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## FUEL REFORMING SYSTEM FOR VEHICLE


### Abstract

A fuel reforming system for a vehicle includes a reciprocating engine mounted on a vehicle, a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas and that stores the carbon, a hydrocarbon fuel supply unit that supplies the hydrocarbon fuel to the decomposer, and a hydrogen gas supply unit that supplies the hydrogen gas into a cylinder. The reciprocating engine performs a cycle including a compression stroke, an expansion stroke, and a re-compression stroke. The decomposer decomposes the hydrocarbon fuel into the carbon and the hydrogen gas utilizing the heat and the pressure of a combustion gas in the re-compression stroke. The decomposer includes a catalyst to which the carbon adheres and a water vapor adsorption portion in which water vapor is adsorbed.



**Inventors:** **SAKIMA; Toshiaki (Aki-gun, JP), HARADA; Yuji (Aki-gun, JP)**

**Applicant:** **Mazda Motor Corporation** (Hiroshima, JP)



**Family ID:** **1000008492183**

**Assignee:** **Mazda Motor Corporation (Hiroshima, JP)**

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## Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION

[0001] The present application claims priority to Japanese application number 2024-021486 filed in the Japanese Patent Office on Feb. 15, 2024, the entire contents of which are incorporated herein by reference.

TECHNICAL FIELD

[0002] The present disclosure relates to a fuel reforming system for a vehicle.

BACKGROUND ART

[0003] Patent Literature 1 describes a decomposition apparatus that directly decomposes hydrocarbon into carbon and hydrogen.

[0004] 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 adheres to the catalyst and a reactant gas containing hydrogen passes through the reactor. A hydrogen refining device on a downstream side relative to the reactor refines the hydrogen in the reactant gas to increase the hydrogen concentration.

CITATION LIST

Patent Literature

[0005] [Patent Literature 1] Japanese Patent Laid-Open No. 2022-104521

SUMMARY

Problems to be Solved by the Disclosure

[0006] 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 carbon dioxide (CO2) from the hydrocarbon fuel as well as improving the thermal efficiency and/or the exhaust emission performance of the engine is required.

[0007] In the vehicle on which the engine using the hydrocarbon fuel is mounted, when carbon or carbon dioxide is intended to be recovered, (1) recovery of carbon dioxide 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.

[0008] Considering that the recovered carbon dioxide or carbon is stored in the vehicle, since carbon dioxide is heavier than carbon (carbon is lighter than carbon dioxide), (2) (i.e., pre-combustion carbon recovery) is more advantageous than (1) (i.e., post-combustion recovery) 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

[0009] Thus, mounting the aforementioned conventional decomposition apparatus on a vehicle can be conceived.

[0010] The conventional decomposition apparatus includes a fluid bed reaction container. The reaction container accommodates a plurality of catalyst particles therein and a raw material gas is injected upward from a fluid bed toward the catalyst particles in the reaction container. Carbon that adheres to the catalyst particles is removed from the catalyst particles such that the catalyst particles are suspended in the raw material gas and the catalyst particles are rubbed against each other.

[0011] Further, the conventional decomposition apparatus includes a catalyst regenerating device outside a reactor. The catalyst regenerating device communicates with the reactor via a catalyst supply line and a catalyst return line. The catalyst regenerating device removes carbon from catalyst particles supplied from the reactor via the catalyst supply line and returns the catalyst particles with the carbon removed to the reactor via the catalyst return line.

[0012] The catalyst regenerating device is, for example, a rotary pipe that removes carbon from catalyst particles by agitating the catalyst particles to cause the catalyst particles to rub against each other, a catalyst dissolution device that removes carbon from catalyst particles by dissolving the catalyst particles, or a catalyst conversion device that removes carbon from catalyst particles by converting carbon into methane, carbon monoxide, or carbon dioxide using hydrogen, water vapor, and oxygen.

[0013] The conventional decomposition apparatus is inevitably enlarged or made in a complicated structure since it includes the aforementioned fluid bed or catalyst regenerating device as a carbon removing mechanism for removing carbon from a catalyst. In addition, in the conventional decomposition apparatus, a heating device to increase the temperature of a catalyst is essential. Therefore, it is difficult to mount the conventional decomposition apparatus on a vehicle.

[0014] Even if the decomposition apparatus can be mounted on a vehicle, there is a concern that in the decomposition apparatus mounted on the vehicle, carbon dioxide is generated due to steam reforming reaction and the associated water gas shift reaction derived from the water vapor in a combustion gas.

[0015] An aspect of the present disclosure is to achieve suppression of generation of carbon dioxide in a fuel reforming system mounted on a vehicle.

Means for Solving the Problems

[0016] A fuel reforming system for a vehicle according to the present disclosure includes: a reciprocating engine that is mounted on the vehicle and in which a piston reciprocates inside a cylinder; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas and that stores the carbon; a hydrocarbon fuel supply unit that supplies the hydrocarbon fuel to the decomposer; and a hydrogen gas supply unit that supplies the hydrogen gas produced by the decomposer into the cylinder, in which the reciprocating engine performs a cycle including at least a compression stroke in which an air-fuel mixture containing the hydrogen gas inside the cylinder is compressed with ascending of the piston, an expansion stroke in which the piston descends with combustion of the air-fuel mixture, and a re-compression stroke in which a combustion gas is compressed with ascending of the piston, the decomposer decomposes the hydrocarbon fuel supplied from the hydrocarbon fuel supply unit into the carbon and the hydrogen gas utilizing heat and pressure of the combustion gas in the re-compression stroke, and the decomposer includes: a catalyst to which the carbon adheres; and a water vapor adsorption portion in which water vapor is adsorbed.

[0017] The reciprocating engine includes the re-compression stroke in which a combustion gas is compressed with ascension of the piston, after the compression stroke and the expansion stroke. The hydrocarbon fuel supply unit supplies the hydrocarbon fuel to the decomposer.

[0018] The decomposer decomposes the hydrocarbon fuel into carbon and a hydrogen gas utilizing the heat and the pressure of the combustion gas in the re-compression stroke. The decomposer can efficiently decompose the hydrocarbon fuel. The carbon is stored in the decomposer.

[0019] The hydrogen gas supply unit supplies, as fuel, the hydrogen gas produced in the decomposer into the cylinder of the reciprocating engine. The reciprocating engine operates by combusting the hydrogen gas. An oxide of carbon resulting from the combustion is not generated. The reciprocating engine can supply the heat and the pressure to the decomposer for the decomposition of the hydrocarbon fuel while outputting the drive power for traveling a vehicle.

[0020] The fuel reforming system can realize carbon neutrality. The fuel reforming system utilizes the heat and the pressure derived from the reciprocating engine, 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 is useful as an on-board system

mounted on a vehicle.
[0021] Further, the decomposer includes the catalyst to which carbon adheres and the water vapor adsorption portion in which water vapor is adsorbed. Here, the water vapor is mixed in the combustion gas to be supplied to the decomposer in some cases.
[0022] In the decomposer, since the water vapor is adsorbed in the water vapor adsorption portion, adsorption of the water vapor in the catalyst is suppressed. In this manner, in the decomposer, a steam reforming reaction and an associated water gas shift reaction are suppressed, so that carbon dioxide is less likely to be generated.
[0023] As described above, generation of carbon dioxide can be suppressed in a fuel reforming system mounted on a vehicle.
[0024] In one embodiment, the water vapor adsorption portion is formed of a material that generates heat when the water vapor is adsorbed therein.
[0025] With such a configuration, a decomposition reaction that decomposes the hydrocarbon fuel into carbon and a hydrogen gas can be promoted with the heat generated when the water vapor is adsorbed in the water vapor adsorption portion.
[0026] In one embodiment, the water vapor adsorption portion is disposed next to the catalyst.
[0027] With such a configuration, it is possible to urge the water vapor to avoid being adsorbed in the catalyst, but adsorbed in the next water vapor adsorption portion.
[0028] In one embodiment, the decomposer includes a carrier, a recess and a projection that are next to each other are provided on a surface of the carrier, the catalyst is carried in one of the recess and the projection, and the water vapor adsorption portion is disposed in the other of the recess and the projection.
[0029] With such a configuration, by providing a step between the catalyst and the water vapor adsorption portion, the adsorption of the water vapor in the water vapor adsorption portion, separated from the catalyst, can be promoted more readily, so the adhesion of the carbon to the catalyst can be similarly promoted.
[0030] In one embodiment, the carrier is in a cylinder shape and carries the catalyst on an inner surface as the surface, the recess and the projection are provided on the inner surface, and the water vapor adsorption portion is positioned on an inner side relative to the catalyst.
[0031] With such a configuration, the water vapor adsorption portion contacts water vapor before the catalyst contacts the water vapor. In this manner, the water vapor can be adsorbed in the water vapor adsorption portion before the water vapor is adsorbed in the catalyst.
[0032] In one embodiment, the carrier forms the water vapor adsorption portion, the projection is exposed as the water vapor adsorption portion, and the recess is covered with the catalyst.
[0033] With such a configuration, it becomes easier to dispose the catalyst and the water vapor adsorption portion on the surface of the carrier.
Advantageous Effects
[0034] According to the present disclosure, generation of carbon dioxide can be suppressed in a fuel reforming system mounted on a vehicle.

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## Description

BRIEF DESCRIPTION OF DRAWINGS
[0035] FIG. **1** shows a fuel reforming system.
[0036] FIG. **2** shows a front-face cross-sectional view of a decomposer and a carbon recovery unit according to a first embodiment.
[0037] FIG. **3** shows a side-face cross-sectional view of the decomposer according to the first embodiment.
[0038] FIG. **4** shows a hydrogen gas supply unit.

[0039] FIG. **5** shows a control system.
[0040] FIG. **6** shows each stroke of a six-stroke cycle according to the first embodiment.
[0041] FIG. **7** schematically shows an inner surface of a carrier of the decomposer according to the first embodiment.
[0042] FIG. **8** schematically shows the inner surface of the carrier of the decomposer according to a second embodiment.
[0043] FIG. **9** shows a front-face cross-sectional view of the decomposer according to a third embodiment.
[0044] FIG. **10** shows each stroke of an irregular four-stroke cycle according to a fourth embodiment.

MODE FOR CARRYING OUT DISCLOSED EMBODIMENTS

[0045] Hereinafter, embodiments of the present disclosure will be described in detail based on the drawings. The descriptions of the following preferred embodiments are substantially mere examples, and are utterly not intended to limit the present disclosure and targets of its application or its purpose.

First Embodiment

(Fuel Reforming System)

[0046] The fuel reforming system **1** for a vehicle according to a first embodiment will be described. FIG. **1** shows the fuel reforming system **1**. The fuel reforming system **1** is mounted on a vehicle. The vehicle is, for example, a four-wheel automobile or a two-wheel automobile. The fuel reforming system **1** decomposes a hydrocarbon fuel (CH fuel) into carbon (C) and a hydrogen gas (H2 gas) by way of a decomposer **50** described later. The carbon is stored in the decomposer **50**. The hydrogen gas is used as fuel for a reciprocating engine **10**. By virtue of this pre-combustion separation and isolation of carbon, the fuel reforming system **1** realizes carbon neutrality of a vehicle.

[0047] The fuel reforming system **1** for a vehicle includes the reciprocating engine **10**, a hydrocarbon fuel supply unit **30** (sometimes referred to as a hydrocarbon fuel supply), a hydrogen gas supply unit **40** (sometimes referred to as a hydrogen gas supply), the decomposer **50**, a carbon recovery unit **70** (sometimes referred to as a carbon recovery system), a control system **80**, and a hydrogen gas passage **90**.

(Reciprocating Engine)

[0048] The reciprocating engine **10** is mounted on a vehicle. The reciprocating engine **10** includes a cylinder **11**, a piston **12**, an intake port **13**, an intake valve **14**, an exhaust port **15**, an exhaust valve **16**, a reforming port **17**, and an on-off valve **18**.

[0049] The cylinder **11** includes a plurality of cylinders **11**. The plurality of cylinders **11** are arranged, for example, in a direction in which a crankshaft of the reciprocating engine **10** extends. The piston **12** is accommodated in each cylinder **11**. The piston **12** reciprocates inside the cylinder **11**. The piston **12** is connected to the crankshaft via a connecting rod. The connecting rod converts the reciprocating movement of the piston **12** into the rotation of the crankshaft. The crankshaft is connected to driving wheels via a transmission. The reciprocating engine **10** outputs drive power for moving the vehicle. Note that the reciprocating engine **10** may be used as a drive source for driving a power generator.

[0050] The intake port **13** communicates with the cylinder **11**. One or a plurality of intake ports **13** are connected to each cylinder **11**. For example, two intake ports **13** are connected to each cylinder **11**. The intake port **13** is connected to an intake pipe. Intake air is introduced into the cylinder **11** through the intake port **13**. The intake air contains fresh air. The intake air may contain an EGR (Exhaust Gas Recirculation) gas. The intake valve **14** is a poppet valve that opens and closes the intake port **13**. When the intake valve **14** opens, the intake air is introduced into the cylinder **11** through the intake port **13**.

[0051] The exhaust port **15** communicates with the cylinder **11**. One or a plurality of exhaust ports

**15** are connected to each cylinder **11**. For example, one exhaust port **15** may be connected to each cylinder **11**. The exhaust port **15** is connected to an exhaust pipe. An exhaust gas is discharged from the inside of the cylinder **11** to the outside of the cylinder **11** through the exhaust port **15**. The exhaust valve **16** is a poppet valve that opens and closes the exhaust port **15**. When the exhaust valve **16** opens, the exhaust gas is discharged from the inside of the cylinder **11** to the outside of the cylinder **11** through the exhaust port **15**.

[0052] The reforming port **17** communicates with the cylinder **11**. At least one reforming port **17** is connected to each cylinder **11**. For example, one reforming port **17** may be connected to each cylinder **11**. The on-off valve **18** is a poppet valve and opens and closes the reforming port **17**.

[0053] A typical reciprocating engine includes two intake ports and two exhaust ports for one cylinder. One of the two exhaust ports may be re-purposed for the reforming port **17**. Alternatively, one of the two intake ports may be repurposed for the reforming port **17**. In the present example, the reciprocating engine **10** includes two intake ports **13**, one exhaust port **15**, and one reforming port **17** for one cylinder **11**. Note that for easier understanding, FIG. **1** illustrates the exhaust port **15** and the reforming port **17** at positions shifted from each other.

[0054] As shown in FIG. **5**, the reciprocating engine **10** includes an intake valve operating device **21**, an exhaust valve operating device **22**, and a reforming valve operating device **23**. The intake valve operating device **21** opens and closes the intake valve **14**. The exhaust valve operating device **22** opens and closes the exhaust valve **16**. The reforming valve operating device **23** opens and closes the on-off valve **18**.

[0055] The intake valve operating device **21** and the exhaust valve operating device **22** include an intake camshaft and an exhaust camshaft mechanically connected to the intake valve **14** and the exhaust valve **16** and can continuously change the valve timing of the intake valve **14** and the exhaust valve **16** (so-called S-VT (Sequential-Valve Timing)). The intake valve operating device **21** and the exhaust valve operating device **22** can also continuously change the valve lifts of the intake valve **14** and the exhaust valve **16** (so-called CVVL (Continuously Variable Valve Lift)). The intake valve operating device **21** and the exhaust valve operating device **22** may adopt a publicly-known hydraulic or electric mechanism.

[0056] The reforming valve operating device **23** includes, for example, a reforming camshaft mechanically connected to the on-off valve **18**. The reforming valve operating device **23** opens the on-off valve **18** twice during one cycle (see FIG. **6**). The reforming valve operating device **23** can stop opening and closing the on-off valve **18**. A publicly-known hydraulic or electric mechanism may be adopted for a valve stopping mechanism to stop opening and closing the on-off valve **18**. The valve stopping mechanism may be, for example, incorporated into a rocker arm interposed between the reforming camshaft and the on-off valve **18**. The valve stopping mechanism may be incorporated into a lash adjuster that supports the rocker arm. Note that the on-off valve **18** may be mechanically connected to the intake camshaft or the exhaust camshaft.

[0057] The reciprocating engine **10** includes an intake port injector **24**, a reforming port injector **25**, and a hydrogen injector **26**. An injection hole of the intake port injector **24** faces the inside of the intake port **13**. The intake port injector **24** injects the hydrocarbon fuel into the intake port **13**. An injection hole of the reforming port injector **25** faces the inside of the reforming port **17**. The reforming port injector **25** injects the hydrocarbon fuel into the reforming port **17**. An injection hole of the hydrogen injector **26** faces the inside of the cylinder **11**. The hydrogen injector **26** injects the hydrogen gas into the cylinder **11**.

[0058] Note that the injector that injects the hydrocarbon fuel may face the inside of the cylinder **11** or the hydrogen injector that injects the hydrogen gas may face the inside of the intake port **13**.

[0059] The reciprocating engine **10** includes a spark plug **27** (see FIG. **5**). The spark plug **27** faces the inside of the cylinder **11**. The spark plug **27** ignites an air-fuel mixture inside the cylinder **11**.

(Hydrocarbon Fuel Supply Unit and Hydrogen Gas Supply Unit)

[0060] The hydrocarbon fuel supply unit **30** is mounted on a vehicle. The hydrocarbon fuel supply

unit **30** is connected to the intake port injector **24**. The hydrocarbon fuel supply unit **30** is also connected to the reforming port injector **25**. The hydrocarbon fuel supply unit **30** selectively supplies the hydrocarbon fuel to the intake port injector **24** and the reforming port injector **25**.
[0061] The hydrocarbon fuel supply unit **30** includes a fuel tank that stores the hydrocarbon fuel and a fuel pump that pumps the hydrocarbon fuel. In the fuel tank, the hydrocarbon fuel is stored. The hydrocarbon fuel is, for example, gasoline. The hydrocarbon fuel may be light oil. The hydrocarbon fuel may be another fuel.
[0062] As described above, the hydrocarbon fuel supply unit **30** supplies the hydrocarbon fuel to the reforming port injector **25**. The reforming port injector **25** supplies the hydrocarbon fuel into the reforming port **17**. The hydrocarbon fuel supplied into the reforming port **17** is supplied to the decomposer **50** described later. In short, the hydrocarbon fuel supply unit **30** supplies the hydrocarbon fuel to the decomposer **50** through the reforming port injector **25** and the reforming port **17**.
[0063] The hydrogen gas supply unit **40** is mounted on a vehicle. The hydrogen gas supply unit **40** is connected to the hydrogen injector **26**. The hydrogen gas supply unit **40** supplies a hydrogen gas to the hydrogen injector **26**. As described above, the hydrogen gas is the hydrogen gas obtained by decomposing the hydrocarbon fuel. The configuration of the hydrogen gas supply unit **40** will be described later.
(Decomposer)
[0064] The decomposer **50** is mounted on a vehicle. The decomposer **50** is connected to the reforming port **17**. The decomposer **50** is attached to each cylinder **11**. The decomposer **50** may be shared in common by the plurality of cylinders **11**. The decomposer **50** is a so-called membrane reactor.
[0065] FIG. **2** shows a front-face cross-sectional view of the decomposer **50**. FIG. **3** shows a side-face cross-sectional view of the decomposer **50** taken along line III. The decomposer **50** includes a carrier **51**, a catalyst **52**, a hydrogen separation membrane **53**, a case **54**, and a water vapor adsorption portion **55**.
[0066] The carrier **51** is formed in a cylinder shape. The cylinder-shaped carrier **51** includes an outer surface **51***a* facing an outer circumferential side and an inner surface **51***b* as a surface facing an inner circumferential side. The carrier **51** is formed of, for example, ceramic. The carrier **51** may be formed of, for example, an aluminum oxide. The carrier **51** may also be formed of another material. The catalyst **52** is carried on the inner surface **51***b* of the cylinder-shaped carrier **51**. In other words, the cylinder-shaped carrier **51** carries the catalyst **52** on the inner surface **51***b*. Specifically, the catalyst **52** is applied on a part or all of the inner surface **51***b* of the cylinder-shaped carrier **51**.
[0067] Carbon of the hydrocarbon fuel adheres to the catalyst **52**. The catalyst **52** is formed of, for example, an Ni—Al—Fe alloy. Note that as the catalyst **52**, various catalysts to which carbon adheres may be adopted. Adhesion of carbon to the catalyst **52** is performed by a chemical reaction.
[0068] The hydrogen separation membrane **53** is formed in a cylinder shape. The cylinder-shaped hydrogen separation membrane **53** includes an outer surface **53***a* facing an outer circumferential side and an inner surface **53***b* facing an inner circumferential side. The hydrogen separation membrane **53** is disposed inside the carrier **51** (inner side relative to the inner surface **51***b* of the carrier **51**). An outer diameter of the hydrogen separation membrane **53** is smaller than an inner diameter of the carrier **51**. A gap A is formed between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53**. Only the hydrogen gas of the hydrocarbon fuel permeates through the hydrogen separation membrane **53**. The hydrogen separation membrane **53** is formed of, for example, a Pd alloy. Note that the hydrogen separation membrane **53** is not limited to a Pd alloy membrane.
[0069] Hereinafter, the right side of FIG. **2** is referred to as one side and the left side of FIG. **2** is referred to as the other side. Note that the direction from one side toward the other side is a

horizontal direction. The upper side of FIG. **2** is simply referred to as an upper side and the lower side of FIG. **2** is simply referred to as a lower side. One end of the carrier **51** is opened. One end of the carrier **51** is connected to (communicates with) the reforming port **17**. The opening at one end of the carrier **51** faces the reforming port **17**. The other end of the carrier **51** is opened. The other end of the carrier **51** is connected to (communicates with) the carbon recovery unit **70** described later. The opening at the other end of the carrier **51** faces the carbon recovery unit **70**.

[0070] One end of the hydrogen separation membrane **53** is closed. One end of the hydrogen separation membrane **53** is recessed toward the other side relative to one end of the carrier **51**. The other end of the hydrogen separation membrane **53** projects toward the other side relative to the other end of the carrier **51**. The other end of the hydrogen separation membrane **53** is opened. The other end of the hydrogen separation membrane **53** is connected to (communicates with) the hydrogen gas passage **90** in a cylinder shape. An outer diameter of the other end of the hydrogen separation membrane **53** fits into an inner diameter of one end of the hydrogen gas passage **90**. The opening at the other end of the hydrogen separation membrane **53** faces the hydrogen gas passage **90**.

[0071] The hydrogen gas passage **90** connects the hydrogen separation membrane **53** and the hydrogen injector **26**. In the middle of the hydrogen gas passage **90**, the hydrogen gas supply unit **40** described later is connected (see FIG. **4**).

[0072] The case **54** is formed in a substantially cylinder shape. The case **54** includes a cylinder portion **54***a* in a cylinder shape and an inwardly extending portion **54***b* extending from one end and the other end of the cylinder portion **54***a* toward the inner side. The cylinder portion **54***a* of the case **54** covers the outer surface **51***a* of the carrier **51**. The inwardly extending portion **54***b* of the case **54** covers one end face and the other end face of the carrier **51**. The case **54** retains the carrier **51** and the hydrogen separation membrane **53**.

[0073] The hydrocarbon fuel, together with a combustion gas described later, is introduced (see a black arrow in FIG. **2**) to the inside (inner side relative to the inner surface **51***b*) of the carrier **51** from the opening at one end of the carrier **51** through the reforming port **17**. The hydrocarbon fuel flows through the gap A between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53** from one side to the other side.

[0074] The carbon of the hydrocarbon fuel flowing through the gap A adheres to the catalyst **52** on the inner surface **51***b* of the carrier **51**. The hydrogen gas of the hydrocarbon fuel flowing through the gap A passes through the hydrogen separation membrane **53** from the outer side toward the inner side to be introduced (see a white arrow in FIG. **2**) to the inner side (inner side relative to the inner surface **53***b*) of the hydrogen separation membrane **53**. The hydrogen gas flows through the inner side (inner side relative to the inner surface **53***b*) of the hydrogen separation membrane **53** toward the other side and passes through the hydrogen gas passage **90** to be supplied to the hydrogen gas supply unit **40** described later.

[0075] The hydrocarbon fuel is supplied from the hydrocarbon fuel supply unit **30** to the decomposer **50** through the reforming port injector **25** and the reforming port **17**. The decomposer **50** decomposes the hydrocarbon fuel into carbon and a hydrogen gas by the carbon adhering to the catalyst **52** and the hydrogen gas passing through the hydrogen separation membrane **53**. The decomposer **50** produces the carbon and the hydrogen gas that are decomposed from each other.

[0076] The decomposer **50** stores the carbon. Specifically, the carbon adhering to the catalyst **52** on the inner surface **51***b* of the carrier **51** remains as it is in the gap A between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53**.

[0077] Decomposition of the hydrocarbon fuel, as an example of isooctane, is represented by the following chemical reaction formula: $iC_8H_{18}(g)=8C(s)+9H_2$.

[0078] The water vapor adsorption portion **55** will be described later.

(Hydrogen Gas Supply Unit)

[0079] FIG. **4** shows the hydrogen gas supply unit **40**. Hereinafter, an upstream side (side of the decomposer **50**) in a hydrogen gas flow is simply referred to as an upstream side and a downstream side (side of the hydrogen injector **26**) in the hydrogen gas flow is simply referred to as a downstream side.

[0080] The hydrogen gas supply unit **40** is mounted on a vehicle. The hydrogen gas supply unit **40** is provided in the middle of the hydrogen gas passage **90**. An upstream end of the hydrogen gas passage **90** is connected to the decomposer **50**. As described above, the decomposer **50** produces a hydrogen gas. A downstream end of the hydrogen gas passage **90** is connected to the hydrogen injector **26**. The hydrogen gas is supplied to the hydrogen gas supply unit **40** from the decomposer **50**. The hydrogen gas supply unit **40** supplies the hydrogen gas to the hydrogen injector **26**. The hydrogen injector **26** injects the hydrogen gas into the cylinder **11**.

[0081] In short, the hydrogen gas supply unit **40** supplies the hydrogen gas produced by the decomposer **50** into the cylinder **11** through the hydrogen gas passage **90** and the hydrogen injector **26**.

[0082] The hydrogen gas supply unit **40** may be shared in common by the plurality of cylinders **11**. The hydrogen gas supply unit **40** may be provided for each cylinder **11**. The hydrogen gas supply unit **40** includes a first tank **41**, a second tank **42**, a bypass passage **43**, a first switching valve **44**, a second switching valve **45**, and a hydrogen pump **46**.

[0083] The first tank **41** is connected to the hydrogen gas passage **90**. The first tank **41** stores the hydrogen gas supplied from the decomposer **50**.

[0084] The bypass passage **43** is formed of a part of the hydrogen gas passage **90** and bypasses the first tank **41**. The first switching valve **44** is connected to the hydrogen gas passage **90** on the upstream side relative to the first tank **41**. The second switching valve **45** is connected to the hydrogen gas passage **90** on the downstream side relative to the first tank **41**. The first switching valve **44** and the second switching valve **45** switch a flow passage of the hydrogen gas between a side of the first tank **41** and a side of the bypass passage **43** upon reception of a control signal from a controller **81** described later.

[0085] The hydrogen pump **46** is connected to the hydrogen gas passage **90** on the downstream side relative to the second switching valve **45**. The hydrogen pump **46** increases the pressure of the hydrogen gas. The second tank **42** is connected to the hydrogen gas passage **90** on a lower side relative to the hydrogen pump **46**. The second tank **42** is positioned between the hydrogen pump **46** and the hydrogen injector **26** in the hydrogen gas passage **90**. The second tank **42** stores a high-pressure hydrogen gas.

[0086] The pressure of the first tank **41** is lower than the pressure of the second tank **42**. The low-pressure first tank **41** lowers the pressure on a secondary side of the hydrogen separation membrane **53** (pressure on the inner side relative to the inner surface **53***b* of the hydrogen separation membrane **53**) as compared to the pressure on a primary side of the hydrogen separation membrane **53** (pressure in the gap A between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53**). The low-pressure first tank **41** increases the pressure difference between the primary side and the secondary side in the hydrogen separation membrane **53**. A large pressure difference promotes permeation of the hydrogen gas through the hydrogen separation membrane **53**. The hydrogen gas produced in the gap A (primary side) between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53** rapidly permeates toward the inner side (secondary side) relative to the inner surface **53***b* of the hydrogen separation membrane **53** so that the decomposition reaction of the hydrocarbon fuel in the decomposer **50** is promoted.

[0087] A combination of the first tank **41** and the heat and the pressure of a combustion gas in a re-compression stroke S**4** described later significantly promotes the decomposition reaction of the hydrocarbon fuel in the decomposer **50**. Even when the decomposer **50** is compact, the promotion of the decomposition reaction of the hydrocarbon fuel makes it possible to secure the hydrogen gas in an amount required for operating the reciprocating engine **10**.

[0088] Similarly, in a state of the flow passage of the hydrogen gas being switched to the side of the bypass passage **43**, the pressure on the secondary side of the hydrogen separation membrane **53** is reduced due to driving of the hydrogen pump **46**. The high-pressure second tank **42** can stably supply the high-pressure hydrogen gas to the hydrogen injector **26**. The hydrogen injector **26** can inject the hydrogen gas into the cylinder **11** at timing near a compression top dead center at which the pressure inside the cylinder **11** is high. The hydrogen pump **46** enables the high-pressure hydrogen gas to be supplied to the hydrogen injector **26** while maintaining the pressure of the first tank **41** at low.

(Carbon Recovery Unit)

[0089] FIG. **2** shows a front-face cross-sectional view of the carbon recovery unit **70**. The carbon recovery unit **70** is mounted on a vehicle. The carbon recovery unit **70** includes a housing **71**, a discharge passage **72**, and a discharge valve **73**.

[0090] The housing **71** includes a cylinder portion **71***a* and a cover portion **71***b*. The cylinder portion **71***a* is in a cylinder shape. One end of the cylinder portion **71***a* of the housing **71** is connected to the other end of the carrier **51** via the inwardly extending portion **54***b* of the case **54**. A portion at the other end of the hydrogen separation membrane **53** and a portion at one end of the hydrogen gas passage **90** are accommodated inside the cylinder portion **71***a* of the housing **71**. A discharge hole **74** is formed on a lower portion of the cylinder portion **71***a* of the housing **71**. The cover portion **71***b* covers an opening at the other end of the cylinder portion **71***a* of the housing **71**. A through-hole is provided in the cover portion **71***b* of the housing **71**. The hydrogen gas passage **90** extends through the through-hole of the cover portion **71***b* of the housing **71**.

[0091] The discharge passage **72** includes a cylinder portion **72***a* and a cover portion **72***b*. The cylinder portion **72***a* of the discharge passage **72** is in a cylinder shape extending in an up-down direction. An upper end of the cylinder portion **72***a* of the discharge passage **72** is connected to the discharge hole **74** provided in the lower portion of the cylinder portion **71***a* of the housing **71**. The cover portion **72***b* covers a lower end of the cylinder portion **72***a* in the discharge passage **72**. The carbon removed from the catalyst **52** of the decomposer **50** is discharged to the discharge passage **72**. The carbon discharged to the discharge passage **72** is stored in the discharge passage **72**.

[0092] The discharge valve **73** opens and closes the discharge passage **72**. Specifically, the discharge valve **73** opens and closes the discharge hole **74** (connecting portion between the housing **71** and the discharge passage **72**) in the lower portion of the cylinder portion **71***a* of the housing **71**. When the discharge valve **73** closes the discharge passage **72**, an inner space of the discharge passage **72** does not communicate with an inner space of the housing **71**. When the discharge valve **73** opens the discharge passage **72**, the inner space of the discharge passage **72** communicates with the inner space of the housing **71**.

[0093] The carbon recovery unit **70** recovers the carbon produced in the decomposer **50**. In particular, the carbon recovery unit **70** recovers the carbon removed from the catalyst **52** of the decomposer **50**. The carbon discharged to the discharge passage **72** of the carbon recovery unit **70** is taken out from a vehicle during, for example, maintenance check of the vehicle. The carbon taken out is reusable as a recycled product.

(Control System)

[0094] FIG. **5** shows a block diagram of the control system **80**. The control system **80** includes the controller **81**. The controller **81** is composed of hardware such as a processor, a memory, and an interface, and software such as a database and a control program. Moreover, the processor may be one or more programmable processors (e.g., CPUs and/or GPUs) that are configured by execution of stored computer readable code, or hardwired processors such as application specific integrated circuit(s) (ASICs) and/or programmable array logic (PAL), or a combination of one or more software configurable processor(s) and one or more hardwired processor(s).

[0095] A rotational speed sensor **82** is electrically connected to the controller **81**. The rotational speed sensor **82** is attached to the reciprocating engine **10**. The rotational speed sensor **82** outputs a measurement signal corresponding to the rotational speed of the crankshaft to the controller **81**. The controller **81** can identify the rotational speed of the reciprocating engine **10** based on the measurement signal from the rotational speed sensor **82**.

[0096] An accelerator position sensor **83** is electrically connected to the controller **81**. The accelerator position sensor **83** is attached to an accelerator pedal. The accelerator position sensor **83** outputs a signal corresponding to a depression amount of the accelerator pedal to the controller **81**. The controller **81** can identify a required load of the reciprocating engine **10** based on the measurement signal from the accelerator position sensor **83**.

[0097] A knock sensor **84** is electrically connected to the controller **81**. The knock sensor **84** is attached to the reciprocating engine **10**. When a knock is generated in the reciprocating engine **10**, the knock sensor **84** outputs a knock detection signal to the controller **81**. The controller **81** can identify the generation of the knock based on the knock detection signal.

[0098] A tank pressure sensor **85** is electrically connected to the controller **81**. The tank pressure sensor **85** is attached to the second tank **42** of the hydrogen gas supply unit **40**. The tank pressure sensor **85** outputs a signal corresponding to a hydrogen gas amount in the second tank **42** to the controller **81**. The controller **81** can determine the hydrogen gas amount that can be supplied to the cylinder **11**, based on the signal from the tank pressure sensor **85**.

[0099] The intake valve operating device **21**, the exhaust valve operating device **22**, and the reforming valve operating device **23** are electrically connected to the controller **81**. The controller **81** outputs a control signal to the intake valve operating device **21**, the exhaust valve operating device **22**, and the reforming valve operating device **23** in accordance with the operating conditions of the reciprocating engine **10**. The intake valve operating device **21** changes the valve timing and/or the valve lift of the intake valve **14** based on the control signal from the controller **81**. The exhaust valve operating device **22** changes the valve timing and/or the valve lift of the exhaust valve **16** based on the control signal from the controller **81**. The reforming valve operating device **23** switches between opening/closing and stopping of the on-off valve **18** based on the control signal from the controller **81**.

[0100] The intake port injector **24**, the reforming port injector **25**, and the hydrogen injector **26** are electrically connected to the controller **81**. The controller **81** outputs a control signal to the intake port injector **24**, the reforming port injector **25**, and the hydrogen injector **26**. The intake port injector **24** injects the hydrocarbon fuel in a predetermined amount into the intake port **13** at predetermined timing based on the control signal from the controller **81**. The reforming port injector **25** injects the hydrocarbon fuel in a predetermined amount into the reforming port **17** at predetermined timing based on the control signal from the controller **81**. The hydrogen injector **26** injects the hydrogen gas in a predetermined amount into the cylinder **11** at predetermined timing based on the control signal from the controller **81**.

[0101] The spark plug **27** is electrically connected to the controller **81**. The spark plug **27** is attached to the reciprocating engine **10**. The controller **81** outputs a control signal to the spark plug **27**. The spark plug **27** ignites an air-fuel mixture inside the cylinder **11** at predetermined timing based on the control signal from the controller **81**.

[0102] The hydrogen gas supply unit **40** is electrically connected to the controller **81**. The controller **81** outputs a control signal to the first switching valve **44**, the second switching valve **45**, and the hydrogen pump **46** of the hydrogen gas supply unit **40**.

[0103] The discharge valve **73** of the carbon recovery unit **70** is electrically connected to the controller **81**. The controller **81** outputs a control signal to the discharge valve **73** of the carbon recovery unit **70**. The discharge valve **73** of the carbon recovery unit **70** opens and closes the discharge passage **72** of the carbon recovery unit **70** based on the control signal from the controller **81**.

(Six-Stroke Cycle)

[0104] The reciprocating engine **10** performs a six-stroke cycle so that the decomposer **50** performs decomposition of a hydrocarbon fuel. FIG. **6** shows each stroke of the six-stroke cycle. The six-stroke cycle includes an intake stroke S**1**, a compression stroke S**2**, an expansion stroke S**3**, the re-compression stroke S**4**, a re-expansion stroke S**5**, and an exhaust stroke S**6**.

[0105] In the intake stroke S**1**, intake air is introduced into the cylinder **11** with descending of the piston **12**. In the intake stroke S**1**, the intake valve **14** opens. The intake air is introduced into the cylinder **11** through the intake port **13**. The intake air contains fresh air. The intake air may contain an EGR gas. The EGR gas is an external EGR gas, which is circulated into the intake pipe through an EGR passage. In the intake stroke S**1**, the exhaust valve **16** may open. When the exhaust valve **16** opens, an exhaust gas is introduced into the cylinder **11** through the exhaust port **15**. The exhaust gas introduced into the cylinder **11** is an internal EGR gas. The on-off valve **18** of the reforming port **17** is closed.

[0106] During the intake stroke S**1**, the hydrogen injector **26** (hydrogen gas supply unit **40**) injects (supplies) a hydrogen gas into the cylinder **11**. In the compression stroke S**2** subsequent to the intake stroke S**1**, the hydrogen injector **26** may inject the hydrogen gas. Over the period from the intake stroke S**1** to the compression stroke S**2**, the hydrogen injector **26** may inject the hydrogen gas. An air-fuel mixture in which the hydrogen gas and the intake air (air) are mixed is produced inside the cylinder **11**.

[0107] When the hydrogen gas is in short supply, in the intake stroke S**1**, the intake port injector **24** may inject the hydrocarbon fuel to the intake port **13** so as to complement the shortage. When there is no hydrogen gas, the intake port injector **24**, in place of the hydrogen injector **26**, may inject the hydrocarbon fuel to the intake port **13** in the intake stroke S**1**. When the hydrogen gas to be supplied into the cylinder **11** is in short supply, the intake port injector **24** injects the hydrocarbon fuel so that a necessary fuel amount of the reciprocating engine **10** is secured. The reciprocating engine **10** can operate using the hydrocarbon fuel or both the hydrocarbon fuel and the hydrogen gas.

[0108] In the compression stroke S**2**, the air-fuel mixture containing the hydrogen gas inside the cylinder **11** is compressed with ascending of the piston **12**. In the compression stroke S**2**, the intake valve **14**, the exhaust valve **16**, and the on-off valve **18** are all closed.

[0109] The spark plug **27** ignites the air-fuel mixture inside the cylinder **11** at timing near a compression top dead center. The air-fuel mixture starts combustion. In the expansion stroke S**3**, the piston **12** descends with the combustion of the air-fuel mixture. In the expansion stroke S**3**, the intake valve **14**, the exhaust valve **16**, and the on-off valve **18** are all closed.

[0110] In the re-compression stroke S**4**, a combustion gas inside the cylinder **11** is compressed with ascending of the piston **12**. In the re-compression stroke S**4**, the on-off valve **18** opens. In the re-compression stroke S**4**, the compressed combustion gas is introduced into the decomposer **50** through the reforming port **17**. In the re-compression stroke S**4**, the reforming port injector **25** injects the hydrocarbon fuel into the reforming port **17**. The hydrocarbon fuel, together with the combustion gas, is introduced into the decomposer **50**. Specifically, in the re-compression stroke S**4**, the hydrocarbon fuel is supplied from the hydrocarbon fuel supply unit **30** to the decomposer **50** via the reforming port injector **25** and the reforming port **17**, and the combustion gas is supplied from the inside of the cylinder **11** to the decomposer **50** via the reforming port **17**.

[0111] In the re-compression stroke S**4**, in the decomposer **50**, the hydrocarbon fuel is decomposed into carbon and a hydrogen gas by means of the heat of the combustion gas and the catalyst **52**. The carbon adheres to the catalyst **52** and is stored in the decomposer **50**. In the re-compression stroke S**4**, the hydrogen gas permeates through the hydrogen separation membrane **53** of the decomposer **50** to be delivered to the hydrogen gas supply unit **40** via the hydrogen gas passage **90** by means of the pressure of the combustion gas.

[0112] Since the high pressure of the combustion gas in the re-compression stroke S**4** is applied to the decomposer **50** (specifically, the gap A between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53**), the hydrogen gas produced in the decomposer **50** (gap A) rapidly permeates through the hydrogen separation membrane **53** to be delivered to the inner side (specifically, inner side relative to the inner surface **53***b* of the hydrogen separation membrane **53**) of the hydrogen separation membrane **53**.

[0113] In this manner, the decomposer **50** decomposes the hydrocarbon fuel supplied from the hydrocarbon fuel supply unit **30** (via the reforming port injector **25** and the reforming port **17**) into the carbon and the hydrogen gas utilizing the heat and the pressure of the combustion gas in the re-compression stroke S**4**. This promotes the decomposition reaction of the hydrocarbon fuel in the decomposer **50**. The decomposer **50**, which is even compact, utilizing the heat and the pressure in the re-compression stroke S**4** of the reciprocating engine **10** can produce the hydrogen gas in an amount required for operating the reciprocating engine **10**.

[0114] In the re-expansion stroke S**5**, the piston **12** descends. In the re-expansion stroke S**5**, the on-off valve **18** may open. When the on-off valve **18** opens, the combustion gas with the carbon and the hydrogen gas removed is introduced into the cylinder **11** from the decomposer **50** through the reforming port **17**. Opening of the on-off valve **18** in the re-expansion stroke S**5** is advantageous in reducing a pumping loss of the reciprocating engine **10**.

[0115] In the exhaust stroke S**6**, the combustion gas inside the cylinder **11** is discharged through the exhaust port **15** with ascending of the piston **12**. In the exhaust stroke S**6**, the exhaust valve **16** opens. Note that in the exhaust stroke S**6**, the intake valve **14** and the on-off valve **18** are closed.

[0116] After the exhaust stroke S**6**, the reciprocating engine **10** returns to the intake stroke S**1**.

[0117] Note that instead of opening of the on-off valve **18** in the re-expansion stroke S**5** or along with opening of the on-off valve **18** in the re-expansion stroke S**5**, the on-off valve **18** may open in the intake stroke S**1**. When the on-off valve **18** opens in the intake stroke S**1**, the combustion gas with the carbon and the hydrogen gas removed is introduced into the cylinder **11** from the decomposer **50** via the reforming port **17**. The combustion gas becomes an EGR gas.

[0118] In the re-expansion stroke S**5**, when the on-off valve **18** is closed, since the hydrocarbon fuel introduced into the decomposer **50** in the re-compression stroke S**4** remains in the decomposer **50** for a long period of time, an advantage of promoting the decomposition reaction of the hydrocarbon fuel can be obtained.

[0119] In this manner, the fuel reforming system **1** including the reciprocating engine **10** that performs the six-stroke cycle stores, in the decomposer **50**, the carbon produced by the decomposition of the hydrocarbon fuel. Since the reciprocating engine **10** 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.

[0120] The fuel reforming system **1** utilizes the heat and the pressure derived from the reciprocating engine **10**, 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.

(Water Vapor Adsorption Portion)

[0121] FIG. **7** schematically shows the inner surface **51***b* of the carrier **51** in the decomposer **50**. Note that FIG. **7** shows a micro region as compared to FIGS. **2** and **3**.

[0122] The carrier **51** is in a cylinder shape. A recess **56** and a projection **57** are provided on the inner surface **51***b* as a surface of the carrier **51**. The recess **56** and the projection **57** are next to each other on the inner surface **51***b* of the carrier **51**. Specifically, the recess **56** and the projection **57** are adjacent to each other on the inner surface **51***b* of the carrier **51**. The recess **56** is recessed to the inner side on the inner surface **51***b* of the carrier **51**. The projection **57** projects to the outer side on the inner surface **51***b* of the carrier **51**.

[0123] The catalyst **52** is carried in the recess **56** on the inner surface **51***b* of the carrier **51**. The water vapor adsorption portion **55** is disposed in the projection **57** on the inner surface **51***b* of the carrier **51**. Specifically, the water vapor adsorption portion **55** is applied on the projection **57** on the inner surface **51***b* of the carrier **51**. The water vapor adsorption portion **55** is in a film form that is

formed on the inner surface **51***b* of the carrier **51**.
[0124] The catalyst **52** in the recess **56** on the inner surface **51***b* of the carrier **51** and the water vapor adsorption portion **55** in the projection **57** on the inner surface **51***b* of the carrier **51** are next to each other. In other words, on the inner surface **51***b* of the carrier **51**, the water vapor adsorption portion **55** is disposed so as to be next to the catalyst **52**. Conversely, on the inner surface **51***b* of the carrier **51**, the catalyst **52** is disposed so as to be next to the water vapor adsorption portion **55**.
[0125] The water vapor adsorption portion **55** in the projection **57** on the inner surface **51***b* of the cylinder-shaped carrier **51** is positioned on the inner side (inner circumferential side, a side of the gap A denoted by J) relative to the catalyst **52** in the recess **56** on the inner surface **51***b* of the cylinder-shaped carrier **51**.
[0126] The water vapor adsorption portion **55** in the projection **57** on the inner surface **51***b* of the cylinder-shaped carrier **51** is positioned closer to the gap A, where the hydrocarbon fuel and the combustion gas are supplied, relative to the catalyst **52** in the recess **56** on the inner surface **51***b* of the cylinder-shaped carrier **51**. The water vapor adsorption portion **55** contacts the hydrocarbon fuel, the combustion gas, and the water vapor described later, before the catalyst **52** contacts the water vapor.
[0127] As described above, carbon (C) of the hydrocarbon fuel (CH fuel) adheres to the catalyst **52**. In this manner, the carbon (C) and the hydrogen gas (H2 gas) are decomposed from the hydrocarbon fuel (CH fuel).
[0128] As described above, in the re-compression stroke S**4**, the hydrocarbon fuel (CH fuel) and the combustion gas are supplied to the decomposer **50** (specifically, the gap A between the inner surface **51***b* of the carrier **51** and the outer surface **53***a* of the hydrogen separation membrane **53**). At this time, water vapor (H2O) is mixed in the combustion gas in some cases. In other words, the water vapor (H2O) in addition to the hydrocarbon fuel (CH fuel) and the combustion gas is present in the decomposer **50**. Further, not only the carbon (C), but also the water vapor (H2O) adheres to the catalyst **52** in some cases.
[0129] In a case where water vapor (H2O) is present in a large amount in the decomposer **50**, when the water vapor (H2O) adheres to the catalyst **52**, the steam reforming reaction and the associated water gas shift reaction that are represented by the following chemical reaction formulae occur, thereby generating carbon dioxide (CO2). C8H18+8H2O=8CO+17H2 (steam reforming reaction). CO+H2O=CO2+H2 (water gas shift reaction).
[0130] In the decomposer **50**, the water vapor adsorption portion **55** is for suppressing the steam reforming reaction and the associated water gas shift reaction so as not to generate carbon dioxide. Water vapor is adsorbed in the water vapor adsorption portion **55**. The water vapor adsorption portion **55** is formed of a material that generates heat when the water vapor is adsorbed therein. The heat generated at this time is adsorbed heat (see white arrow). The water vapor adsorption portion **55** is formed of, for example, zeolite and silica gel. The water vapor adsorption portion **55** may be formed of another material.
Function and Effect
[0131] The reciprocating engine **10** includes the re-compression stroke S**4** in which a combustion gas is compressed with ascending of the piston **12**, after the compression stroke S**2** and the expansion stroke S**3**. The hydrocarbon fuel supply unit **30** supplies the hydrocarbon fuel to the decomposer **50**.
[0132] The decomposer **50** decomposes the hydrocarbon fuel into carbon and a hydrogen gas utilizing the heat and the pressure of the combustion gas in the re-compression stroke S**4**. The decomposer **50** can efficiently decompose the hydrocarbon fuel. The carbon is stored in the decomposer **50**.
[0133] The hydrogen gas supply unit **40** supplies, as fuel, the hydrogen gas produced in the decomposer **50** into the cylinder **11** of the reciprocating engine **10**. The reciprocating engine **10** operates by combusting the hydrogen gas. An oxide of carbon resulted from the combustion is not

generated. The reciprocating engine **10** can supply the heat and the pressure to the decomposer **50** for the decomposition of the hydrocarbon fuel while outputting the drive power for traveling a vehicle.
[0134] The fuel reforming system **1** can realize carbon neutrality. The fuel reforming system **1** utilizes the heat and the pressure derived from the reciprocating engine **10**, 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 mounted on a vehicle.
[0135] Further, the decomposer **50** includes the catalyst **52** to which carbon adheres and the water vapor adsorption portion **55** in which water vapor is adsorbed. Here, the water vapor is mixed in the combustion gas to be supplied to the decomposer **50** in some cases.
[0136] In the decomposer **50**, since the water vapor is adsorbed in the water vapor adsorption portion **55**, adsorption of the water vapor in the catalyst **52** is suppressed. In this manner, in the decomposer **50**, the steam reforming reaction and the associated water gas shift reaction are suppressed, so that carbon dioxide is less likely to be generated.
[0137] As described above, generation of carbon dioxide can be suppressed in the fuel reforming system **1** mounted on a vehicle.
[0138] With the heat generated when the water vapor is adsorbed in the water vapor adsorption portion **55**, the decomposition reaction that decomposes the hydrocarbon fuel into carbon and a hydrogen gas can be promoted.
[0139] Since the water vapor adsorption portion **55** is next to the catalyst **52**, it is possible to urge the water vapor not to be adsorbed in the catalyst **52**, but in the next water vapor adsorption portion **55**.
[0140] The catalyst **52** is carried in the recess **56** on the inner surface (surface) **51***b* of the carrier **51** and the water vapor adsorption portion **55** is disposed in the projection **57** on the inner surface (surface) **51***b* of the carrier **51**. By providing a step between the catalyst **52** (recess **56**) and the water vapor adsorption portion **55** (projection **57**), the adsorption of the water vapor in the water vapor adsorption portion **55**, separated from the catalyst **52**, can be more promoted, so that the adhesion of the carbon to the catalyst **52** can be more promoted.
[0141] The water vapor adsorption portion **55** in the projection **57** on the inner surface **51***b* of the cylinder-shaped carrier **51** is positioned on the inner side (the side of the gap A denoted by J) relative to the catalyst **52** in the recess **56** on the inner surface **51***b* of the cylinder-shaped carrier **51**. Thus, the water vapor adsorption portion **55** contacts water vapor before the catalyst **52** contacts the water vapor. In this manner, the water vapor can be adsorbed in the water vapor adsorption portion **55** before the water vapor is adsorbed in the catalyst **52**.
Second Embodiment
[0142] The fuel reforming system **1** for a vehicle according to a second embodiment will be described. In the following description, the same components as those of the aforementioned embodiment are assigned the same reference signs and the detailed descriptions are omitted in some cases. FIG. **8** schematically shows a cross section of the inner surface **51***b* of the carrier **51** of the decomposer **50** according to the second embodiment.
[0143] The carrier **51** forms the water vapor adsorption portion **55** by itself. The carrier **51** is formed of, for example, zeolite and silica gel. The water vapor adsorption portion **55** may be formed of another material.
[0144] The carrier **51** is formed in a cylinder shape. The recess **56** and the projection **57** that are next to each other are provided on the inner surface **51***b* as the surface of the carrier **51**. The recess **56** and the projection **57** on the inner surface **51***b* of the carrier **51** may be formed by intentionally processing or the like or may be naturally formed as surface roughness over the course of the production.
[0145] The projection **57** on the inner surface **51***b* of the carrier **51** is exposed on the inner side (the

side of the gap A denoted by J) as the water vapor adsorption portion **55**. The recess **56** on the inner surface **51***b* of the carrier **51** is covered with the catalyst **52**. The catalyst **52** is preferably smaller than the recess **56** on the inner surface **51***b* of the carrier **51**. The catalyst **52** may cover only a part or all of the recess **56** on the inner surface **51***b* of the carrier **51**.

[0146] The other configurations are the same as those of the first embodiment.

[0147] According to the present embodiment, the carrier **51** forms the water vapor adsorption portion **55**, and the recess **56** and the projection **57** are provided on the inner surface (surface) **51***b*. When the catalyst **52** is intended to be disposed on the inner surface (surface) **51***b* of such a carrier **51**, on the inner surface (surface) **51***b* of the carrier **51**, the catalyst **52** naturally rolls into the recess **56** and the projection **57** is naturally exposed as the water vapor adsorption portion **55**.

[0148] It is easier to dispose the catalyst **52** and the water vapor adsorption portion **55** on the inner surface (surface) **51***b* of the carrier **51**.

[0149] Further, the water vapor adsorption portion **55** is more likely to contact the water vapor before the catalyst **52** contacts the water vapor. Therefore, the water vapor can be adsorbed in the water vapor adsorption portion **55** before the water vapor is adsorbed in the catalyst **52**.

Third Embodiment

[0150] The fuel reforming system **1** for a vehicle according to a third embodiment will be described. In the following description, the same components as those of the aforementioned embodiments are assigned the same reference signs and the detailed descriptions are omitted in some cases. FIG. **9** shows a front-face cross-sectional view of the decomposer **50** according to the third embodiment.

[0151] The decomposer **50** may include a cylinder-shaped hydrogen separation membrane support body **58** (hereinafter, simply referred to as a support body **58**), a plurality of ball-shaped carriers **51** filled inside the support body **58**, the catalyst **52** carried on an outer surface **51***c* as a surface of the ball-shaped carrier **51**, the hydrogen separation membrane **53** provided inside the support body **58**, the water vapor adsorption portion **55** disposed on the outer surface **51***c* as the surface of the ball-shaped carrier **51**, and a case **59** that accommodates the support body **58**. The support body **58** is formed of, for example, porous ceramic (for example, zirconia). The support body **58** may be disposed on the inner side of the hydrogen separation membrane **53** (the hydrogen separation membrane **53** may be disposed on an outer side of the support body **58**).

[0152] The gap A is formed between the outer surfaces (surfaces) **51***c* of the plurality of ball-shaped carriers **51**. In the gap A, a hydrocarbon fuel (CH fuel), a combustion gas, and water vapor (H2O) are present.

[0153] As in the same manner as shown in FIG. **7**, the recess **56** and the projection **57** that are next to each other are provided on the outer surface (surface) **51***c* of the ball-shaped carrier **51**. The catalyst **52** is carried in the recess **56** on the outer surface (surface) **51***c* of the ball-shaped carrier **51**. The water vapor adsorption portion **55** is disposed in the projection **57** on the outer surface (surface) **51***c* of the ball-shaped carrier **51**. On the outer surface (surface) **51***c* of the ball-shaped carrier **51**, the water vapor adsorption portion **55** is disposed so as to be next to the catalyst **52**.

[0154] The water vapor adsorption portion **55** in the projection **57** on the outer surface (surface) **51***c* of the ball-shaped carrier **51** is positioned on the outer side (the side of the gap A, the side closer to the water vapor) relative to the catalyst **52** in the recess **56** on the outer surface (surface) **51***c* of the ball-shaped carrier **51**.

[0155] Carbon adheres to the catalyst **52**. Water vapor is adsorbed in the water vapor adsorption portion **55**. The water vapor adsorption portion **55** is formed of a material that generates heat when the water vapor is adsorbed therein.

[0156] As in the same manner as shown in FIG. **8**, the ball-shaped carrier **51** may form the water vapor adsorption portion **55** by itself. In this case, the projection **57** on the outer surface (surface) **51***c* of the ball-shaped carrier **51** is exposed on the outer side (the side of the gap A, the side closer to water vapor) as the water vapor adsorption portion **55**. The recess **56** on the outer surface

(surface) **51***c* of the ball-shaped carrier **51** is covered with the catalyst **52**.

[0157] The other configurations are the same as those of the first and the second embodiments.

Fourth Embodiment

[0158] The fuel reforming system **1** for a vehicle according to a fourth embodiment will be described. In the following description, the same components as those of the aforementioned embodiments are assigned the same reference signs and the detailed descriptions are omitted in some cases. FIG. **10** shows each stroke of an irregular four-stroke cycle according to the fourth embodiment.

[0159] The reciprocating engine **10** performs the irregular four-stroke cycle. The irregular four-stroke cycle includes a compression stroke T**1** in which an air-fuel mixture containing a hydrogen gas inside the cylinder **11** is compressed with ascending of the piston **12**, an expansion stroke T**2** in which the piston **12** descends with the combustion of the air-fuel mixture, a re-compression stroke T**3** in which a combustion gas is compressed with ascending of the piston **12**, and a scavenging stroke T**4** in which an exhaust gas inside the cylinder **11** is discharged through the exhaust port **15** and intake air is introduced into the cylinder **11** through the intake port **13** with descending of the piston **12**.

[0160] The other configurations are the same as those of the first to third embodiments.

OTHER EMBODIMENTS

[0161] The present disclosure has been described above with preferable embodiments, but these descriptions are not limitations and it goes without saying that various modifications, replacements, or combinations are available.

[0162] On the surfaces **51***b*, **51***c* of the carrier **51**, the catalyst **52** may be carried in the projection **57** and the water vapor adsorption portion **55** may be disposed in the recess **56**.

[0163] The surfaces **51***b*, **51***c* of the carrier **51** may be flat and may not be provided with the recess **56** or the projection **57**. The water vapor adsorption portion **55** may not be next to the catalyst **52**. The water vapor adsorption portion **55** may be disposed separately from the carrier **51**, instead of being disposed on the surfaces **51***b*, **51***c* of the carrier **51**.

[0164] The carrier may be, for example, in a plate shape. In this case, it is preferable that the hydrogen separation membrane is inserted between the inner surfaces of two plate-shaped carriers and the catalyst and the water vapor adsorption portion are disposed (carried) on the inner surfaces of the plate-shaped carriers. The decomposer **50** may be in any structure as long as it can decompose a hydrocarbon fuel utilizing the heat and the pressure of a combustion gas.

[0165] The reciprocating engine **10** may perform a cycle other than the six-stroke cycle and the irregular four-stroke cycle. The cycle may only need to include at least the compression stroke, the expansion stroke, and the re-compression stroke.

[0166] The reciprocating engine **10** may be a compression-ignition engine.

REFERENCE SIGNS LIST

[0167] S**1** intake stroke [0168] S**2** compression stroke [0169] S**3** expansion stroke [0170] S**4** re-compression stroke [0171] S**5** re-expansion stroke [0172] S**6** exhaust stroke [0173] T**1** compression stroke [0174] T**2** expansion stroke [0175] T**3** re-compression stroke [0176] T**4** scavenging stroke [0177] A gap [0178] J inner side [0179] **1** fuel reforming system [0180] **10** reciprocating engine [0181] **11** cylinder [0182] **12** piston [0183] **17** reforming port [0184] **18** on-off valve [0185] **25** reforming port injector [0186] **26** hydrogen injector [0187] **30** hydrocarbon fuel supply unit [0188] **40** hydrogen gas supply unit [0189] **50** decomposer [0190] **51** carrier [0191] **51***a* outer surface [0192] **51***b* inner surface (surface) [0193] **51***c* outer surface (surface) [0194] **52** catalyst [0195] **53** hydrogen separation membrane [0196] **53***a* outer surface [0197] **53***b* inner surface [0198] **54** case [0199] **55** water vapor adsorption portion [0200] **56** recess [0201] **57** projection [0202] **58** support body [0203] **70** carbon recovery unit [0204] **71** housing [0205] **72** discharge passage [0206] **73** discharge valve [0207] **74** discharge hole

## Claims

**1**. A fuel reforming system for a vehicle, the fuel reforming system comprising: a reciprocating engine that is mounted on the vehicle, the reciprocating engine having a piston that reciprocates inside a cylinder; a decomposer that decomposes a hydrocarbon fuel into carbon and a hydrogen gas and that stores the carbon; a hydrocarbon fuel supply that supplies the hydrocarbon fuel to the decomposer; and a hydrogen gas supply that supplies the hydrogen gas produced by the decomposer into the cylinder, wherein the reciprocating engine is arranged to perform a cycle including at least a compression stroke in which an air-fuel mixture containing the hydrogen gas inside the cylinder is compressed with an ascension of the piston, an expansion stroke in which the piston descends with combustion of the air-fuel mixture, and a re-compression stroke in which a combustion gas is compressed with another ascension of the piston, the decomposer includes components that decompose the hydrocarbon fuel supplied from the hydrocarbon fuel supply into the carbon and the hydrogen gas utilizing heat and pressure of the combustion gas in the re-compression stroke, and components of the decomposer include: a catalyst to which the carbon adheres; and a water vapor adsorption portion in which water vapor is adsorbed.
**2**. The fuel reforming system for a vehicle according to claim 1, wherein the water vapor adsorption portion is formed of a material that generates heat in response to adsorption of the water vapor therein.
**3**. The fuel reforming system for a vehicle according to claim 1, wherein the water vapor adsorption portion is disposed next to the catalyst.
**4**. The fuel reforming system for a vehicle according to claim 2, wherein the water vapor adsorption portion is disposed next to the catalyst.
**5**. The fuel reforming system for a vehicle according to claim 3, wherein the decomposer includes a carrier, a recess and a projection that is next to the recess are provided on a surface of the carrier, the catalyst is carried in one of the recess and the projection, and the water vapor adsorption portion is disposed in another of the recess and the projection.
**6**. The fuel reforming system for a vehicle according to claim 4, wherein the decomposer includes a carrier, a recess and a projection that is next to the recess are provided on a surface of the carrier, the catalyst is carried in one of the recess and the projection, and the water vapor adsorption portion is disposed in another of the recess and the projection.
**7**. The fuel reforming system for a vehicle according to claim 5, wherein the carrier has a cylinder shape and carries the catalyst on an inner surface of the cylinder shape, the recess and the projection are provided on the inner surface, and the water vapor adsorption portion is positioned on an inner side relative to the catalyst.
**8**. The fuel reforming system for a vehicle according to claim 6, wherein the carrier has a cylinder shape and carries the catalyst on an inner surface of the cylinder shape, the recess and the projection are provided on the inner surface, and the water vapor adsorption portion is positioned on an inner side relative to the catalyst.
**9**. The fuel reforming system for a vehicle according to claim 5, wherein the carrier forms the water vapor adsorption portion, the projection is exposed as the water vapor adsorption portion, and the recess is covered with the catalyst.
**10**. The fuel reforming system for a vehicle according to claim 6, wherein the carrier forms the water vapor adsorption portion, the projection is exposed as the water vapor adsorption portion, and the recess is covered with the catalyst.
**11**. A fuel reforming system for a vehicle, the fuel reforming system comprising: a reciprocating engine having a cylinder and a piston sized to reciprocate inside the cylinder; a decomposer having a catalyst and water vapor adsorption material that cooperate to decompose a hydrocarbon fuel into carbon and a hydrogen gas in the presence of heat and pressure of combustion gas during a re-

compression stroke of the piston in the cylinder, the catalyst has a carbon adhesion property that causes the carbon to adhere to the catalyst, and the water vapor adsorption portion has a property that causes water vapor to be adsorbed by the water vapor adsorption portion; a hydrocarbon fuel supply that supplies the hydrocarbon fuel to the decomposer; and a hydrogen gas supply that supplies the hydrogen gas produced by the decomposer into the cylinder, wherein the reciprocating engine is arranged to perform a cycle including at least a compression stroke in which an air-fuel mixture containing the hydrogen gas inside the cylinder is compressed with an ascension of the piston, an expansion stroke in which the piston descends with combustion of the air-fuel mixture, and the re-compression stroke in which the combustion gas is compressed with another ascension of the piston.

**12**. The fuel reforming system for a vehicle according to claim 11, wherein the water vapor adsorption portion is formed of a material that generates heat in response to adsorption of the water vapor therein.

**13**. The fuel reforming system for a vehicle according to claim 11, wherein the water vapor adsorption portion is disposed next to the catalyst.

**14**. The fuel reforming system for a vehicle according to claim 12, wherein the water vapor adsorption portion is disposed next to the catalyst.

**15**. The fuel reforming system for a vehicle according to claim 13, wherein the decomposer includes a carrier, a recess and a projection that is next to the recess are provided on a surface of the carrier, the catalyst is carried in one of the recess and the projection, and the water vapor adsorption portion is disposed in another of the recess and the projection.

**16**. The fuel reforming system for a vehicle according to claim 14, wherein the decomposer includes a carrier, a recess and a projection that is next to the recess are provided on a surface of the carrier, the catalyst is carried in one of the recess and the projection, and the water vapor adsorption portion is disposed in another of the recess and the projection.

**17**. The fuel reforming system for a vehicle according to claim 15, wherein the carrier has a cylinder shape and carries the catalyst on an inner surface of the cylinder shape, the recess and the projection are provided on the inner surface, and the water vapor adsorption portion is positioned on an inner side relative to the catalyst.

**18**. The fuel reforming system for a vehicle according to claim 16, wherein the carrier has a cylinder shape and carries the catalyst on an inner surface of the cylinder shape, the recess and the projection are provided on the inner surface, and the water vapor adsorption portion is positioned on an inner side relative to the catalyst.

**19**. The fuel reforming system for a vehicle according to claim 15, wherein the carrier forms the water vapor adsorption portion, the projection is exposed as the water vapor adsorption portion, and the recess is covered with the catalyst.

**20**. The fuel reforming system for a vehicle according to claim 16, wherein the carrier forms the water vapor adsorption portion, the projection is exposed as the water vapor adsorption portion, and the recess is covered with the catalyst.

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