuel refers to the time from injection of the hydrocarbon fuel by a hydrocarbon fuel supply device through vaporization of the hydrocarbon fuel to decomposition of the hydrocarbon fuel into the carbon and the hydrogen gas by the decomposer, during which the reaction is available. The reaction available time is mainly determined by the operating conditions of the reciprocating engine. For example, when the rotational speed of the reciprocating engine is high, the reaction available time is reduced.

[0013] The technique disclosed herein increases yields of carbon and a hydrogen gas in a fuel reforming system mounted on a vehicle.

[0014] Specifically, the technique disclosed herein relates to a fuel reforming system for a vehicle with an engine mounted thereon. The fuel reforming system includes: a reciprocating engine that is mounted on a vehicle and in which a piston in a cylinder reciprocates; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas; and a hydrocarbon fuel supply device that supplies the hydrocarbon fuel to the decomposer, in which the reciprocating engine includes an intake port, an exhaust port, and a third port that allows the cylinder and the decomposer to communicate with each other and that is opened and closed by an on-off valve, the on-off valve opens in a stroke in which a combustion gas inside the cylinder is supplied to the decomposer with ascending of the piston and in a stroke in which a combustion gas with the carbon and the hydrogen gas removed is introduced from the third port to the cylinder with descending of the piston, and the hydrocarbon fuel supply device injects the hydrocarbon fuel into the third port between the on-off valve and the decomposer during a stroke in which the on-off valve is closed.

[0015] The fuel reforming system includes the decomposer and the hydrocarbon fuel supply device.

[0016] The hydrocarbon fuel supply device supplies a hydrocarbon fuel to the decomposer. A fuel tank mounted on a vehicle may store the hydrocarbon fuel. The hydrocarbon fuel supply device supplies the hydrocarbon fuel in the fuel tank to the decomposer.

[0017] The decomposer communicates with the cylinder via the third port. The on-off valve opens in the stroke in which the combustion gas inside the cylinder is supplied to the decomposer with ascending of the piston. The combustion gas inside the cylinder pushed by the piston is supplied to the decomposer through the third port. The decomposer decomposes the hydrocarbon fuel supplied from the hydrocarbon fuel supply device, utilizing heat of the combustion gas supplied from the cylinder and a pressure of the combustion gas in accordance with ascending of the piston. Note that the decomposer may store carbon. The hydrogen gas may be used as fuel for the reciprocating engine.

[0018] The on-off valve also opens in the stroke in which the combustion gas with the carbon and the hydrogen gas removed is introduced from the third port to the cylinder with descending of the piston.

[0019] The hydrocarbon fuel supply device injects the hydrocarbon fuel into the third port between the on-off valve and the decomposer during the stroke in which the on-off valve is closed. The hydrocarbon fuel injected into the third port vaporizes inside the third port. The vaporized hydrocarbon fuel is delivered to the decomposer by means of the combustion gas flowing from the cylinder to the decomposer at timing of the on-off valve being opened and the piston ascending. Then, after the piston descends and the on-off valve is closed, the hydrocarbon fuel remains in the decomposer until the on-off valve opens next. Since the hydrocarbon fuel remains in the decomposer for a relatively long period of time, a sufficiently long reaction available time of the hydrocarbon fuel can be secured. The yields of the carbon and the hydrogen gas in the fuel reforming system are increased.

[0020] Another fuel reforming system disclosed herein includes: a reciprocating engine that is mounted on a vehicle and in which a piston in a cylinder reciprocates; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas; and a hydrocarbon fuel supply device that supplies the hydrocarbon fuel to the decomposer, in which the reciprocating engine includes an intake port, an exhaust port, and a third port that allows the cylinder and the decomposer to communicate with each other and that is opened and closed by an on-off valve, the on-off valve opens in a stroke in which a combustion gas inside the cylinder is supplied to the decomposer with ascending of the piston and in a stroke in which a combustion gas with the carbon and the hydrogen gas removed is introduced from the third port to the cylinder with descending of the piston, the decomposer includes a catalyst portion that decomposes the hydrocarbon fuel using a catalyst and a space that is on a side opposite to the third port across the catalyst portion, the space being connected to the catalyst portion, and the hydrocarbon fuel supply device injects the hydrocarbon fuel into the space during a stroke in which the on-off valve is opened and the piston is ascending.

[0021] In this fuel reforming system, the hydrocarbon fuel supply device injects the hydrocarbon fuel during the stroke in which the on-off valve is opened and the piston is ascending. The hydrocarbon fuel supply device injects the hydrocarbon fuel into the space that is on a side opposite to a side of the third port across the catalyst portion. The injected hydrocarbon fuel is delivered from the space to the catalyst portion by means of the flow of the combustion gas returning from the decomposer toward the cylinder at timing of the piston descending. Then, after the on-off valve is closed, the hydrocarbon fuel remains in the catalyst portion until the on-off valve opens next. Since the hydrocarbon fuel remains in the catalyst portion for a relatively long period of time, a sufficiently long reaction available time of the hydrocarbon fuel can be secured. The yields of the carbon and the hydrogen gas in the fuel reforming system are increased.

[0022] The hydrocarbon fuel supply device may inject the hydrocarbon fuel into the third port immediately after closing of the opened on-off valve.

[0023] When the hydrocarbon fuel is injected into the third port immediately after the on-off valve is closed, the time from the injection of the hydrocarbon fuel to the delivery of the hydrocarbon fuel to the decomposer in accordance with opening of the on-off valve can be used for vaporization of the hydrocarbon fuel. There is an advantage in improving the yields of the carbon and the hydrogen gas in the fuel reforming system.

[0024] The hydrocarbon fuel supply device may inject the hydrocarbon fuel into the space in a latter part of a stroke in which the piston is ascending.

[0025] In the latter part of the stroke in which the piston is ascending, a pressure and a temperature inside the third port including the decomposer increase. Since the hydrocarbon fuel is injected into the space under an environment with the high pressure and temperature, there is an advantage in the vaporization of the hydrocarbon fuel. Since the vaporized hydrocarbon fuel can be decomposed into the carbon and the hydrogen gas for a short period of time, the yields of the carbon and the hydrogen gas in the fuel reforming system are improved.

[0026] The reciprocating engine may perform a six-stroke cycle, the six-stroke cycle including: an intake stroke in which at least intake air is introduced into the cylinder through the intake port with descending of the piston; a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; a re-expansion stroke in which the piston descends; and an exhaust stroke in which an exhaust gas is discharged through the exhaust port with ascending of the piston, and the on-off valve may open in the re-compression stroke and the re-expansion stroke and may close in the intake stroke, the compression stroke, the expansion stroke, and the exhaust stroke.

[0027] The reciprocating engine performs the six-stroke cycle. In the six-stroke cycle, the re-compression stroke in which the combustion gas is compressed with ascending of the piston and the re-expansion stroke in which the piston descends are added to the cycle of the typical four-stroke cycle including the intake stroke, the compression stroke, the expansion stroke, and the exhaust stroke, between the expansion stroke and the exhaust stroke.

[0028] The on-off valve opens in the re-compression stroke and the re-expansion stroke. The fuel reforming system can decompose the hydrocarbon fuel utilizing the heat and the pressure of the combustion gas in the re-compression stroke. The on-off valve is closed between the exhaust stroke subsequent to the re-expansion stroke and the expansion stroke.

[0029] When performing injection into the third port between the on-off valve and the decomposer, the hydrocarbon fuel supply device injects the hydrocarbon fuel between the exhaust stroke and the expansion stroke. In order for the reaction available time of the hydrocarbon fuel to be as long as possible, the hydrocarbon fuel supply device may inject the hydrocarbon fuel into the third port during the exhaust stroke.

[0030] When performing injection into the space on the side opposite to the third port across the catalyst portion, the hydrocarbon fuel supply device injects the hydrocarbon fuel in the re-compression stroke. The hydrocarbon fuel supply device may inject the hydrocarbon fuel into the space in the latter part of the re-compression stroke so that the hydrocarbon fuel is injected under the environment with the high pressure and temperature in the decomposer and the third port.

[0031] The reciprocating engine may perform an irregular four-stroke cycle, the irregular four-stroke cycle including: a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; and a scavenging stroke in which an exhaust gas inside the cylinder is discharged through the exhaust port and at least intake air is introduced into the cylinder through the intake port with descending of the piston, and the on-off valve may open in the re-compression stroke and the scavenging stroke and may close in the compression stroke and the expansion stroke.

[0032] The reciprocating engine performs the irregular four-stroke cycle. In the irregular four-stroke cycle, in place of the exhaust stroke and the intake stroke of the typical four-stroke cycle including the intake stroke, the compression stroke, the expansion stroke, and the exhaust stroke, the re-compression stroke in which the combustion gas is compressed with ascending of the piston

is performed after the expansion stroke, and the scavenging stroke in which the exhaust and intake are simultaneously performed is performed at the time of the piston descending after the re-compression stroke.
[0033] The on-off valve opens in the re-compression stroke subsequent to the expansion stroke and the scavenging stroke, and closes in the compression stroke and the expansion stroke. The fuel reforming system can decompose the hydrocarbon fuel utilizing the heat and the pressure of the combustion gas in the re-compression stroke.
[0034] When performing injection into the third port between the on-off valve and the decomposer, the hydrocarbon fuel supply device injects the hydrocarbon fuel between the compression stroke and the expansion stroke. In order for the reaction available time of the hydrocarbon fuel to be as long as possible, the hydrocarbon fuel supply device may inject the hydrocarbon fuel into the third port during the compression stroke.
[0035] When performing injection into the space on the side opposite to the third port across the catalyst portion, the hydrocarbon fuel supply device injects the hydrocarbon fuel in the re-compression stroke. The hydrocarbon fuel supply device may inject the hydrocarbon fuel into the third port in the latter part of the re-compression stroke so that the hydrocarbon fuel is injected under the environment with the high pressure and temperature in the decomposer and the third port.
Advantageous Effects
[0036] The fuel reforming system for a vehicle with an engine mounted thereon is suitable for being mounted on a vehicle and can increase yields of carbon and a hydrogen gas.

Description

BRIEF DESCRIPTION OF DRAWINGS
[0037] FIG. **1** shows a fuel reforming system mounted on a vehicle.
[0038] FIG. **2** shows a decomposer that decomposes a hydrocarbon fuel.
[0039] FIG. **3** shows a control system for a vehicle.
[0040] FIG. **4** shows each stroke of a six-stroke cycle.
[0041] FIG. **5** shows a control map of a reciprocating engine.
[0042] FIG. **6** shows lift curves of an intake valve, an exhaust valve, and an on-off valve.
[0043] FIG. **7** shows a flowchart of engine control.
[0044] FIG. **8** shows injection timing of a hydrocarbon fuel.
[0045] FIG. **9** shows the decomposer according to a modification.
[0046] FIG. **10** shows injection timing of a hydrocarbon fuel according to the modification.
[0047] FIG. **11** shows each stroke of an irregular four-stroke cycle.
[0048] FIG. **12** shows each stroke of the irregular four-stroke cycle according to a modification.
DETAILED DESCRIPTION
[0049] Hereinafter, an embodiment of a fuel reforming system for a vehicle with an engine mounted thereon will be described with reference to the drawings. The system described herein is an example.
(Configuration of Fuel Reforming System)
[0050] FIG. **1** shows a fuel reforming system **1** mounted on a vehicle. A fuel tank mounted on the vehicle stores a hydrocarbon fuel. The hydrocarbon fuel is, for example, gasoline. The hydrocarbon fuel is not limited to gasoline. The fuel reforming system **1** decomposes the hydrocarbon fuel into carbon and a hydrogen gas. The carbon is stored in a decomposer **6** described later. The hydrogen gas is used as fuel for a reciprocating engine **3**. The fuel reforming system **1** realizes carbon neutrality of the vehicle on which the hydrocarbon fuel is mounted.
[0051] The fuel reforming system **1** includes the reciprocating engine **3**. The reciprocating engine **3** includes a cylinder **31** and a piston **32** that reciprocates inside the cylinder **31**. The reciprocating

engine **3** includes a plurality of cylinders **31**. The plurality of cylinders **31** are arranged, for example, in a direction in which a crankshaft of the reciprocating engine **3** extends. The piston **32** of each cylinder **31** is connected to the crankshaft via a connecting rod. The connecting rod converts the reciprocating movement of the piston **32** into the rotation of the crankshaft. The crankshaft is connected to driving wheels via a transmission. The reciprocating engine **3** outputs drive power for traveling the vehicle. Note that the reciprocating engine **3** may be used as a drive source for driving a power generator.

[0052] The reciprocating engine **3** includes an intake port **33**. The intake port **33** communicates with the cylinder **31**. Each cylinder **31** includes one or a plurality of intake ports **33**. Each cylinder **31** may include, for example, two intake ports **33**. The intake port **33** is connected to an intake pipe. As will be described later, intake air is introduced into the cylinder **31** through the intake port **33**. The intake air contains at least fresh air. The intake air may contain an EGR (Exhaust Gas Recirculation) gas.

[0053] The reciprocating engine **3** includes an intake valve **34**. The intake valve **34** is a poppet valve that opens and closes the intake port **33**. When the intake valve **34** opens, the intake air is introduced into the cylinder **31**. An intake valve operating device **41** shown in FIG. **3** opens and closes the intake valve **34**. The intake valve operating device **41** includes, for example, an intake camshaft mechanically connected to the intake valve **34**. The intake valve operating device **41** can continuously change the valve timing of the intake valve **34** (so-called S-VT (Sequential-Valve Timing)). The intake valve operating device **41** can also continuously change the valve lift of the intake valve **34** (so-called CVVL (Continuously Variable Valve Lift)). The intake valve operating device **41** may adopt a publicly-known hydraulic or electric mechanism. The intake valve operating device **41** changes the valve timing and/or the valve lift in accordance with the operating conditions of the reciprocating engine **3**.

[0054] The reciprocating engine **3** includes an exhaust port **35**. The exhaust port **35** communicates with the cylinder **31**. Each cylinder **31** includes one or a plurality of exhaust ports **35**. Each cylinder **31** may include, for example, one exhaust port **35**. The exhaust port **35** is connected to an exhaust pipe. As will be described later, an exhaust gas is discharged from the inside of the cylinder **31** through the exhaust port **35**.

[0055] The reciprocating engine **3** includes an exhaust valve **36**. The exhaust valve **36** is a poppet valve that opens and closes the exhaust port **35**. When the exhaust valve **36** opens, an exhaust gas is discharged to the outside of the cylinder **31**. An exhaust valve operating device **42** shown in FIG. **3** opens and closes the exhaust valve **36**. The exhaust valve operating device **42** includes, for example, an exhaust camshaft mechanically connected to the exhaust valve **36**. The exhaust valve operating device **42** can continuously change the valve timing of the exhaust valve **36** (so-called S-VT). The exhaust valve operating device **42** can also continuously change the valve lift of the exhaust valve **36** (so-called CVVL). The exhaust valve operating device **42** may adopt a publicly-known hydraulic or electric mechanism. The exhaust valve operating device **42** changes the valve timing and/or the valve lift in accordance with the operating conditions of the reciprocating engine **3**.

[0056] The reciprocating engine **3** includes a third port **37**. The third port **37** communicates with the cylinder **31**. Each cylinder **31** includes at least one third port **37**. Each cylinder **31** may include, for example, one third port **37**.

[0057] A typical reciprocating engine includes two intake ports and two exhaust ports for one cylinder. One of the two exhaust ports may be repurposed for the third port **37**. The reciprocating engine **3** of FIG. **1** includes two intake ports **33**, one exhaust port **35**, and one third port **37** for one cylinder **31**. Note that for easier understanding, FIG. **1** illustrates the exhaust port **35** and the third port **37** at positions shifted from each other.

[0058] Note that one of the two intake ports may be repurposed for the third port **37**. However, the two intake ports **33** are advantageous in that a lot of fresh air can be introduced into the cylinder **31**.

When the exhaust port or the intake port is repurposed for the third port **37**, the typical reciprocating engine can be reused for the reciprocating engine **3** of the fuel reforming system **1**. Note that the reciprocating engine **3** may include two intake ports **33**, two exhaust ports **35**, and one third port **37** for one cylinder **31**.

[0059] The reciprocating engine **3** includes an on-off valve **38**. The on-off valve **38** is a poppet valve that opens and closes the third port **37**. A third valve operating device **43** shown in FIG. **3** opens and closes the on-off valve **38**. The third valve operating device **43** includes, for example, a third camshaft mechanically connected to the on-off valve **38**. The third valve operating device **43** opens the on-off valve **38** twice during one cycle in some cases (see FIG. **6**). The third valve operating device **43** can also stop opening and closing the on-off valve **38**. A publicly-known hydraulic or electric mechanism may be adopted for a valve stopping mechanism to stop opening and closing the on-off valve **38**. The valve stopping mechanism may be, for example, incorporated into a rocker arm interposed between the third camshaft and the on-off valve **38**. The valve stopping mechanism may also be incorporated into a lash adjuster that supports the rocker arm. Note that the on-off valve **38** may be mechanically connected to the intake camshaft or the exhaust camshaft.

[0060] An intake port injector **44** is attached to the reciprocating engine **3**. An injection hole of the intake port injector **44** faces the inside of the intake port **33**. The intake port injector **44** injects the hydrocarbon fuel into the intake port **33**. A hydrocarbon fuel supply unit **45** is connected to the intake port injector **44**. The hydrocarbon fuel supply unit **45** includes a fuel tank that stores the hydrocarbon fuel and a fuel pump that pumps the hydrocarbon fuel. The hydrocarbon fuel supply unit **45** supplies the hydrocarbon fuel to the intake port injector **44**.

[0061] A third port injector **46** is attached to the reciprocating engine **3**. An injection hole of the third port injector **46** faces the inside of the third port **37**. More specifically, in an example of FIG. **1**, the third port injector **46** is positioned between the decomposer **6** and the on-off valve **38** in the third port **37**. The third port injector **46** injects the hydrocarbon fuel into the third port **37**. The third port injector **46** is an example of a hydrocarbon fuel supply device. The hydrocarbon fuel supply unit **45** is also connected to the third port injector **46**. The hydrocarbon fuel supply unit **45** selectively supplies the hydrocarbon fuel to the intake port injector **44** and the third port injector **46**.

[0062] A hydrogen injector **47** is attached to the reciprocating engine **3**. An injection hole of the hydrogen injector **47** faces the inside of the cylinder **31**. The hydrogen injector **47** injects the hydrogen gas into the cylinder **31**.

[0063] Note that the injector that injects the hydrocarbon fuel may be attached to the reciprocating engine **3** so as to face the inside of the cylinder **31** and the hydrogen injector that injects the hydrogen gas may be attached to the reciprocating engine **3** so as to face the inside of the intake port **33**.

[0064] A hydrogen gas supply unit **5** is connected to the hydrogen injector **47**. The hydrogen gas supply unit **5** supplies the hydrogen gas to the hydrogen injector **47**. As described above, the hydrogen gas is the hydrogen gas decomposed from the hydrocarbon fuel.

[0065] The decomposer **6** is connected to the third port **37**. The decomposer **6** decomposes the hydrocarbon fuel into carbon and a hydrogen gas. The decomposer **6** is attached to each cylinder **31**. The decomposer **6** may be shared in common by the plurality of cylinders **31**.

[0066] FIG. **2** shows the structure of the decomposer **6**. The decomposer **6** decomposes the hydrocarbon fuel into carbon and a hydrogen gas using a catalyst, and separates the hydrogen gas using a separation membrane **63**. The decomposer **6** is a so-called membrane reactor. Decomposition of the hydrocarbon fuel, for example, isooctane, is represented by the following chemical reaction formula.

[00001] $iC_8H_{18}(g) = 8C(s) + 9H_2$

[0067] Recovering carbon as a solid suppresses an increase in the vehicle weight. The fuel

reforming system **1** is suitable for an on-board system.
[0068] The decomposer **6** includes a catalyst carrier **61**. The catalyst that can be used for decomposition of the hydrocarbon fuel is, for example, an Ni—Al—Fe alloy. As the catalyst, various catalysts that are available for decomposition of the hydrocarbon fuel can be used.
[0069] For the carrier **61**, for example, an aluminum oxide plate member can be used. The catalyst is applied on the surface of the plate member. The carrier **61** is supported on an inner surface of a case **62** of the decomposer **6**. The case **62** is, for example, in a cylinder shape. Note that the shape of the carrier **61** is not limited to a particular shape. The carbon produced by decomposition of the hydrocarbon fuel adheres to the surface of the carrier **61**. The decomposer **6** also stores the carbon.
[0070] The decomposer **6** includes the separation membrane **63**. The separation membrane **63** is positioned on an inner side of the case **62** relative to the carrier **61**. The separation membrane **63** is, for example, in a cylinder shape. The separation membrane **63** has a function of allowing only the hydrogen gas to permeate therethrough. The separation membrane **63** is, for example, a Pd alloy membrane. Note that the separation membrane **63** is not limited to the Pd alloy membrane.
[0071] The third port **37** is connected to a first end of the case **62**. A second end of the case **62** is closed. A combustion gas from the cylinder **31** and the hydrocarbon fuel injected by the third port injector **46** flow into a space between the catalyst carrier **61** and the separation membrane **63** as denoted by a black arrow in FIG. **2**. The catalyst decomposes the hydrocarbon fuel into carbon and a hydrogen gas. The decomposed hydrogen gas permeates through the separation membrane **63** as denoted by a white arrow in FIG. **2**.
[0072] The decomposer **6** includes a catalyst portion **64** including the aforementioned catalyst carrier **61** and separation membrane **63**. The catalyst portion **64** is positioned on a side of the third port **37** in the case **62**, and a space **65** is formed on a side opposite to the third port **37** across the catalyst portion **64** in the case **62**. As will be described later, the gas remaining inside the decomposer **6** at the start of a re-compression stroke is pushed out to the inside of the space **65** in accordance with the inflow of the combustion gas and the hydrocarbon fuel into the decomposer **6**. As a result, the hydrocarbon fuel is spread over the entire catalyst portion **64** and decomposition of the hydrocarbon fuel is promoted.
[0073] A hydrogen gas passage **50** is connected to one end of a cylinder body composed of the separation membrane **63**. The hydrogen gas passage **50** is connected to the hydrogen gas supply unit **5** (see FIG. **1**). The hydrogen gas passage **50** guides the hydrogen gas from the decomposer **6** to the hydrogen gas supply unit **5**. The hydrogen gas is delivered to the hydrogen injector **47** via the hydrogen gas supply unit **5**. The hydrogen gas supply unit **5** includes, for example, a hydrogen gas tank and a hydrogen gas pump.
(Configuration of Control System)
[0074] FIG. **3** is a block diagram of a control system **2** for a vehicle on which the fuel reforming system **1** is mounted. The control system **2** includes a controller **21**. The controller **21** is composed of hardware such as a processor, a memory, and an interface, and software such as a database and a control program.
[0075] A crank angle sensor **22** is electrically connected to the controller **21**. The crank angle sensor **22** is attached to the reciprocating engine **3**. The crank angle sensor **22** outputs a measurement signal corresponding to a rotation angle of the crankshaft to the controller **21**. The controller **21** can identify the rotational speed of the reciprocating engine **3** based on the measurement signal from the crank angle sensor **22**.
[0076] An accelerator position sensor **23** is electrically connected to the controller **21**. The accelerator position sensor **23** is attached to an accelerator pedal. The accelerator position sensor **23** outputs a signal corresponding to a depression amount of the accelerator pedal to the controller **21**. The controller **21** can identify a required load of the reciprocating engine **3** based on the measurement signal from the accelerator position sensor **23**.
[0077] The aforementioned intake valve operating device **41**, exhaust valve operating device **42**,

and third valve operating device **43** are each electrically connected to the controller **21**. The controller **21** outputs a control signal to each of the intake valve operating device **41**, the exhaust valve operating device **42**, and the third valve operating device **43** in accordance with the operating conditions of the reciprocating engine **3**. The intake valve operating device **41** changes the valve timing and/or the valve lift of the intake valve **34** based on the control signal from the controller **21**. The exhaust valve operating device **42** changes the valve timing and/or the valve lift of the exhaust valve **36** based on the control signal from the controller **21**. The third valve operating device **43** switches between opening/closing and stopping of the on-off valve **38** based on the control signal from the controller **21**.

[0078] The aforementioned intake port injector **44**, third port injector **46**, and hydrogen injector **47** are each electrically connected to the controller **21**. The controller **21** outputs a control signal to each of the intake port injector **44**, the third port injector **46**, and the hydrogen injector **47**. The intake port injector **44** injects the hydrocarbon fuel in a predetermined amount into the intake port **33** at predetermined timing based on the control signal from the controller **21**. The third port injector **46** injects the hydrocarbon fuel in a predetermined amount into the third port **37** at predetermined timing based on the control signal from the controller **21**. The hydrogen injector **47** injects the hydrogen gas in a predetermined amount into the cylinder **31** based on the control signal from the controller **21**.

[0079] The control system **2** includes a spark plug **26**. The spark plug **26** is attached to the reciprocating engine **3** so as to face the inside of the cylinder **31**. The spark plug **26** is electrically connected to the controller **21**. The controller **21** outputs a control signal to the spark plug **26**. The spark plug **26** ignites an air-fuel mixture inside the cylinder **31** at predetermined timing based on the control signal from the controller **21**.

[0080] The control system **2** also includes an electric motor **27**. The electric motor **27** is an assist motor that complements an output shortage of the reciprocating engine **3**. The electric motor **27** operates by receiving power supplied from a battery through an inverter **28**. The electric motor **27** and the reciprocating engine **3** may be connected in series or may be connected in parallel. A combination of the reciprocating engine **3** and the electric motor **27** can output drive power required for traveling a vehicle. The inverter **28** is electrically connected to the controller **21**. The controller **21** outputs a control signal to the inverter **28**. The inverter **28** operates the electric motor **27** based on the control signal from the controller **21**.

[0081] The aforementioned hydrocarbon fuel supply unit **45** and hydrogen gas supply unit **5** are each electrically connected to the controller **21**. The controller **21** outputs a control signal to the hydrocarbon fuel supply unit **45** or the hydrogen gas supply unit **5**.

(Six-Stroke Cycle)

[0082] The reciprocating engine **3** performs a six-stroke cycle so that the decomposer **6** performs decomposition of a hydrocarbon fuel. FIG. **4** shows each stroke included in the six-stroke cycle.

[0083] S**11** is an intake stroke. In the intake stroke S**11**, the reciprocating engine **3** introduces intake air into the cylinder **31** with descending of the piston **32**. In the intake stroke S**11**, the intake valve **34** opens. Intake air is introduced into the cylinder **31** through the intake port **33**. The intake air contains at least fresh air. The intake air may contain an EGR gas. The EGR gas is a so-called external EGR gas, which is circulated into the intake pipe through an EGR passage. In the intake stroke S**11**, the exhaust valve **36** may open. When the exhaust valve **36** opens, an exhaust gas is introduced into the cylinder **31** through the exhaust port **35**. The exhaust gas introduced into the cylinder **31** is a so-called internal EGR gas. Note that the on-off valve **38** of the third port **37** is closed.

[0084] In FIG. **4**, during the intake stroke S**11**, the hydrogen injector **47** injects a hydrogen gas into the cylinder **31**. In a compression stroke S**12** subsequent to the intake stroke S**11**, the hydrogen injector **47** may inject the hydrogen gas. Over the period from the intake stroke S**11** to the compression stroke S**12**, the hydrogen injector **47** may inject the hydrogen gas.

[0085] Note that when the hydrogen gas is in short supply, in the intake stroke S**11**, the intake port injector **44** may inject the hydrocarbon fuel to the intake port **33** so as to complement the shortage. Further, when there is no hydrogen gas, the intake port injector **44**, in place of the hydrogen injector **47**, may inject the hydrocarbon fuel to the intake port **33** in the intake stroke S**11**. When the hydrogen gas to be supplied into the cylinder **31** is in short supply, the intake port injector **44** injects the hydrocarbon fuel so that a required fuel amount of the reciprocating engine **3** is secured. The reciprocating engine **3** can operate using the hydrocarbon fuel or both the hydrocarbon fuel and the hydrogen gas.
[0086] S**12** is a compression stroke. In the compression stroke S**12**, the reciprocating engine **3** compresses an air-fuel mixture inside the cylinder **31** with ascending of the piston **32**. The intake valve **34**, the exhaust valve **36**, and the on-off valve **38** are all closed.
[0087] The spark plug **26** ignites the air-fuel mixture inside the cylinder **31** at timing near a compression top dead center. The air-fuel mixture starts combustion. S**13** is an expansion stroke. In the expansion stroke S**13**, the piston **32** descends with the combustion of the air-fuel mixture. The intake valve **34**, the exhaust valve **36**, and the on-off valve **38** are all closed.
[0088] S**14** is a re-compression stroke. In the re-compression stroke S**14**, the reciprocating engine **3** compresses a combustion gas inside the cylinder **31** with ascending of the piston **32**. In the re-compression stroke S**14**, the on-off valve **38** opens. The compressed combustion gas is introduced into the decomposer **6** through the third port **37**. As will be described later, the hydrocarbon fuel that the third port injector **46** injected into the third port **37** in an exhaust stroke S**16**, together with the combustion gas, is introduced into the decomposer **6**. In the decomposer **6**, the hydrocarbon fuel is decomposed into carbon and a hydrogen gas by means of the heat of the combustion gas and the catalyst. The carbon is stored in the decomposer **6**. The hydrogen gas permeates through the separation membrane **63** of the decomposer **6** to be delivered to the hydrogen gas supply unit **5** by means of the pressure of the combustion gas.
[0089] Since the high pressure of the combustion gas in the re-compression stroke S**14** is applied to the decomposer **6**, the hydrogen gas produced in the decomposer **6** rapidly permeates through the separation membrane **63**. Since the hydrogen gas on the right side of the aforementioned chemical reaction formula is discharged from the decomposer **6**, the decomposition reaction of the hydrocarbon fuel in the decomposer **6** is promoted. The decomposer **6**, which is even compact, utilizing the pressure in the re-compression stroke S**14** of the reciprocating engine **3** can produce the hydrogen gas in an amount required for operating the reciprocating engine **3**.
[0090] S**15** is a re-expansion stroke. In the re-expansion stroke S**15**, the piston **32** descends. In the re-expansion stroke S**15**, the on-off valve **38** opens. When the on-off valve **38** opens, the combustion gas with the carbon and the hydrogen gas removed is introduced into the cylinder **31** through the third port **37**. Opening of the on-off valve **38** in the re-expansion stroke S**15** is advantageous in reducing a pumping loss of the reciprocating engine **3**.
[0091] S**16** is the exhaust stroke. In the exhaust stroke S**16**, the reciprocating engine **3** discharges the combustion gas inside the cylinder **31** through the exhaust port **35** with ascending of the piston **32**. In the exhaust stroke S**16**, the exhaust valve **36** opens. Note that in the exhaust stroke S**16**, the intake valve **34** and the on-off valve **38** are closed. Although the details will be described later, in the exhaust stroke S**16**, the third port injector **46** injects the hydrocarbon fuel into the third port **37**.
[0092] After the exhaust stroke S**16**, the reciprocating engine **3** returns to the intake stroke S**11**.
[0093] In this manner, the fuel reforming system **1** including the reciprocating engine **3** that performs the six-stroke cycle stores, in the decomposer **6**, the carbon produced by the decomposition of the hydrocarbon fuel. Further, since the reciprocating engine **3** combusts the hydrogen gas produced by the decomposition of the hydrocarbon fuel, an oxide of carbon resulted from the combustion is not generated. The fuel reforming system **1** can realize carbon neutrality.
[0094] Further, the fuel reforming system **1** utilizes the heat and the pressure derived from the reciprocating engine **3**, and thus, does not require a separate dedicated device for generating the

heat and/or the pressure necessary for the decomposition of the hydrocarbon fuel. The fuel reforming system **1** is useful as an on-board system.

[0095] Note that when the carbon storage amount in the decomposer **6** increases, the carbon is recovered from the decomposer **6**.

(Switching Between Six-Stroke Cycle and Four-Stroke Cycle)

[0096] The reciprocating engine **3** included in the fuel reforming system **1** is also an engine that outputs drive power for traveling a vehicle. The operating conditions of the reciprocating engine **3** significantly change from a low load to a high load and from a low speed to a high speed. When the rotational speed of the reciprocating engine **3** is low, since the time per cycle is relatively long, the decomposer **6** can efficiently decompose the hydrocarbon fuel into carbon and a hydrogen gas. However, when the rotational speed of the reciprocating engine **3** is high, since the time per cycle is short, it is difficult to secure the time for the decomposition reaction, in other words, the reaction available time of the hydrocarbon fuel.

[0097] Thus, the control system **2** for a vehicle switches between the six-stroke cycle that performs decomposition of the hydrocarbon fuel and the four-stroke cycle that does not perform decomposition of the hydrocarbon fuel, in accordance with the operating conditions of the rotational speed and the required load of the reciprocating engine **3**.

[0098] FIG. **5** shows a control map **101** of the reciprocating engine **3**. The control map **101** corresponds to an operating region of the reciprocating engine **3** that are defined based on the rotational speed and the required load of the engine. The controller **21** operates the reciprocating engine **3** in accordance with the control map **101**.

[0099] In the control map **101**, the operating region of the reciprocating engine **3** is divided into a first region **102** and a second region **103**. The first region **102** is a region where the rotational speed is lower than a first rotational speed N**1**. The first region **102** also includes a region where the rotational speed is equal to or higher than the first rotational speed N**1** and the required load is lower than a load Pe**1**. The second region **103** is a region where the rotational speed is equal to or higher than the first rotational speed N**1** and the required load is equal to or greater than the load Pe**1**. The first rotational speed N**1** may be a rotational speed included in a medium speed region when the operating region of the reciprocating engine **3** is trisected into a low speed region, the medium speed region, and a high speed region in a rotational speed direction. The load Pe**1** may be a load included in a medium load region when the operating region of the reciprocating engine **3** is trisected into a low load region, the medium load region, and a high load region in a load direction.

[0100] The controller **21** causes the reciprocating engine **3** to perform the six-stroke cycle in the first region **102**. Specifically, the controller **21** opens the on-off valve **38** at predetermined timing via the third valve operating device **43** while opening the intake valve **34** and the exhaust valve **36** at predetermined timing via the intake valve operating device **41** and the exhaust valve operating device **42**.

[0101] FIG. **6** illustrates lift curves of the intake valve **34**, the exhaust valve **36**, and the on-off valve **38**. The lateral axis of FIG. **6** represents a crank angle and the longitudinal axis represents a valve lift. A chart **601** is an example of the lift curves of the intake valve **34**, the exhaust valve **36**, and the on-off valve **38** when the six-stroke cycle is performed.

[0102] In the chart **601**, the on-off valve **38** opens in the re-compression stroke and opens in the re-expansion stroke. In the re-compression stroke, a combustion gas inside the cylinder **31** is introduced into the third port **37** and in the re-expansion stroke, the combustion gas flows into the cylinder **31** through the third port **37**.

[0103] The chart **601** shows the lift curves when the required load is relatively low. In the exhaust stroke subsequent to the re-expansion stroke, the exhaust valve **36** opens. An exhaust gas inside the cylinder **31** is discharged to the exhaust port **35**. Then, in the intake stroke subsequent to the exhaust stroke, the exhaust valve **36** reopens. Part of the exhaust gas inside the exhaust port **35** is re-introduced into the cylinder **31** as the EGR gas. When the load of the reciprocating engine **3** is

relatively low, the valve lift of the exhaust valve **36** that opens in the intake stroke is at the maximum, for example. Further, in the intake stroke, the intake valve **34** also opens. In the chart **601**, the valve lift of the intake valve **34** is at the maximum. Fresh air introduced into the cylinder **31** is relatively large in amount and the EGR gas is relatively small in amount.
[0104] Here, during the six-stroke cycle being performed by the reciprocating engine **3**, there are two more strokes per cycle as compared to the time when the four-stroke cycle is performed. The output of the reciprocating engine **3** during the six-stroke cycle being performed is two-thirds of the output during the four-stroke cycle being performed. When the required load of the reciprocating engine **3** increases, it is difficult for the reciprocating engine **3** during the six-stroke cycle being performed to satisfy the required load.
[0105] Thus, in the control system **2** for a vehicle, when the reciprocating engine **3** is performing the six-stroke cycle and the required load of the reciprocating engine **3** is equal to or greater than a load Pe**2**, the electric motor **27** is operated (see FIG. **5**). The electric motor **27** functions as an assist motor to complement an output shortage of the reciprocating engine **3**. The drive power required for traveling the vehicle is output by the reciprocating engine **3** and the electric motor **27** cooperating with each other.
[0106] Note that the load Pe**2** may be a load included in a high load region when the operating region of the reciprocating engine **3** is trisected into the low load region, the medium load region, and the high load region in the load direction.
[0107] When the required load is low, the amount of the combustion gas introduced into the decomposer **6** is reduced. Even when the rotational speed of the reciprocating engine **3** is high to thus reduce the reaction available time, if the decomposition capability of the decomposer **6** is high, the decomposer **6** can decompose the hydrocarbon fuel. Thus, in the control map **101** of FIG. **5**, the first region **102** where the six-stroke cycle is performed is expanded to the region of a high speed and a low load. The expansion of the first region **102** reduces the region where the hydrocarbon fuel is combusted, and is thus advantageous in terms of carbon neutrality. Note that the first region **102** may only be a region of the rotational speed lower than the first rotational speed N**1**.
[0108] The controller **21** also causes the reciprocating engine **3** to perform the four-stroke cycle in the second region **103**. Specifically, the controller **21** stops opening the on-off valve **38** via the third valve operating device **43** while opening the intake valve **34** and the exhaust valve **36** at predetermined timing via the intake valve operating device **41** and the exhaust valve operating device **42**. A chart **602** of FIG. **6** shows the lift curves of the intake valve **34** and the exhaust valve **36** when the four-stroke cycle is performed. When the four-stroke cycle is performed, the re-compression stroke and the re-expansion stroke are omitted, and therefore, the pumping loss of the reciprocating engine **3** is reduced. Although the reciprocating engine **3** is operated using the hydrocarbon fuel, the fuel consumption can be suppressed. Note that the reciprocating engine **3** includes a mechanism for changing the speed ratio between the crankshaft and the camshaft in switching between the six-stroke cycle and the four-stroke cycle.
[0109] A flowchart of FIG. **7** shows control procedures on switching between the six-stroke cycle and the four-stroke cycle. In step S**131** after the start, the controller **21** reads various signals, and in the subsequent step S**132**, the controller **21** determines, based on the read signal and the control map **101**, whether the operating conditions of the reciprocating engine **3** are in the first region **102**. When the determination in step S**132** is Yes, that is, when the operating conditions of the reciprocating engine **3** are in the first region **102**, the controller **21** opens and closes the on-off valve **38** of the third port **37** in step S**133**. Further, in step S**134**, the controller **21** causes the third port injector **46** to inject the hydrocarbon fuel to the third port **37**. The reciprocating engine **3** performs the six-stroke cycle.
[0110] In step S**135**, the controller **21** adjusts the opening of the intake valve **34** and/or the exhaust valve **36** in accordance with the required output. In step S**136**, the controller **21** determines whether the required load Pe is equal to or greater than the load Pe**2**. When the determination in step S**136** is

Yes, the controller **21** operates the electric motor **27** to cause the electric motor **27** to assist the reciprocating engine **3** in step S**137**. When the determination in step S**136** is No, the controller **21** does not operate the electric motor **27**.

[0111] Returning to step S**132**, when the determination in step S**132** is No, the controller **21** stops the on-off valve **38** in step S**138**. The reciprocating engine **3** performs the four-stroke cycle.

[0112] In step S**139**, the controller **21** adjusts the opening of the intake valve **34** and/or the exhaust valve **36** in accordance with the required output.

(Fuel Injection Timing)

[0113] The fuel reforming system **1** decomposes a hydrocarbon fuel using the piston strokes of the reciprocating engine **3**. In this case, it is required to secure the reaction available time of the hydrocarbon fuel sufficiently long. This is because if the reaction available time cannot be secured long, the yields of carbon and a hydrogen gas in the fuel reforming system **1** are reduced.

[0114] The fuel reforming system **1** is characterized in the timing at which the third port injector **46** injects the fuel.

[0115] FIG. **8** shows fuel injection timing of the third port injector **46**. A chart **801** of FIG. **8** shows the valve lifts of the intake valve **34**, the exhaust valve **36**, and the on-off valve **38**, and the fuel injection timing of the third port injector **46**. In the chart **801** of FIG. **8**, the fuel injection timing of the third port injector **46** is denoted by a reference sign **461**. Further, a chart **802** of FIG. **8** shows changes in pressure of the third port **37** and the decomposer **6**.

[0116] The third port injector **46** injects the hydrocarbon fuel to the third port **37** during a period in which the on-off valve **38** is closed. More specifically, as shown in S**16**-S**13** of FIG. **8**, the third port injector **46** injects the hydrocarbon fuel to the third port **37** between the decomposer **6** and the on-off valve **38** during the exhaust stroke. In other words, the third port injector **46** injects the fuel to the upstream side of the decomposer **6** relative to the flow of the fuel gas flowing from the cylinder **31** to the decomposer **6**. The injected hydrocarbon fuel vaporizes while the on-off valve **38** is closed, specifically, while the reciprocating engine **3** undergoes the exhaust stroke, the intake stroke, the compression stroke, and the expansion stroke.

[0117] Here, the third port injector **46** is an injector having a high injection pressure so as to enable all the hydrocarbon fuel in a required amount to be injected during the period in which the on-off valve **38** is closed. For the third port injector **46**, a gasoline direct injector may be used. The gasoline direct injector is also advantageous in vaporization of the hydrocarbon fuel since the injected fuel is finely granulated.

[0118] At the timing of the third port injector **46** injecting the hydrocarbon fuel, the gas flow does not substantially exist in the third port **37**. This is because the on-off valve **38** is closed. The third port injector **46** having a high injection pressure is advantageous in promoting the vaporization of the hydrocarbon fuel in injecting the hydrocarbon fuel to the third port **37** where the gas flow does not substantially exist.

[0119] Note that the third port injector **46** may inject the hydrocarbon fuel during the period in which the on-off valve **38** is closed, and when the third port injector **46** injects the fuel at timing that is the most apart from the timing of opening the on-off valve **38**, the longest vaporization time of the hydrocarbon fuel can be secured. The third port injector **46** may inject the hydrocarbon fuel immediately after the on-off valve **38** is closed. The timing immediately after the on-off valve **38** is closed corresponds to the aforementioned exhaust stroke.

[0120] The on-off valve **38** opens in the re-compression stroke as described above. As denoted by a black arrow in S**14**, the combustion gas flows from the cylinder **31** to the decomposer **6**. The combustion gas carries the hydrocarbon fuel inside the third port **37** toward the decomposer **6**. At least part of the hydrocarbon fuel is decomposed into carbon and a hydrogen gas by the catalytic reaction in the decomposer **6**. The carbon is stored in the decomposer **6** and the hydrogen gas passes through the hydrogen gas passage **50** to be delivered to the hydrogen gas supply unit **5**. When the piston **32** reaches the top dead center in the re-compression stroke, the combustion gas containing the hydrocarbon fuel and part of the carbon and the hydrogen gas flow into the space **65** by passing through the catalyst portion **64** of the decomposer **6**.

[0121] In the re-expansion stroke subsequent to the re-compression stroke, the on-off valve **38** opens and the piston **32** descends. In accordance with descending of the piston **32**, the gas inside the third port **37** flows from the decomposer **6** toward the cylinder **31** (see a white arrow in S**15**). The combustion gas containing the hydrocarbon fuel and part of the carbon and the hydrogen gas inside the space **65** flow toward the catalyst portion **64** along with the gas flow and remain there.

[0122] Once the on-off valve **38** closes in the exhaust stroke after the re-expansion stroke, the on-off valve **38** remains closed during the period of the subsequent exhaust stroke, intake stroke, compression stroke, and expansion stroke (see S**16**-S**13**). Since the hydrocarbon fuel remains in the catalyst portion **64**, the decomposition time of the hydrocarbon fuel can be secured sufficiently long in the period until the on-off valve **38** opens in the re-compression stroke S**14**.

[0123] The third port injector **46** injects the hydrocarbon fuel during the stroke in which the on-off valve **38** is closed, so that the vaporization time of the hydrocarbon fuel can be secured long and the time of the hydrocarbon fuel remaining in the catalyst portion **64** of the decomposer **6** can be secured long, thereby increasing the yields of the carbon and the hydrogen gas in the fuel reforming system **1**.

[0124] Note that as described above, during the exhaust stroke in S**16**-S**13**, the third port injector **46** injects the hydrocarbon fuel so that the vaporization is promoted. In the subsequent re-compression stroke in S**14**, the vaporized hydrocarbon fuel is transported to the catalyst portion **64** by means of the combustion gas.

(Modification of Timing of Fuel Injection to Third Port)

[0125] FIG. **9** shows a modification of the third port injector **46**. In the modification, the third port injector **46** is positioned in the space **65** of the decomposer **6** and injects the hydrocarbon fuel into the space **65**. In other words, the third port injector **46** is positioned on a downstream side of the catalyst portion **64** of the decomposer **6** relative to the flow direction of the combustion gas flowing from the cylinder **31** to the decomposer **6**.

[0126] FIG. **10** shows fuel injection timing of the third port injector **46** that injects the hydrocarbon fuel into the space **65**. A chart **801** of FIG. **10** shows the valve lifts of the intake valve **34**, the exhaust valve **36**, and the on-off valve **38**, and the fuel injection timing of the third port injector **46**. In the chart **801** of FIG. **10**, the fuel injection timing of the third port injector **46** is denoted by a reference sign **462**. Further, a chart **802** of FIG. **10** shows changes in pressure of the third port **37** and the decomposer **6**.

[0127] The third port injector **46** injects the hydrocarbon fuel to the space **65** during a period in which the on-off valve **38** is opened and the piston **32** is ascending. More specifically, as shown in S**14** of FIG. **10**, the third port injector **46** injects the hydrocarbon fuel into the space **65** of the decomposer **6** during the re-compression stroke.

[0128] Here, the third port injector **46** may inject the hydrocarbon fuel into the space **65** in a latter part of the re-compression stroke. The latter part of the re-compression stroke may be the latter half when the re-compression stroke is bisected into the former half and the latter half. The reason is that since in the latter part of the re-compression stroke, the pressure inside the third port **37** and the decomposer **6** is high and the temperature inside the third port **37** and the decomposer **6** is also high, there is an advantage in the vaporization of the injected hydrocarbon fuel. Further, as will be described later, injecting the hydrocarbon fuel into the space **65** in the latter part of the re-compression stroke has an advantage also in maintaining the hydrocarbon fuel in the catalyst portion **64** utilizing the gas flow in the re-expansion stroke.

[0129] In the re-expansion stroke subsequent to the re-compression stroke, the injected hydrocarbon fuel reaches the catalyst portion **64** of the decomposer **6** from the space **65** along with the flow of gas flowing from the decomposer **6** toward the cylinder **31**, and remains there (see S**15**). Thereafter, during the period in which the on-off valve **38** is closed, specifically, during the exhaust stroke, the intake stroke, the compression stroke, and the expansion stroke, the hydrocarbon fuel vaporizes and is decomposed into carbon and a hydrogen gas by means of the catalyst (see S**16**-S**13**). The carbon adheres to the surface of the catalyst carrier **61**.

[0130] Thereafter, the on-off valve **38** opens in the re-compression stroke (see S**14**). As denoted by a black arrow, the combustion gas flows from the cylinder **31** toward the decomposer **6**. Because of the gas flow inside the third port **37**, the hydrogen gas passes through the separation membrane **63** to reach the hydrogen gas passage **50** and is delivered to the hydrogen gas supply unit **5** through the hydrogen gas passage **50**.

[0131] Then, as described above, during the re-compression stroke, the third port injector **46** injects the hydrocarbon fuel into the space **65**.

[0132] The third port injector **46** injects the hydrocarbon fuel during the stroke in which the on-off valve **38** is opened and the piston **32** is ascending, so that the vaporization time of the hydrocarbon fuel can be secured long and the time of the hydrocarbon fuel remaining in the catalyst portion **64** of the decomposer **6** can be secured long, thereby increasing the yields of the carbon and the hydrogen gas in the fuel reforming system **1**.

(Irregular Four-Stroke Cycle)

[0133] The reciprocating engine **3** may perform an irregular four-stroke cycle in place of the six-stroke cycle. FIG. **11** shows each stroke included in the irregular four-stroke cycle. Note that in FIG. **11**, the third port injector **46** injects the hydrocarbon fuel between the decomposer **6** and the on-off valve **38**.

[0134] S**21** is the compression stroke. In the compression stroke S**21**, the reciprocating engine **3** compresses an air-fuel mixture inside the cylinder **31** with ascending of the piston **32**. The intake valve **34**, the exhaust valve **36**, and the on-off valve **38** are all closed.

[0135] The hydrogen injector **47** injects the hydrogen gas into the cylinder **31** during the compression stroke S**21**. Note that when the hydrogen gas is in short supply, in a scavenging stroke S**24** described later, the intake port injector **44** may inject the hydrocarbon fuel to the intake port **33** so as to complement the shortage. Further, when there is no hydrogen gas, the intake port injector **44**, in place of the hydrogen injector **47**, may inject the hydrocarbon fuel to the intake port **33** in the scavenging stroke S**24**. When the hydrogen gas to be supplied into the cylinder **31** is in short supply, the intake port injector **44** injects the hydrocarbon fuel so that a required fuel amount of the reciprocating engine **3** is secured. The reciprocating engine **3** can operate using the hydrocarbon fuel or both the hydrocarbon fuel and the hydrogen gas.

[0136] Further, in the compression stroke S**21**, the third port injector **46** injects the hydrocarbon fuel into the third port **37**. As described above, the vaporization time of the hydrocarbon fuel is secured long.

[0137] The spark plug **26** ignites an air-fuel mixture inside the cylinder **31** at timing near a compression top dead center. The air-fuel mixture starts combustion. S**22** is the expansion stroke. In the expansion stroke S**22**, the piston **32** descends with the combustion of the air-fuel mixture. The intake valve **34**, the exhaust valve **36**, and the on-off valve **38** are all closed.

[0138] S**23** is the re-compression stroke. In the re-compression stroke S**23**, the reciprocating engine **3** compresses a combustion gas inside the cylinder **31** with ascending of the piston **32**. In the re-compression stroke S**23**, the on-off valve **38** opens. The compressed combustion gas is introduced into the decomposer **6** through the third port **37**. The hydrocarbon fuel injected into the third port **37** in the compression stroke S**21** is introduced into the decomposer **6** together with the combustion gas. As described above, in the decomposer **6**, the hydrocarbon fuel is decomposed into carbon and a hydrogen gas by means of the heat of the combustion gas and the catalyst. The carbon is stored in the decomposer **6**. The hydrogen gas permeates through the separation membrane **63** of the decomposer **6** to be delivered to the hydrogen gas supply unit **5** by means of the pressure of the combustion gas.

[0139] S**24** is the scavenging stroke. In the scavenging stroke S**24**, the piston **32** descends. In the scavenging stroke S**24**, the on-off valve **38** opens. When the on-off valve **38** opens, the combustion gas with the carbon and the hydrogen gas removed is introduced into the cylinder **31** through the third port **37**.

[0140] In the scavenging stroke S**24**, the exhaust valve **36** opens. The combustion gas inside the cylinder **31** is discharged to the exhaust port **35**. In the scavenging stroke S**24**, the intake valve **34** also opens. Intake air is introduced into the cylinder **31** through the intake port **33**. The intake air contains at least fresh air. The intake air may contain an EGR gas. The EGR gas is a so-called external EGR gas, which is circulated into the intake pipe through an EGR passage. In the scavenging stroke S**24**, the reciprocating engine **3** performs gas exchange inside the cylinder **31**.

[0141] After the scavenging stroke S**24**, the reciprocating engine **3** returns to the compression stroke S**21**.

[0142] In this manner, the fuel reforming system **1** including the reciprocating engine **3** that performs the irregular four-stroke cycle can store, in the decomposer **6**, the carbon produced by decomposition of the hydrocarbon fuel. Further, since the reciprocating engine **3** combusts the hydrogen gas produced by the decomposition of the hydrocarbon fuel, an oxide of carbon resulted from the combustion is not generated. The fuel reforming system **1** can realize carbon neutrality.

[0143] Further, the third port injector **46** injects the hydrocarbon fuel into the third port **37** in the compression stroke S**21** in the period in which the on-off valve **38** is closed, so that the vaporization time of the hydrocarbon fuel can be secured long and the decomposition time of the hydrocarbon fuel can also be secured long.

[0144] FIG. **12** shows a modification of the third port injector **46** in the reciprocating engine **3** that performs the irregular four-stroke cycle. The third port injector **46** injects the hydrocarbon fuel into the space **65** of the decomposer **6**.

[0145] The third port injector **46** injects the hydrocarbon fuel into the space **65** in the re-compression stroke S**23** which is the timing at which the on-off valve **38** is opened and in which the piston **32** is ascending. As described above, in the subsequent scavenging stroke S**24**, the hydrocarbon fuel injected into the space **65** reaches the catalyst portion **64** because of the gas flow from the decomposer **6** to the cylinder **31**. Thereafter, the hydrocarbon fuel is decomposed into carbon and a hydrogen gas, between the compression stroke S**21** and the expansion stroke S**22**. The third port injector **46** injects the hydrocarbon fuel to the downstream side of the catalyst portion **64** in the re-compression stroke S**23** which is the period of the on-off valve **38** being opened and in which the piston **32** is ascending, so that the vaporization time of the hydrocarbon fuel can be secured long and the decomposition time of the hydrocarbon fuel can also be secured long.

[0146] Note that the technique disclosed herein is not limited to the aforementioned configurations. For example, the reciprocating engine **3** may be a compression-ignition engine.

[0147] Further, the decomposer **6** of the fuel reforming system **1** is not limited to the membrane reactor. As long as the hydrocarbon fuel can be decomposed utilizing the heat and the pressure of the combustion gas, the decomposer **6** may be in any structure.

REFERENCE SIGNS LIST

[0148] **1** fuel reforming system [0149] **3** reciprocating engine [0150] **31** cylinder [0151] **32** piston [0152] **33** intake port [0153] **35** exhaust port [0154] **37** third port [0155] **38** on-off valve [0156] **6** decomposer [0157] **64** catalyst portion [0158] **65** space [0159] S**11** intake stroke [0160] S**12** compression stroke [0161] S**13** expansion stroke [0162] S**14** re-compression stroke [0163] S**15** re-expansion stroke [0164] S**16** exhaust stroke [0165] S**21** compression stroke [0166] S**22** expansion stroke [0167] S**23** re-compression stroke [0168] S**24** scavenging stroke

Claims

1. A fuel reforming system for a vehicle, the fuel reforming system comprising: a reciprocating engine mounted on the vehicle and in which a piston in a cylinder reciprocates; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas; and a hydrocarbon fuel supply device that supplies the hydrocarbon fuel to the decomposer, wherein the reciprocating engine includes an intake port, an exhaust port, and a third port that allows the cylinder and the decomposer to communicate and that is opened and closed by an on-off valve, the on-off valve opens in a stroke in which a combustion gas inside the cylinder is supplied to the decomposer with ascending of the piston, the on-off valve opens in a stroke in which a combustion gas, in which the carbon and the hydrogen gas has been removed, is introduced from the third port to the cylinder with descending of the piston, and the hydrocarbon fuel supply device injects the hydrocarbon fuel into the third port between the on-off valve and the decomposer during a stroke in which the on-off valve is closed.

2. The fuel reforming system according to claim 1, wherein the hydrocarbon fuel supply device injects the hydrocarbon fuel into the third port immediately after closing the opened on-off valve.

3. The fuel reforming system according to claim 1, wherein the reciprocating engine performs a six-stroke cycle, the six-stroke cycle including: an intake stroke in which at least intake air is introduced into the cylinder through the intake port with descending of the piston; a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; a re-expansion stroke in which the piston descends; and an exhaust stroke in which an exhaust gas is discharged through the exhaust port with ascending of the piston, the on-off valve opens in the re-compression stroke and the re-expansion stroke, and the on-off valve closes in the intake stroke, the compression stroke, the expansion stroke, and the exhaust stroke.

4. The fuel reforming system according to claim 1, wherein the reciprocating engine performs an irregular four-stroke cycle, the irregular four-stroke cycle including: a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; and a scavenging stroke in which an exhaust gas inside the cylinder is discharged through the exhaust port and at least intake air is introduced into the cylinder through the intake port with descending of the piston, the on-off valve opens in the re-compression stroke and the scavenging stroke, and the on-off valve closes in the compression stroke and the expansion stroke.

5. A fuel reforming system for a vehicle, the fuel reforming system comprising: a reciprocating engine mounted on the vehicle and in which a piston in a cylinder reciprocates; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas; and a hydrocarbon fuel supply device that supplies the hydrocarbon fuel to the decomposer, wherein the reciprocating engine includes an intake port, an exhaust port, and a third port that allows the cylinder and the decomposer to communicate and that is opened and closed by an on-off valve, the on-off valve opens in a stroke in which a combustion gas inside the cylinder is supplied to the decomposer with ascending of the piston, the on-off valve opens in a stroke in which a combustion gas, in which the carbon and the hydrogen gas has been removed, is introduced from the third port to the cylinder with descending of the piston, the decomposer includes a catalyst portion that decomposes the hydrocarbon fuel using a catalyst and a space that is on a side opposite to the third port across the catalyst portion, the space being connected to the catalyst portion, and the hydrocarbon fuel supply device injects the hydrocarbon fuel into the space during a stroke in which the on-off valve is opened and the piston is ascending.

6. The fuel reforming system according to claim 5, wherein the hydrocarbon fuel supply device injects the hydrocarbon fuel into the space during a stroke in which the piston is ascending.

7. The fuel reforming system according to claim 5, wherein the reciprocating engine performs a six-stroke cycle, the six-stroke cycle including: an intake stroke in which at least intake air is introduced into the cylinder through the intake port with descending of the piston; a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; a re-expansion stroke in which the piston descends; and an exhaust stroke in which an exhaust gas is discharged through the exhaust port with ascending of the piston, the on-off valve opens in the re-compression stroke and the re-expansion stroke, and the on-off valve closes in the intake stroke, the compression stroke, the expansion stroke, and the exhaust stroke.

8. The fuel reforming system according to claim 5, wherein the reciprocating engine performs an irregular four-stroke cycle, the irregular four-stroke cycle including: a compression stroke in which an air-fuel mixture containing the hydrogen gas supplied into the cylinder is compressed with ascending of the piston; an expansion stroke in which the piston descends with combustion of the air-fuel mixture; a re-compression stroke in which a combustion gas is compressed with ascending of the piston; and a scavenging stroke in which an exhaust gas inside the cylinder is discharged through the exhaust port and at least intake air is introduced into the cylinder through the intake port with descending of the piston, the on-off valve opens in the re-compression stroke and the scavenging stroke, and the on-off valve closes in the compression stroke and the expansion stroke.