(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
12 December 2019 (12.12.2019)

WIPO | PCT

(10) International Publication Number
WO 2019/236147 A2

(51) International Patent Classification:
F02D 19/06 (2006.01)

(21) International Application Number:
PCT/US2019/014764

(22) International Filing Date:
23 January 2019 (23.01.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
15/960,735 24 April 2018 (24.04.2018) US

(71) Applicant: **WISCONSIN ALUMNI RESEARCH FOUNDATION** [US/US]; 614 Walnut Street, 13th Floor, Madison, WI 53726 (US).

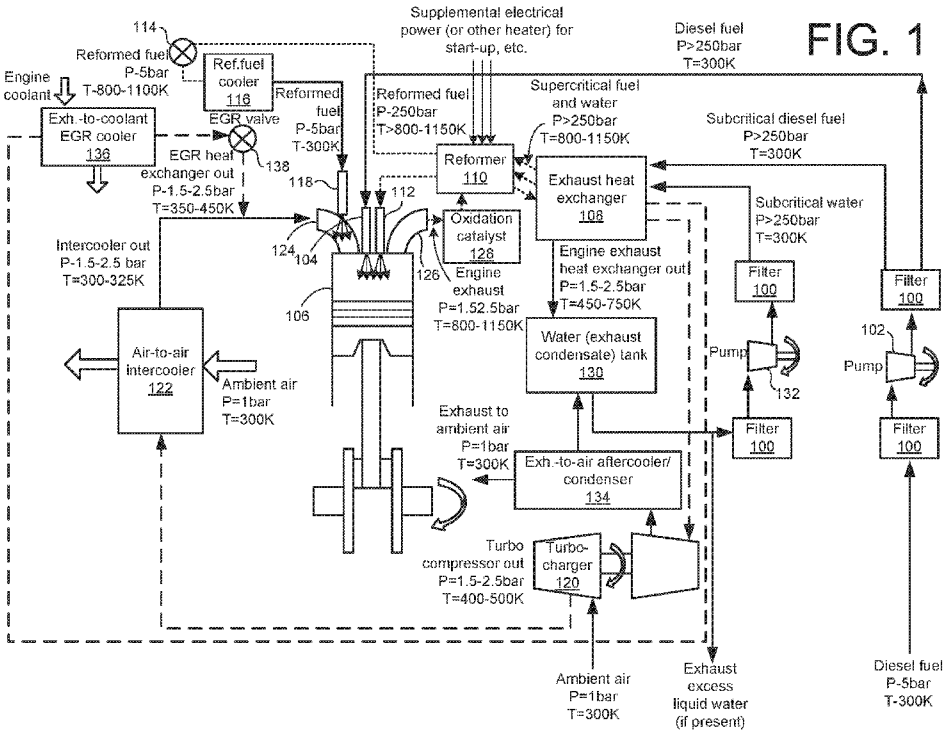
(72) Inventors: **KOKJOHN, Sage**; 782 Ridge View Lane, Oregon, WI 53575 (US). **WICKMAN, David**; 1031 E. Gorham Street, Madison, WI 53703 (US). **DAL FORNO CHUAHY, Flavio**; 1015 Mound Street, Madison, WI 53715 (US).

(74) Agent: **FIESCHKO, Craig** et al.; Dewitt Ross & Stevens S.C., 2 East Mifflin Street, Suite 600, Madison, WI 53703 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH,

(54) Title: ENGINES USING SUPERCRITICAL SYNGAS



(57) Abstract: A first engine fuel, for example diesel fuel, is reformed (preferably via steam reforming) to produce syngas for use as a second engine fuel, with the fuels then both being used in an internal combustion engine to perform Reactivity Controlled Compression Ignition (RCC1). The syngas is produced and supplied to the engine as a supercritical fluid, thereby avoiding the pumping losses that would occur if syngas was pressurized for supply/injection. The reforming is done by a reformer which is provided as a unit with the engine (e.g., both the engine and reformer are onboard a vehicle), thereby effectively allowing use of a single fuel for RCCI engine operation.

WO 2019/236147 A2

[Continued on next page]

GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

ENGINES USING SUPERCRITICAL SYNGAS

Statement Regarding Federally Sponsored Research

This invention was made with government support under N00014-14-1-0695 awarded by the NAVY/ONR. The government has certain rights in the invention.

Field of the Invention

This document concerns an invention relating generally to combustion methods for internal combustion engines operating on reformed fuel, and more specifically to reactivity controlled compression ignition (RCCI) combustion utilizing synthesis gas as a fuel.

Background of the Invention

Reactivity controlled compression ignition (RCCI), a promising combustion method for internal combustion engines, can provide high efficiency with near zero nitrous oxide (NOx) and soot emissions. See, for example, US Patents 8616177, 8851045, 9057321, 9080501, and 9376955. However, a drawback of RCCI is that it requires at least two fuels of different reactivity, for example, diesel fuel and gasoline. RCCI engines therefore typically require at least two fuel reservoirs (or at least one fuel reservoir, and at least one reservoir for a reactivity-altering fuel additive). This need for two reservoirs, and more particularly for two fuels, has been an obstacle to widespread use of RCCI technology.

Synthesis gas ("syngas"), a gas mixture which primarily contains hydrogen (H2) and carbon monoxide (CO), is useful in many applications, including use as a combustible fuel, and/or as raw material for production of plastics, other fuels, fertilizers, pesticides, and other materials. Syngas can be produced from hydrocarbons (including coal, natural gas, biomass, etc.) via a process known as "reforming." Many different reforming techniques are known, with perhaps the most common being steam reformation. In steam reformation, a hydrocarbon feedstock is reacted with steam in a "reformer," in the presence of a catalyst, to generate syngas.

The inventors contemplated installation of a reformer within a vehicle having an RCCI engine, or otherwise providing a reformer in close proximity to an RCCI engine, such that a hydrocarbon fuel (e.g., diesel fuel) could be used as one of the RCCI fuels, and syngas could be produced for use as the second RCCI fuel by reforming a portion of the hydrocarbon fuel. While

results were promising, premature auto-ignition often occurred when the syngas was premixed in the intake stream (e.g., supplying it to the intake manifold, or otherwise supplying it upstream from the intake port), leading to severe losses in engine efficiency. To remedy the auto-ignition, the inventors contemplated direct injection of syngas at high pressure near top dead center. However, this requires compressing the gas-phase syngas to the high pressures needed for direct injection (typically above 200 bar), and such compression requires a substantial portion of the engine's output power.

Summary of the Invention

The invention, which is defined by the claims set forth at the end of this document, involves reforming a first RCCI engine fuel, for example diesel fuel, to produce syngas for use as a second RCCI engine fuel, with the reformation taking place in close proximity to the engine (e.g., both the engine and reformer are onboard a vehicle), thereby effectively allowing use of a single fuel for RCCI engine operation. Another aspect of the invention relates to reforming the first RCCI engine fuel at high pressure to generate syngas in a supercritical fluid state. (A supercritical fluid results when a substance is at a pressure and temperature above its critical point, where distinct liquid and gas phases do not exist: it can effuse through solids like a gas, and dissolve materials like a liquid.) Reforming is performed on the pressurized first fuel to generate syngas above its critical pressure, resulting in a supercritical mixture of H2 and CO. Considering diesel fuel as an exemplary first fuel, the syngas mixture can be injected early in the combustion cycle to create a premixed charge, with the diesel fuel being injected later in the cycle to produce a stratified charge for RCCI. Reforming at supercritical conditions alleviates the need to pressurize gaseous syngas, and avoids the losses arising therefrom.

To briefly summarize exemplary versions of the invention, supercritical syngas is produced from hydrocarbons via reforming, and is supplied to a combustion chamber of an internal combustion engine while in the supercritical state, preferably via direct injection into the combustion chamber. If desired, the engine can be operated using syngas alone, including operation at a stoichiometric air/fuel ratio. As is well known, diesel (compression ignition) engines run at a lean air-to-fuel ratio (with more air than necessary to fully react with the fuel), rather than at a stoichiometric air-to-fuel ratio (with just the right amount of air to fully react with the supplied fuel), because stoichiometric operation tends to result in high unburned

hydrocarbon (soot) formation. A benefit of the invention is that syngas does not form soot, thereby allowing stoichiometric operation without the need for expensive exhaust after-treatment measures. However, it is particularly preferred that the supercritical syngas and hydrocarbons both be used for RCCI operation of the engine, such that both the syngas and the hydrocarbons are concurrently present in the combustion chamber as a stratified mixture prior to ignition (with regions of higher hydrocarbon concentration are spaced from regions of higher syngas concentration). As an example, the syngas may be produced from a portion of a diesel fuel supply and may be directly injected into the combustion chamber sufficiently prior to top dead center to achieve a high degree of premixed homogeneity within the chamber, and the diesel fuel may then be directly injected into the chamber closer to top dead center to generate the stratified mixture.

Preferably, all of the fuel reservoir containing the hydrocarbons, the reformer for producing the supercritical syngas from the hydrocarbons, and the engine are provided as a unit, that is, they are all onboard a vehicle or are otherwise transported with each other. The reformer preferably uses steam reforming (which technically need not use steam, and can use water in other forms, here typically in the form of supercritical water), and can beneficially use water captured from the engine's exhaust gas. The heat required by the reformer for the reforming process can also beneficially be supplied by the exhaust gas and/or engine heat. The reformer therefore needs no or little energy or material supply to sustain the process of reforming the hydrocarbon fuel.

Further advantages, features, and objects of the invention will be apparent from the remainder of this document in conjunction with the associated drawings.

Brief Description of the Drawings

FIG. 1 is a schematic diagram of an exemplary internal combustion engine and reformer system useful for performance of RCCI combustion using only a single hydrocarbon fuel.

FIG. 2 is a schematic diagram of an exemplary internal combustion engine and reformer system which may operate using syngas alone or in combination with the hydrocarbon fuel from which the syngas was produced, and which may use either compression ignition or spark ignition.

Detailed Description of Exemplary Versions of the Invention

The exemplary engine/reformer systems of the aforementioned drawings will now be reviewed. Throughout the following discussion, exemplary temperatures and pressures will be noted for the various fluids used in the systems. It should be understood that these temperatures and pressures may vary depending on the choice of components used in the systems, the fuels used in the systems, ambient conditions, and similar factors.

FIG. 1 illustrates an exemplary engine/reformer system which can be used to perform RCCI operation using only a single supplied hydrocarbon fuel (here diesel fuel, though other hydrocarbon fuels may be used instead). Looking to the bottom right of **FIG. 1**, diesel fuel (P=5 bar, T=300K) from a pressurized reservoir (not shown) is filtered at filter **100**, and then further pressurized at pump **102** to a pressure suitable for direct injection, typically over 200 bar (here P>250 bar, T=300K). An appropriate portion of this fuel can then be supplied to a diesel injector **104** of a combustion chamber **106** for use as a first RCCI fuel, while the remaining portion can be reformed into syngas for use as a second RCCI fuel. This remaining portion of the pressurized fuel is first supplied to a heat exchanger **108** to convert the fuel to a supercritical state (P>250 bar, T=800-1150 K). The supercritical fuel is then provided to a reformer **110** to generate supercritical syngas (P>250 bar, T>800-1150K) consisting of H2, CO, and other trace species. The supercritical syngas may then be provided to a syngas injector **112** for injection into the combustion chamber **106** at a time and amount suitable to create a stratified diesel/syngas mixture for RCCI combustion. Alternatively or additionally, at least some of the syngas produced in the reformer **110** can be used as a gaseous (non-supercritical) fuel, perhaps using other than RCCI combustion, at least under some speed-load conditions. Thus, as seen near the top right of **FIG. 1**, the supercritical syngas from the reformer **110** is throttled at valve **114** to decrease its pressure (P ~5 bar, T~800–1100K), and cooled at cooler **116** (P ~5 bar, T~300K), for supply to a port injector **118**.

Now considering the system's air intake, looking near the bottom middle of **FIG. 1**, ambient air (P=1 bar, T=300K) is preferably pressurized by a turbocharger **120** (P=1.5-3.5 bar, T=300-600K). The air is then preferably cooled in an air-to-air intercooler/heat exchanger **122** so that its temperature is closer to ambient (P=1.5-3.5 bar, T=300-350K) prior to supply to the engine's air intake manifold **124**. The turbocharger **120** may be omitted and the engine may simply be naturally aspirated, but turbocharging can usefully increase power output and

efficiency.

Now considering the system's exhaust, exhaust gas (P=1.0-4.0 bar, T=500-1150K) from the exhaust manifold **126** is first preferably provided to a catalytic converter **128**, where an oxidation catalyst further converts any unburned CO and hydrocarbons (if present) to carbon dioxide and water vapor. The hot exhaust is then supplied to the reformer **110** so that its heat assists the reforming process, and then in turn goes to an exhaust heat exchanger **108** to further capture "waste" heat to assist in converting the input fuel and water into the supercritical state. As the exhaust gas cools in the heat exchanger **108**, condensing water vapor may be captured and collected in a tank **130** for use in the reforming process, as will be described in greater detail below. Typically, during ordinary operation of the system, the exhaust will contain more than enough water for use in the reforming process, and any excess water may simply be jettisoned to the surrounding environment. (Conversely, the water tank **130** may be "primed" with a small amount of water upon first operation of the system so that sufficient water is present to execute reforming.) The water can then be filtered at filter(s) **100**, and pumped to high pressure at pump **132** to elevate it closer to the supercritical state (P>250 bar, T=300K). The exhaust heat exchanger **108** can then heat the subcritical water to the supercritical state (P>250 bar, T=800-1150K) for supply to the reformer **110** for production of the supercritical syngas.

Following removal of (at least some) water from the exhaust gas at the exhaust heat exchanger **108** (P=1.5–2.5 bar, T=450–750K), the exhaust drives the input turbine of the turbocharger **120** used to pressurize the engine's ambient air supply. After the exhaust leaves the turbocharger **120** (P=1 bar, T=400–650K), it may be further cooled in an exhaust-to-air aftercooler/condenser **134** to further condense any residual water for supply to the water tank **130**. The exhaust is then released to the environment (P=1 bar, T=300K).

Because combustion is at relatively low temperature compared to traditional diesel combustion, NOx emissions are low or negligible, which beneficially allows the omission of expensive NOx exhaust after-treatment equipment. Nonetheless, if desired, at least some of the exhaust may be used for exhaust gas recirculation (EGR) for further reduction of nitrogen oxide (NOx) emissions. Looking to the exhaust heat exchanger **108**, the portion of the exhaust gas which does not drive the turbocharger **120** is cooled at exhaust-to-coolant cooler **136** via heat exchange with engine coolant (P=1.5–2.5 bar, T=350–450K). The cooled exhaust gas can then be admitted to the intake manifold **124** as needed via EGR valve **138**.

Beneficially, the reformer **110** can typically operate using waste exhaust/engine heat and water captured from the exhaust. At start-up or other conditions where there is low exhaust / engine temperature, heat may be provided to the reformer **110** via a supplemental (electrical or other) heater to heat the fuel and water.

FIG. 2 illustrates an exemplary engine/reformer system which can operate solely on syngas generated from a single supplied hydrocarbon fuel, and which can additionally or alternatively use the hydrocarbon fuel under at least some speed/load conditions (and which might use either compression ignition or spark ignition depending on conditions). In this example, gasoline will be considered as the hydrocarbon fuel, though other hydrocarbon fuels might be used instead (diesel fuel, jet fuel, etc.). When operating solely or primarily on syngas, the system can be operated at stoichiometric conditions without significant soot emission.

Looking to the bottom right of **FIG. 2**, gasoline (P=5 bar, T=300K) from a pressurized reservoir (not shown) can be provided to port injector **218** when gasoline-only operation is desired, e.g., at start-up and low load operation, and possibly during transient periods during which the engine is changing between different speed/load states. A spark plug **240** is provided on the combustion chamber **206** to enable standard spark-ignited gasoline operation.

To produce syngas for use as an alternative or additional fuel, the gasoline is filtered at filter **200**, and then further pressurized at pump **202** (P>250 bar, T=300K), and heated in heat exchanger **208**, to reach a supercritical state (P>250 bar, T=800-1150 K). The supercritical fuel is then provided to a reformer **210** to generate supercritical syngas (P>250 bar, T>800-1150K) consisting of H2, CO, and other trace species. The supercritical syngas may then be provided to a syngas injector **212** for injection into the combustion chamber **206**, where it might be ignited via compression ignition or spark ignition, and with or without gasoline in the chamber **206**, with the ignition mode and fuel(s) being chosen in accordance with speed/load conditions.

Now considering the system's air intake, looking near the bottom middle of **FIG. 2**, ambient air (P=1 bar, T=300K) is preferably pressurized by a turbocharger **220** (P=1.5-3.5 bar, T=300-600K). The air is then preferably cooled in an air-to-air intercooler/heat exchanger **222** so that its temperature is closer to ambient (P=1.5-3.5 bar, T=300-350K) prior to supply to the engine's air intake manifold **224**. The turbocharger **220** may be omitted and the engine may simply be naturally aspirated, but turbocharging can usefully increase power output and efficiency.

Now considering the system's exhaust, exhaust gas (P=1.0-4.0 bar, T=500-1150K) from the exhaust manifold **226** is first preferably provided to a catalytic converter **228**, where an oxidation catalyst further converts any unburned CO and hydrocarbons (if present) to carbon dioxide and water vapor. The hot exhaust is then supplied to the reformer **210** so that its heat assists the reforming process, and then in turn goes to an exhaust heat exchanger **208** to further capture "waste" heat to assist in converting the input fuel and water into the supercritical state. As the exhaust gas cools in the heat exchanger **208**, condensing water vapor may be captured and collected in a tank **230** for use in the reforming process, as will be described in greater detail below. Typically, during ordinary operation of the system, the exhaust will contain more than enough water for use in the reforming process, and any excess water may simply be jettisoned to the surrounding environment. (Conversely, the water tank **230** may be "primed" with a small amount water upon first operation of the system so that sufficient water is present to execute reforming.) The water can then be filtered at filter(s) **200**, and pumped to high pressure at pump **232** to elevate it closer to the supercritical state (P>250 bar, T=300K). The exhaust heat exchanger **208** can then heat the subcritical water to the supercritical state (P>250 bar, T=800-1150K) for supply to the reformer **210** for production of the supercritical syngas.

Following removal of (at least some) water from the exhaust gas at the exhaust heat exchanger **208** (P=1.5–2.5 bar, T=450–750K), the exhaust drives the input turbine of the turbocharger **220** used to pressurize the engine's ambient air supply. After the exhaust leaves the turbocharger **220** (P=1 bar, T=400–650K), it may be further cooled in an exhaust-to-air aftercooler/condenser **234** to further condense any residual water for supply to the water tank **230**. The exhaust is then released to the environment (P=1 bar, T=300K).

The system of **FIG. 2** may also be adapted to incorporate features of the system of **FIG. 1**. For example, the syngas might also or alternatively be provided to a port injector similar to the port injector **118** of **FIG. 1** (and preferably after throttling and cooling), and the gasoline might also or alternatively be provided to a direct injector similar to the direct injector **104** for diesel fuel in **FIG. 1**. If desired, the system of **FIG. 2** could incorporate an exhaust gas recirculation (EGR) system, as in **FIG. 1**. Features could instead be removed; for example, the low-pressure gasoline port injector **218** might be omitted (and spark plug **240** as well), leaving only direct injection of syngas via injector **212**. In this case, the engine would operate solely on syngas using compression ignition either at lean or stoichiometric conditions. Under lean

conditions it is expected that a combination of exhaust gas recirculation (EGR), as in FIG. 1, and Selective Catalytic Reduction (SCR) might be used for emissions control. Under stoichiometric conditions, a three-way catalyst (TWC) might be used for emissions control.

It should be understood that the versions of the invention described above are merely exemplary, and the invention is not intended to be limited to these versions. Rather, the scope of rights to the invention is limited only by the claims set out below, and the invention encompasses all different versions that fall literally or equivalently within the scope of these claims.

Claims

What is claimed is:

1. A combustion method for an internal combustion engine, the method including the steps of:

   a. producing syngas from hydrocarbons; and

   b. supplying the syngas to a combustion chamber of the internal combustion engine,

   wherein both the producing step and the supplying step are performed at a temperature and pressure at which the produced syngas is a supercritical fluid.

2. The method of claim 1 wherein the syngas is supplied to the combustion chamber via direct injection.

3. The method of claim 1 further wherein the syngas is present in the combustion chamber at a stoichiometric air-fuel ratio during combustion.

4. The method of claim 1 further including the step of also supplying the hydrocarbons to the combustion chamber of the internal combustion engine, such that both the hydrocarbons and the syngas are present in the combustion chamber during combustion.

5. The method of claim 4 wherein the hydrocarbons are supplied to the combustion chamber of the internal combustion engine after the syngas.

6. The method of claim 4 wherein the hydrocarbons and the syngas define a stratified mixture within the combustion chamber of the internal combustion engine during a compression stroke, whereby regions of higher hydrocarbon concentration are spaced from regions of higher syngas concentration.

7. The method of claim 4 wherein the syngas is supplied to the combustion chamber via direct injection.

8. The method of claim 1 wherein:
   a. the syngas is produced from the hydrocarbons in a reformer; and
   b. the method further includes the step of transferring heat to the reformer from the exhaust gas, wherein the transferred heat is the primary source of heat received by the reformer.

9. The method of claim 1 wherein:
   a. the syngas is produced from the hydrocarbons via steam reforming, and
   b. the steam reforming utilizes water captured from exhaust gas from the internal combustion engine.

10. The method of claim 1 wherein the syngas is produced from:
   a. the hydrocarbons, and
   b. water,
wherein both the hydrocarbons and the water are in a supercritical state.

11. A combustion method for an internal combustion engine, the method including the steps of:
   a. reforming hydrocarbons to produce supercritical syngas; and
   b. supplying the supercritical syngas to a combustion chamber of the internal combustion engine.

12. The method of claim 11 wherein the supplying step includes directly injecting at least a portion of the supercritical syngas into the combustion chamber of the internal combustion engine.

13. The method of claim 11:
    a. further including the step of supplying the hydrocarbons to the combustion chamber of the internal combustion engine,
    b. wherein the supercritical syngas and the hydrocarbons are concurrently present in the combustion chamber.

14. The method of claim 13 wherein the supercritical syngas is supplied to the combustion chamber of the internal combustion engine prior to the hydrocarbons.

15. The method of claim 14 wherein the supercritical syngas and the hydrocarbons are stratified within the combustion chamber during a compression stroke, such that regions of higher syngas concentration are spaced from regions of higher hydrocarbon concentration.

16. A combustion method for an internal combustion engine, the method including the steps of:
    a. producing syngas from hydrocarbons; and
    b. directly injecting the syngas into a combustion chamber of the internal combustion engine.

17. The combustion method of claim 16 wherein the syngas is a supercritical fluid from production through injection.

18. The method of claim 16 wherein:
    a. the syngas is produced from the hydrocarbons in a reformer; and
    b. the method further includes the steps of:
        (1) transferring heat to the reformer from the exhaust gas, and
        (2) supplying water to the reformer from the exhaust gas.

19. The method of claim 16 further including the step of also directly injecting the hydrocarbons into the combustion chamber of the internal combustion engine.

20. The method of claim 19 wherein the hydrocarbons and the syngas define a stratified mixture within the combustion chamber of the internal combustion engine during a compression stroke, whereby regions of higher hydrocarbon concentration are spaced from regions of higher syngas concentration.

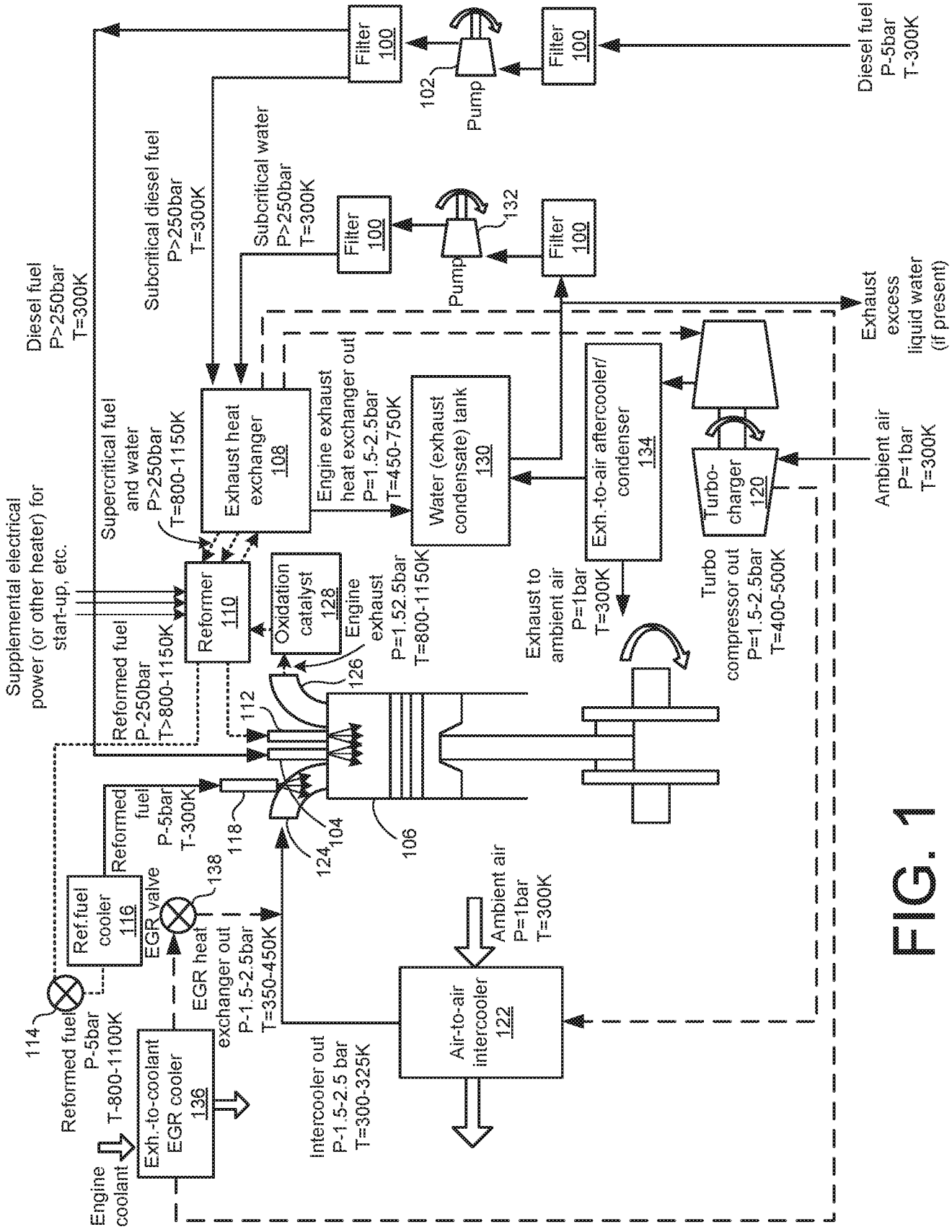

Diesel fuel
P>250bar
T=300K
Filter
100
Pump
102
Diesel fuel
P-5bar
T-300K
Subcritical diesel fuel
P>250bar
T=300K
Subcritical water
P>250bar
T=300K
Filter
100
Pump
132
Filter
100
Supplemental electrical
power (or other heater) for
start-up, etc.
Supercritical fuel
and water
P>250bar
T=800-1150K
Exhaust heat
exchanger
108
Engine exhaust
heat exchanger out
P=1.5-2.5bar
T=450-750K
Water (exhaust
condensate) tank
130
Exhaust
excess
liquid water
(if present)
Exh.-to-air aftercooler/
condenser
134
Turbo-
charger
120
Ambient air
P=1bar
T=300K
Reformed fuel
P-250bar
T>800-1150K
Reformer
110
Oxidation
catalyst
128
Engine
exhaust
P=1.52.5bar
T=800-1150K
126
112
Exhaust to
ambient air
P=1bar
T=300K
Turbo
compressor out
P=1.5-2.5bar
T=400-500K
Reformed
fuel
P-5bar
T-300K
118
124
104
106
Ref.fuel
cooler
116
EGR valve
138
EGR heat
exchanger out
P-1.5-2.5bar
T=350-450K
Ambient air
P=1bar
T=300K
114
Reformed fuel
P-5bar
T-800-1100K
Engine
coolant
Exh.-to-coolant
EGR cooler
136
Intercooler out
P-1.5-2.5 bar
T=300-325K
Air-to-air
intercooler
122

FIG. 1

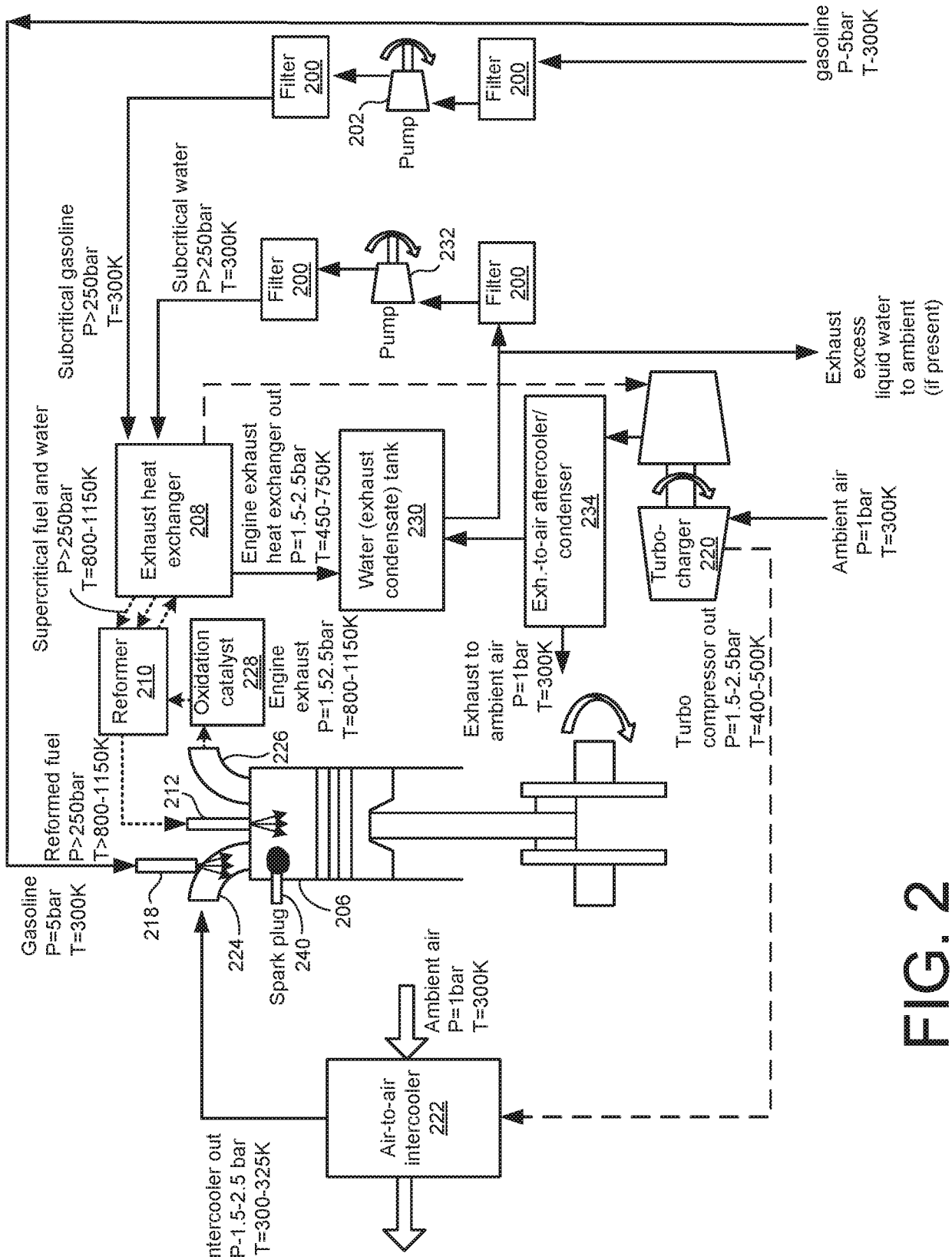

gasoline
P-5bar
T-300K
Filter
200
Filter
200
202
Pump
Subcritical water
P>250bar
T=300K
Subcritical gasoline
P>250bar
T=300K
Filter
200
Filter
200
Pump
232
Supercritical fuel and water
P>250bar
T=800-1150K
Exhaust heat
exchanger
208
Engine exhaust
heat exchanger out
P=1.5-2.5bar
T=450-750K
Water (exhaust
condensate) tank
230
Exhaust
excess
liquid water
to ambient
(if present)
Exh.-to-air aftercooler/
condenser
234
Turbo-
charger
220
Ambient air
P=1bar
T=300K
Reformed fuel
P>250bar
T>800-1150K
Reformer
210
Oxidation
catalyst
228
Engine
exhaust
P=1.52.5bar
T=800-1150K
Exhaust to
ambient air
P=1bar
T=300K
Turbo
compressor out
P=1.5-2.5bar
T=400-500K
212
226
Gasoline
P=5bar
T=300K
218
224
Spark plug
240
206
Ambient air
P=1bar
T=300K
Air-to-air
intercooler
222
Intercooler out
P-1.5-2.5 bar
T=300-325K

FIG. 2