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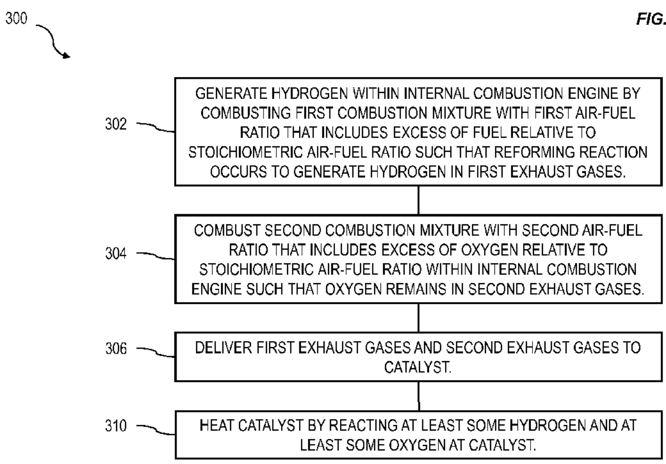
(54) Title: LOW TEMPERATURE CATALYST LIGHT-OFF

FIG. 3



(57) Abstract: A catalyst (122) associated with an internal combustion engine (100) can be heated to improve emissions performance of the engine (100). Hydrogen can be generated within the internal combustion engine (100) by combusting a first combustion mixture having a first air- fuel ratio including excess fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during the combusting of the first combustion mixture. A second combustion mixture having a second air-fuel ratio including excess oxygen can be combusted within the internal combustion engine (100) such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture. The first exhaust gases and the second exhaust gases can be delivered to the catalyst (122) and the catalyst (122) is heated by reacting at least some of the hydrogen and at least some of the oxygen at the catalyst (122). Internal combustion engines, systems, vehicles engine management systems, and method are disclosed.

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LOW TEMPERATURE CATALYST LIGHT-OFF

CROSS-REFERENCE TO RELATED APPLICATION

[001] The current application claims priority under to U.S. provisional patent application serial number 61/821,584, filed on May 9, 2013, which is incorporated by reference herein in its entirety.

TECHNICAL FIELD

[002] The subject matter described herein relates to internal combustion engines in general and more specifically to catalytic converters for removal of pollutants from internal combustion engine exhaust.

BACKGROUND

[003] Catalytic converters are incredibly efficient at converting pollutants into benign gases. For example, hydrocarbon and carbon monoxide gases in the exhaust are reacted with a small amount of excess oxygen in the presence of the catalyst to convert hydrocarbons and carbon monoxide into water and carbon dioxide. However, a catalytic converter generally requires heating to a temperature in excess of 200° C before becoming effective. The temperature at which a catalyst becomes effective for removal of pollutants can be referred to as its light-off temperature or its minimum target operating temperature. During the heat-up phase, exhaust pollutants pass out of the system untreated as energy in the exhaust gas is used to heat up the catalyst until it reaches a sufficiently elevated temperature to catalyze the necessary pollutant-removal reactions. In many cases, these untreated pollutants can constitute a significant (in some cases a majority) fraction of the total pollutants emitted during a drive cycle.

[004] Previously described approaches to the issue of cold catalyst pollutant emissions have focused on pre-heating the catalyst, for example by electrolyzing water to create hydrogen and oxygen, which can be delivered to the catalyst at engine start-up so that spontaneous catalytic recombination of the hydrogen and oxygen can rapidly raise the temperature of the catalyst substrate to a temperature at which the desired pollutant-removal reactions occur efficiently. Such an approach can be undesirable in that an extra energy input is required, which can lead to higher running costs. The added system complexity involved in including a water source and electrolysis apparatus is also generally undesirable.

[005] Another concern with existing catalytic converters is the injection of extra fresh air, known as secondary air injection, in the exhaust manifold, to bring the catalytic converter up to light-off temperature more quickly. When the engine is cold, the secondary air assists in cleaning up the extra-rich exhaust which is being produced during engine warm-up, thereby generating heat which assists in heating up the catalytic converter. After the light-off temperature of the catalytic converter is reached, the secondary air assists with conversion of carbon monoxide and unbumed hydrocarbons. However, such a system requires a pump to inject the air in effectively, which can create an extra load on the engine and hence increases energy usage. Additionally, since the secondary air is injected continuously, throughout all engine operation conditions, the resulting excess oxygen can limit the effectiveness of a three-way catalyst to reduce nitrogen oxides. Both of these effects can tend to increase emissions above the levels required to meet increasingly stringent emissions requirements.

SUMMARY

[006] Aspects of the current subject matter can provide improved approaches to heating a catalyst of a catalytic converter to an operating temperature as quickly as possible, for example by generating hydrogen and excess oxygen through manipulation of combustion conditions in one or more combustion chambers of an internal combustion engine when the catalyst is determined to be at a measured catalyst temperature that is below a target operating temperature.

[007] In one aspect, a method for heating a catalyst associated with an internal combustion engine, includes generating hydrogen within the internal combustion engine. The generating of the hydrogen includes combusting a first combustion mixture having a first air-fuel ratio, which includes an excess of fuel relative to a stoichiometric air-fuel ratio such that a reforming reaction occurs during the combusting of the first combustion mixture to generate the hydrogen in first exhaust gases. The method also includes combusting a second combustion mixture having a second air-fuel ratio within the internal combustion engine. The second air-fuel ratio includes an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture. The first exhaust gases and the second exhaust gases are delivered to the catalyst, which is heated by reacting at least some of the hydrogen and at least some of the oxygen at the catalyst.

[008] In another aspect, an internal combustion engine includes a combustion mixture delivery system, and a controller configured to control the combustion mixture delivery system to provide a first combustion mixture having a first air-fuel ratio. The first air-fuel ratio includes an excess of fuel relative to a stoichiometric air-fuel ratio such that a reforming

reaction occurs during combustion of the first combustion mixture to generate hydrogen in first exhaust gases. The controller is further configured to provide a second combustion mixture having a second air-fuel ratio that includes an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture. The internal combustion system further includes an exhaust system that delivers the first and second exhaust gases to a catalyst such that at least some of the delivered hydrogen reacts with at least some of the delivered oxygen, thereby heating the catalyst.

[009] In a further aspect, a system includes an internal combustion engine a catalyst arranged to receive the first and second exhaust gases. The internal combustion engine is configured to operate consistent with the method discussed above.

[0010] In yet another aspect, a vehicle includes the above-described system and/or internal combustion engine.

[0011] In a yet further aspect an engine management system includes computer hardware configured to perform operations that include controlling a combustion mixture delivery system of an internal combustion engine to provide a first combustion mixture having a first air-fuel ratio that includes an excess of fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during combustion of the first combustion mixture to generate hydrogen in first exhaust gases. The operations also include controlling the combustion mixture delivery system to provide a second combustion mixture having a second air-fuel ratio that includes an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture. The engine management system performs the controlling based on determining that a measured temperature of the catalyst is below a minimum target operating temperature of the catalyst. The computer hardware can optionally include one or more programmable processors, and optionally one or more memories or machine-readable storages storing instructions that cause the one or more programmable processors to perform the operations.

[0012] In yet a further aspect, a computer program product includes a computer-readable storage medium storing instructions that, when executed by a computing system that includes at least one programmable processor, cause the computing system to perform operations, which include controlling a combustion mixture delivery system of the engine to provide a first combustion mixture having a first air-fuel ratio that includes an excess of fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during combustion of the first combustion mixture to generate hydrogen in first exhaust gases. The operations also include controlling the combustion mixture delivery system to provide a second combustion mixture having a second air-fuel ratio that includes an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture.

[0013] In optional variations, one or more of the following features can be included in implementations of any aspect of the current subject matter in any feasible combination.

[0014] A temperature of the catalyst can be determined to be below a minimum target operating temperature of the catalyst, and the generating of the hydrogen and the combusting of the second combustion mixture based on the determining.

[0015] In some implementations, the at least some of the hydrogen and the at least some of the oxygen can be brought together at the catalyst. In other implementations, one or both of the at least some of the generated hydrogen and the at least some of the excess oxygen can be adsorbed onto a surface in the flow path to facilitate delivery of the at least some of the hydrogen and the at least some of the oxygen to the catalyst.

[0016] The combusting of the first combustion mixture and the second combustion mixture can include manipulating at least one of a valve timing of the internal combustion engine, an operation of one or more fuel injectors or a carburetor of the internal combustion engine, a compression ratio of the internal combustion engine, and a spark timing of the internal combustion engine.

[0017] In some implementations, the combusting of the first combustion mixture can occur in a first cylinder of the internal combustion engine and the combusting of the second combustion mixture can occur in a second cylinder of the internal combustion engine. Optionally, the second cylinder may fire sequentially or non-sequentially to the first cylinder.

[0018] In some implementations, the combusting of the first combustion mixture and the combusting of the second combustion mixture can occur in a same engine cylinder. The combusting of the first combustion mixture can occur in a first engine cycle and the combusting of the second combustion mixture can occur in a second engine cycle. Optionally the first and second cycles can be sequential or non-sequential. In some implementations, the internal combustion engine may be an opposed-piston engine.

[0019] In some implementations, the combusting of the first combustion mixture and the combusting of the second combustion mixture can occur at a temporal separation within an engine cycle. The generating hydrogen may comprise injecting a first quantity of fuel after combusting the second combustion mixture within the engine cycle. Advantageously, the injecting of the first quantity of fuel can occur during an expansion stroke of the engine cycle and preferably towards an end of the expansion stroke. Desirably, the first quantity of fuel can be approximately 20% of a second quantity of fuel present in the second combustion mixture and the combusting of the second combustion mixture can include providing approximately 20% excess air relative to a stoichiometric air-fuel ratio for the second quantity of fuel.

[0020] The details of one or more variations of the subject matter described herein are set forth in the accompanying drawings and the description below. Other features and advantages of the subject matter described herein will be apparent from the description and drawings, and from the claims. While certain features of the currently disclosed subject matter are described for illustrative purposes in relation to an enterprise resource software system or other business software solution or architecture, it should be readily understood that such features are not intended to be limiting. The claims that follow this disclosure are intended to define the scope of the protected subject matter.

BRIEF DESCRIPTION OF DRAWINGS

[0021] The accompanying drawings, which are incorporated in and constitute a part of this specification, show certain aspects of the subject matter disclosed herein and, together with the description, help explain some of the principles associated with the disclosed implementations. In the drawings,

[0022] FIG. 1 shows a diagram illustrating aspects of a system showing features consistent with implementations of the current subject matter;

[0023] FIG. 2 shows a process flow diagram illustrating aspects of a method having one or more features consistent with implementations of the current subject matter;

[0024] FIG. 3 shows a process flow diagram illustrating aspects of another method having one or more features consistent with implementations of the current subject matter; and

[0025] FIG. 4 shows a chart illustrating an engine work cycle having one or more features consistent with implementations of the current subject matter.

[0026] When practical, similar reference numbers denote similar structures, features, or elements.

DETAILED DESCRIPTION

[0027] Implementations of the current subject matter can include features relating to more rapidly heating a catalyst or catalytic converter from an initial, low temperature at which it is not effective at removing exhaust pollutants to an elevated operating temperature at which such pollutants are efficiently removed from engine exhaust. In some examples, an internal combustion engine can be operated at a rich mixture condition during times that the current temperature of the catalyst is below a target minimum operating temperature. Such times can include initial engine start-up or other times when the catalyst temperature drops below the target minimum operating temperature.

[0028] Operation of at least part of the combustion chamber of an internal combustion engine with a rich combustion mixture (e.g. with an excess of fuel relative to the stoichiometric ratio) can lead to the generation of hydrogen gas (H_2) as part of the exhaust or effluent exiting the combustion chamber (e.g. a cylinder) during an exhaust phase of an engine cycle of the internal combustion engine. The generation of hydrogen in a combustion system with less than the stoichiometric amount of oxygen for full conversion of the fuel to water and carbon dioxide is generally referred to as reforming.

[0029] Hydrogen reforming occurs in the presence of steam (e.g. water vapor), which is generally present in internal combustion engine exhaust as a result of the combustion of hydrocarbons. The chemical reactions involved in reforming can include the following. The first as follows:

[0030] $$C_nH_m + nH_20 \rightleftarrows nCO + (n+m/2)H_2 \qquad (1)$$

[0031] $$CO + H_20 \rightleftarrows CO_2 + H_2 \qquad (2)$$

[0032] Reaction (1) represents a relatively high-temperature reaction between water vapor and a hydrocarbon molecule while reaction (2), in which the carbon monoxide produced in reaction (1) is converted to carbon dioxide and additional hydrogen, generally proceeds at a lower temperature .

[0033] Because H_2 is more readily (relative to unburned hydrocarbons and carbon monoxide) reacted by the catalyst in the presence of oxygen (i.e. to form water, H_20), the presence of an hydrogen and oxygen in the exhaust stream reaching a catalyst can cause a reaction at the catalyst that can contribute to heating the catalyst more quickly than absorption of energy from the exhaust, either alone or in combination with a small amount of reaction energy generated by conversion of carbon monoxide and hydrocarbons to water and carbon dioxide when the catalyst is cold.

[0034] Exhaust gases in an engine operated with a richer than stoichiometric air-fuel ratio can contain insufficient amounts of oxygen to allow reaction at the catalyst of the formed H_2. Some implementations of the current subject matter can address this problem such that a sufficient quantity of oxygen is present at the catalyst.

[0035] FIG. 1 shows a diagram of an example engine 100 showing features consistent with one or more implementations of the current subject matter. It will be understood by one of ordinary skill in the art that the features shown in FIG. 1 are merely exemplary and not in any way intended to be limiting. Implementations of the current subject matter are compatible with a variety of engine configurations and operating modes, including spark ignited and compression ignited engines, fuel injected and carbureted fuel delivery systems, etc. In some examples, the engine 100 can be an opposed piston engine, in which two pistons occupy a cylinder with motion of the pistons bringing their respective piston crowns into relative proximity at top dead center and relatively further apart at bottom dead center engine timing. A non-limiting example of such an engine is described in co-owned U.S. patent no. 7,559,298 An opposed piston engine need not be operated with both of the opposed pistons having the same timing, for example as described in co-owned U.S. patent no. 8,413,619. In other examples, the engine 100 can be a conventional engine in which one piston occupies each cylinder of the internal combustion engine.

[0036] The engine 100 can have any number of cylinders, each of which can include a combustion chamber formed at least in part by at least one piston crown and optionally also one or more of a cylinder head, a cylinder wall formed as part of an engine block, a second piston crown (e.g. in an opposed piston engine), a sleeve valve body (e.g. in an engine in which one or more intake or exhaust ports to serve the combustion chamber are controlled by a reciprocating sleeve valve), or other engine structures. Fuel and air (or some other oxidant) are provided into the combustion chamber to form a combustion mixture. Exhaust gases from at least partial combustion of the combustion mixture are vented from the combustion chamber via one or more exhaust ports as discussed below. For the remainder of this disclosure, the term "cylinder" is intended to generally equate to the term "combustion chamber" unless such an interpretation is incongruous with the context in which the term is used.

[0037] With further reference to FIG 1, an exhaust passage 102 can transmit exhaust gases from an exhaust manifold 104 that receives effluent gases from one or more cylinders 106. Air and fuel are provided to the cylinders 106 under the control of one or more valves (not shown). A fuel control device 108 can control the flow of fuel to the one or more cylinders 106. In cooperation with an air flow rate of intake air delivered via an intake manifold 110, the fuel control device 108 can produce a desired air-fuel ratio for the combustion mixture delivered to each cylinder. The fuel control device 108 can be controlled by commands from an engine control module (ECM) 112, which can also optionally control an ignition control device 114 (e.g. a spark plug or spark plug control). The ECM 112 can also receive data signals from one or more oxygen sensors (OX) 116 placed in the exhaust passage 102 (e.g. upstream and downstream of a catalytic converter 122), to thereby obtain information as to how well the catalyst is working. For example, if the percentage of oxygen downstream of the catalyst is higher than that upstream of the catalyst, that would indicate that the catalyst is working effectively to reduce nitrogen oxides, whereas if the percentage is lower, that indicates that the catalyst has not reached sufficient a temperature to be operating effectively, for example its minimum target operating temperature. The ECM 112 can also receive data from a catalyst temperature sensor (Tc) 120 positioned to measure a current temperature of the catalyst contained within the catalytic converter 122 through which the exhaust passage 102 directs the exhaust gases. The catalyst temperature sensor (Tc) 120 can be a thermocouple or any other suitable device providing temperature data in a reproducible manner. The measured temperature provides an indication as to whether or not the catalyst has reached its minimum target operating temperature and accordingly whether or not it is has reached an efficient operating temperature.

[0038] As noted above, accelerated heating of the catalyst in a catalytic converter 122 can be achieved consistent with implementations of the current subject matter by supplying both hydrogen and oxygen to the catalyst. For an example in which the engine 100 is a multi-cylinder engine, hydrogen to be provided to the catalyst can be produced consistent with the description of reforming provided above by creating a richer than stoichiometric air-fuel mixture (e.g. an air-fuel ratio that includes less oxygen than is required for stoichiometric combustion of the provided fuel) in a first cylinder of the engine 100. Oxygen can be supplied to the catalyst by running a second cylinder of the engine 100 with a leaner than stoichiometric mixture (e.g. an air-fuel ratio that includes more oxygen than is required for stoichiometric combustion of the provided fuel). The second cylinder running the lean mixture provides excess oxygen in its exhaust gas effluent. When the exhaust gas effluents from the first and second cylinders mix and are delivered to the catalyst, sufficient hydrogen and oxygen can be present (e.g. the hydrogen formed by reforming in the first cylinder operated with the richer mixture and oxygen provided from the second cylinder operated with the leaner mixture) to allow catalytic oxidation of the hydrogen to occur, thereby leading to a rapid heating of the catalyst. This approach can be used for two or more cylinders feeding the catalyst.

[0039] Thus in this multi-cylinder implementation described in the preceding paragraph, a first region of combustion (e.g. the first cylinder) is supplied with an excess quantity of fuel above that which can be burned by the air present under stoichiometric combustion, while a second region of combustion (e.g. the second cylinder) is supplied with an excess of air above that which is required for stoichiometric combustion of the fuel present. The hydrogen generated by the reforming reactions in the first cylinder and the excess oxygen provided by the lean combustion in the second cylinder may not reach the catalyst at exactly the same time. However, sufficient mixing of the exhaust gases from the two cylinders can occur in the exhaust manifold 104 and the exhaust passage 102 on the way to the catalyst such that at least some of the produced hydrogen and at least some of the excess oxygen will be present at the catalyst to enable the desired reaction to occur to heat the catalyst.

[0040] In order to improve the mixing of the generated hydrogen and the excess oxygen, one possible implementation is to vary the size, in particular the length, of the portion of the exhaust manifold which is connected to each of the two cylinders. For example, the pipe through which the exhaust from the first cylinder flows can be made longer than the pipe to which the second cylinder is connected. Thus the time taken for the exhaust gases from the first cylinder to reach the catalyst would be longer than the time taken for the exhaust gases from the second cylinder to reach the catalyst. In this way, there is an increased likelihood that more of the generated hydrogen and excess oxygen would be present at the catalyst at the same time for the desired reaction. It may also be desirable to configure the exhaust manifold such that the two pipes join together upstream of the catalyst so that the hydrogen and oxygen is able to mix prior to arrival at the catalyst. This may improve the proportions of the generated hydrogen and excess oxygen that react, thereby enabling faster heating of the catalyst.

[0041] In an engine 100 having more than two cylinders, the cylinders could be used in the above-described method in pairs such that a first of each pair of cylinders is operated with a richer than stoichiometric mixture to generate hydrogen via reforming reactions and the second of each pair of cylinders is operated with a leaner than stoichiometric mixture to provide excess oxygen for reaction with the hydrogen at the catalyst. In this implementation, it may be advantageous to incorporate the above-discussed exhaust manifold configuration with respect to two cylinders only, in order to avoid too much exhaust gas backing up as a result of the longer time taken for the exhaust to flow through the first pipe. While the amount of hydrogen gas arriving at the catalyst may be lower for a cylinder that is not connected to a longer pipe relative to the pipes of other cylinders, some hydrogen would nevertheless be available at the catalyst to react with oxygen. Alternatively, just two of the cylinders of the engine 100 could form such a pair in any one cycle and the particular two could vary cycle to cycle. The pairs could be sequentially-firing cylinders or non-sequentially firing cylinders.

[0042] When a typical three-way catalyst is used with narrow-band oxygen sensors, the resulting feedback loop between the sensors and the ECM results in the stoichiometry of the fuel-air mixture oscillating between slightly lean and slightly rich. Typically, lambda (the ratio of actual air-fuel ratio to stoichiometric air-fuel ratio) oscillates between about $\lambda=0.992$ in the rich direction and $\lambda=1.003$ in the lean direction. In implementations of the current subject matter, such as the multi-cylinder example just discussed, the first cylinder can be arranged to operate at approximately $\lambda=0.85$ or $\lambda=0.75$, or as rich as $\lambda=0.5$, or at any value between these extremes, while the second cylinder can be arranged to operate at approximately $\lambda=1.3$. This compares to a lean end of around $\lambda=1.15$-1.2 for a conventional engine without catalyst running a conventional combustion cycle, because such an engine is unable to run very lean for too long at such a lean mixture richness due to the increased chance of misfires and engine damage. However, because an engine or system in which the current subject matter is implemented advantageously runs lean only on some cylinders for a limited period of time (e.g. when heating of the catalyst is required), this reduces the chance of possible problems. The lean cycle may not include as large of a deviation from stoichiometric as the rich cycle. However, the quantity of air into the lean cylinder can be controlled as compared to the cylinder which is generating the hydrogen, such that a multi-cycle average of close to stoichiometric is maintained. This approach can assist in minimizing unburned fuel passing to the catalyst in the exhaust gases. This control of the quantity of oxygen can be effected across multiple cylinders, optionally including cylinders of a multi-cylinder engine that are not specifically running rich or lean. The rich and lean cycles can be alternated with stoichiometric cycles if desired, which may assist in protecting the engine against the effects of rich or lean running.

[0043] Another associated adjustment to the running of the engine 100 which can be used in conjunction with the above-described features for generating hydrogen and excess oxygen can include, in the case of a spark-ignited combustion process, controlling the spark plug, which ignites the combustion mixture in the first cylinder, to spark late, for example up to as much as 20 degrees after top dead center. This approach can limit the peak temperature in the combustion chamber, which would favor reactions (1) and (2). This adjustment can be achieved by suitable programming of the ECM 112 and may assist in maintaining a stable speed at idle and/or load conditions. Suitable control of the fuel control device, e.g., a mechanical or electric throttle, can be made by the ECM 112 by suitable programming, possibly to increase airflow in non-rich cycles (i.e. which are not generating hydrogen), which may improve the feel of the engine to a driver of a vehicle in which it is installed. However, these are not essential features.

[0044] A further possible adjustment to running of the engine 100 which can be used in conjunction with the above-described features which generate hydrogen and excess oxygen is to cause opening of the exhaust valve later than in normal running of the engine 100. The engine 100 could be arranged such that the exhaust valve opens as late as 45 degrees after top dead center. Such an approach can be used together with the late spark timing described in the previous paragraph. A result would be that some exhaust would remain in the cylinder until the next time the cylinder fires, which would increase the temperature of the gases in the cylinder and hence the temperature of the gases in the exhaust. This approach can assist with heating up the catalytic converter 122, as a result of the hotter exhaust gases passing over it. Such an approach can optionally be used in the cylinder which is generating the hydrogen, although could be used alternatively or additionally in the lean cylinder, within the limits of combustion stability.

[0045] In another example featuring an engine with only one cylinder or one combustion chamber, a similar effect of running a richer than stoichiometric mixture to cause hydrogen generation by reforming and a leaner than stoichiometric mixture to provide excess oxygen for reaction of the generated hydrogen at the catalyst for rapid heating can be achieved by alternating the air-fuel ratio of the mixture within the cylinder from one engine cycle to a next engine cycle. The "richer" cycles generate hydrogen through reforming reactions (e.g. as described above), and the "leaner" cycles provide excess oxygen to allow reaction of the hydrogen at the catalyst. Concurrent presence of excess oxygen from the lean cycles and hydrogen from the rich cycles can be achieved by one or more approaches, such as for example a sufficiently long residence time of exhaust gases in one or more of the exhaust passage 102, in the exhaust manifold 104, at the catalytic converter, etc. to allow gases provided in the effluent of at least two alternated cycles to mix. Alternatively, adsorption of either or both of hydrogen and oxygen onto one or more surfaces in the exhaust system can be encouraged through the use of suitably adsorptive materials such that a first of the two reactants persists and is present at least a sufficient amount of the second of the two reactants becomes available.

[0046] Another example of an engine in which features of the current subject matter can be implemented is a compression ignition engine, for example a diesel engine. One possible approach in this case is to create the excess fuel condition followed by the excess air condition at different points in a single engine stroke. A situation of excess fuel beyond that which is burned in the regular combustion process can be created by an additional injection of fuel in the expansion stroke of a four-stroke engine, for example relatively late in the expansion stroke. The late-injected additional fuel would be heated to a moderate temperature for a relatively short time, which can cause the fuel molecules to disassociate to form hydrogen in accordance with reactions (1) and (2). Since much of the fuel is consumed in those reactions, the injection of additional fuel in this manner would generate relatively small amounts (if any) of soot.

[0047] In the above-discussed example, because the regular combustion process in a diesel engine occurs at higher than stoichiometric air-fuel ratio anyway, no special procedure is required to provide excess oxygen for reaction with the generated hydrogen. Rather, sufficient oxygen is naturally present. In other words, the main combustion event is caused to occur lean by the regular running conditions of the engine. The extra injection of fuel could occur in sequential or non-sequential cycles as desired to heat the catalyst up as quickly as possible.

[0048] An example of a combustion cycle for a diesel engine operating in accordance with the implementation described in the previous two paragraphs is shown diagrammatically in the chart 400 of FIG. 4, which shows cylinder volume plotted against cylinder pressure. For multiple cylinders, each cylinder would run a similar cycle. The plot is similar to that which would be expected for a normal diesel engine. However, in the present example, point A, which is the point of highest pressure but lowest volume, represents the first injection. This can occur at any timing between approximately 20 degrees before top dead center (TDC) and TDC. The expansion stroke conforms generally to the expected curve, indicating an increasing volume and decreasing pressure in the cylinder, the pressure dropping at a rate that falls slightly as the piston approaches bottom dead center (BDC). However, in FIG. 4, there is a point labeled as B, which indicates the second injection of fuel, which can occur at any timing between approximately 90 and 120 degrees after TDC. This point is characterized by a momentary stabilization of the cylinder pressure. Other timings could be used, depending on the particular implementation.

[0049] A further example in which the present subject matter can be implemented is a gasoline direct injection (GDI) engine. As for the above-described example of a diesel engine, an extra injection of fuel (e.g. gasoline) can be made during the expansion stroke, and advantageously towards the end of the expansion stroke, such that the extra fuel dissociates to form hydrogen by reforming, as described with respect to the diesel fuel. This addition of excess fuel can be considered a first combustion mixture. Gasoline engines are generally operated at close to a stoichiometric air-fuel ratio. Thus, to optimize heating of the catalyst, an excess of oxygen can be provided by running the regular combustion process with a mixture that is leaner than stoichiometric. In other words, an excess of air above a stoichiometric air-fuel ratio can be supplied to the cylinder during the regular air intake stroke as part of a "second" combustion mixture (which in this case is provided to the cylinder prior to a first combustion mixture that includes an excess off fuel). Following the combustion process with this second combustion mixture, there would be some leftover air (oxygen), which would remain in the combustion chamber and then exit the combustion chamber with the exhaust gases during the expansion stroke. Thus at least some of the excess oxygen present in the excess air (as part of the second combustion mixture) and at least some of the generated hydrogen produced by reforming reactions promoted in first combustion mixture formed by addition of the excess fuel during the expansion stroke are both delivered to the catalyst, where catalytic oxidation of at least some of the delivered hydrogen by at least some of the delivered oxygen can occur. In one example, the excess of air in the second combustion mixture can include approximately a 20% excess relative to a stoichiometric air-fuel ratio. The excess of fuel in the first combustion ratio can include approximately a 20% excess relative to a stoichiometric air-fuel ratio. Alternatively, the lambda values indicated in respect of previously described implementations could be used.

[0050] As previously discussed, an existing approach to providing excess oxygen to enable oxidation at a catalyst is a secondary air injection system, such as for example those that can be used for engines on motorcycles or relatively low weight vehicles to allow richer than stoichiometric operation. Richer than stoichiometric operation in such engines can reduce combustion temperatures and thereby lessen the formation of oxides of nitrogen (NO_χ), another pollutant of concern. Rich mixtures can lead to insufficient oxygen in the exhaust to allow the catalyst to react unburned hydrocarbons and carbon monoxide in the exhaust into H_20 and $C0_2$. However, secondary injection is typically used continuously throughout operation of the engine rather than being used intermittently when the catalyst temperature is too low for efficient conversion of pollutants. Implementations of the current subject matter can avoid the use of a secondary air injection system requiring dedicated hardware in favor of an approach to providing excess oxygen for oxidation of hydrogen at the catalyst 106 through temporary adjustment of combustion conditions in one or more cylinders of the engine 100.

[0051] FIG. 2 shows a process flow chart 200 illustrating features of a method consistent with an implementation of the current subject matter. One or more of these features can be included in other implementations. At 202, a temperature of a catalyst through which exhaust gases of an internal combustion engine are passed for removal of pollutants is determined to be below a minimum target operating temperature. With reference to FIG. 1, the catalyst temperature sensor 120 measures a catalyst temperature of the catalyst in the catalytic converter 122 and provides this information to the ECM 112. The ECM 112, which includes a controller or processor, determines whether or not the measured catalyst temperature is below a predetermined threshold temperature, which represents the minimum target operating temperature. In implementations of the current subject matter, the minimum target operating temperature can optionally be the catalyst light-off temperature. Alternatively, the minimum target operating temperature can be above, below, or approximately equal to the catalyst light-off temperature. A further alternative or addition can include determining whether the catalyst is functioning effectively by reference to the output from the oxygen sensors 116, which can provide an indirect measure of catalyst temperature.

[0052] If the measured catalyst temperature is above the minimum target operating temperature, engine operation can proceed as in a conventional engine. However, if the measured catalyst temperature is below the minimum target operating temperature, the method proceeds as follows. At 204, a first combustion mixture that is sufficiently rich (excess fuel relative to stoichiometric) to cause generation of hydrogen (e.g. by one or more reforming reactions) is provided within a first region of the engine 100 (for example a cylinder such as one of the cylinders 106 in FIG. 1 or a cylinder in any of the engine types previously described) during engine operation. At 206, exhaust effluent containing at least some of the hydrogen gas generated at 204 is directed to the catalyst.

[0053] At 210 and 212, excess oxygen is provided to the catalyst as part of exhaust gases generated within the engine 100. For example, a second combustion mixture that is leaner than stoichiometric (excess oxygen) can be burned at 210 (e.g. within a second region of the engine) during engine operation and exhaust effluent containing excess oxygen present after the burning of the second combustion mixture can be directed to the catalyst at 212.

[0054] It will be appreciated that in some implementations consistent with the current subject matter the processes described can occur in an order other than that described above. For example, excess oxygen can be provided to the catalyst (e.g. as at 210 and 212) either prior to or after generation and delivery of hydrogen to the catalyst (e.g. as at 204 and 206).

[0055] At 214, at least some of the delivered hydrogen and delivered excess oxygen react at the catalyst to generate heat, thereby heating the catalyst. At 216, when the temperature of the catalyst is determined to have reached the minimum target operating temperature, operation of the engine is resumed using normal operating condition combustion mixtures. Again, with reference to FIG. 1, this decision can be made by the ECM using input from the catalyst temperature sensor 120, indicating the temperature of the catalyst. The ECM may decide to switch to normal engine operation when the measured catalyst temperature exceeds the minimum target operating temperature (e.g. the light-off temperature of the catalyst), or optionally when the measured catalyst temperature reaches a temperature within a programmed tolerance of the minimum target operating temperature, such as for example within 5 °C, 3 °C, 1 °C, etc.).

[0056] In some examples, the first and second combustion mixtures can be used in two different cylinders of the same engine. In other examples, such as for an engine with a single combustion chamber or single cylinder, the first and second combustion mixtures can be provided in sequential engine cycles. In the case of an engine with multiple cylinders, the mixture in any one cylinder can optionally be varied between the richer than stoichiometric condition to produce hydrogen and the leaner than stoichiometric condition to provide excess oxygen. In another implementation, the first and second combustion mixtures can be provided by temporal separation of fuel addition into the same cylinder during the same engine cycle, such as for example by an extra injection of fuel after the main combustion event, when the temperature in the cylinder will be sufficient for a hydrogen reforming reaction to occur. Such an approach can be used, for example, in a compression ignition engine (e.g. a diesel engine, a homogeneous charge compression ignition engine, etc.), a gasoline direct injection engine, or the like.

[0057] As noted above, a temporal separation may occur in the providing of excess fuel to generate hydrogen and the providing of a lean combustion mixture to provide excess oxygen, for example because of the use of two cylinders firing at different times or the use of two different engine cycles or different points in an engine cycle. Mixing of an exhaust gas volume containing hydrogen with an exhaust gas volume containing excess oxygen sufficient to enable reaction of these compounds at the catalyst can occur in one or more locations in the engine 100, such as for example in the exhaust manifold 104, the exhaust passage 102, at the catalyst 122 itself, or even in the cylinder or combustion chamber.

[0058] FIG. 3 shows an additional process flow chart 300 illustrating features of an additional method consistent with an implementation of the current subject matter. One or more of these features can be included in other implementations. At 302, hydrogen is generated within an internal combustion engine. This generating of the hydrogen includes combusting a first combustion mixture having a first air-fuel ratio that includes an excess of fuel relative to a stoichiometric air-fuel ratio such that a reforming reaction occurs during the combusting of the first combustion mixture to generate the hydrogen in first exhaust gases. At 304, a second combustion mixture having a second air-fuel ratio is combusted within the internal combustion engine. The second air-fuel ratio includes an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture. It will be appreciated that the combusting of the first combustion mixture can occur prior to or after the combusting of the second combustion mixture, depending on the implementation. The first exhaust gases and the second exhaust gases are delivered to the catalyst at 306, and at 310 the catalyst is heated by reacting at least some of the hydrogen and at least some of the oxygen at the catalyst.

[0059] It will be understood by those skilled in the art that one or more aspects or features of the ECM 112 can be realized in digital electronic circuitry, integrated circuitry, specially designed application specific integrated circuits (ASICs), field programmable gate arrays (FPGAs) computer hardware, firmware, software, and/or combinations thereof. These various aspects or features can include implementation in one or more computer programs that are executable and/or interpretable on a programmable system including at least one programmable processor, which can be special or general purpose, coupled to receive data and instructions from, and to transmit data and instructions to, a storage system, at least one input device, such as the catalyst temperature sensor 120 and the oxygen sensors 116, and at least one output device, such as the ignition control 114 an the fuel control 108.

[0060] These computer programs, which can also be referred to as programs, software, software applications, applications, components, or code, include machine instructions for a programmable processor, and can be implemented in a high-level procedural and/or object-oriented programming language, and/or in assembly/machine language. As used herein, the term "machine-readable medium" refers to any computer program product, apparatus and/or device, such as for example magnetic discs, optical disks, memory, and Programmable Logic Devices (PLDs), used to provide machine instructions and/or data to a programmable processor, including a machine-readable medium that receives machine instructions as a machine-readable signal. The term "machine-readable signal" refers to any signal used to provide machine instructions and/or data to a programmable processor. The machine-readable medium can store such machine instructions non-transitorily, such as for example as would a non-transient solid-state memory or a magnetic hard drive or any equivalent storage medium. The machine-readable medium can alternatively or additionally store such machine instructions in a transient manner, such as for example as would a processor cache or other random access memory associated with one or more physical processor cores.

[0061] The implementations set forth in the foregoing description do not represent all implementations consistent with the subject matter described herein. Instead, they are merely some examples consistent with aspects related to the described subject matter. Although a few variations have been described in detail herein, other modifications or additions are possible. In particular, further features and/or variations can be provided in addition to those set forth herein. For example, the implementations described above can be directed to various combinations and sub-combinations of the disclosed features and/or combinations and sub-combinations of one or more features further to those disclosed herein. In addition, the process steps depicted in the accompanying figures and/or described herein do not necessarily require the particular order shown, or sequential order, to achieve desirable results.

[0062] In the descriptions above and in the claims, phrases such as "at least one of or "one or more of may occur followed by a conjunctive list of elements or features. The term "and/or" may also occur in a list of two or more elements or features. Unless otherwise implicitly or explicitly contradicted by the context in which it used, such a phrase is intended to mean any of the listed elements or features individually or any of the recited elements or features in combination with any of the other recited elements or features. For example, the phrases "at least one of A and B;" "one or more of A and B;" and "A and/or B" are each intended to mean "A alone, B alone, or A and B together." A similar interpretation is also intended for lists including three or more items. For example, the phrases "at least one of A, B, and C;" "one or more of A, B, and C;" and "A, B, and/or C" are each intended to mean "A alone, B alone, C alone, A and B together, A and C together, B and C together, or A and B and C together."

[0063] Use of the term "based on," above and in the claims is intended to mean, "based at least in part on," such that an unrecited feature or element is also permissible.

[0064] The scope of the following claims may include other implementations or embodiments.

CLAIMS

What is claimed is:

1. A method for heating a catalyst associated with an internal combustion engine, comprising:

generating hydrogen within the internal combustion engine, the generating of the hydrogen comprising combusting a first combustion mixture having a first air-fuel ratio, the first air-fuel ratio comprising an excess of fuel relative to a stoichiometric air-fuel ratio such that a reforming reaction occurs during the combusting of the first combustion mixture to generate the hydrogen in first exhaust gases;

combusting a second combustion mixture having a second air-fuel ratio within the internal combustion engine, the second air-fuel ratio comprising an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture;

delivering the first exhaust gases and the second exhaust gases to the catalyst; and

heating the catalyst by reacting at least some of the hydrogen and at least some of the oxygen at the catalyst.

2. The method of claim 1, further comprising:

determining that a temperature of the catalyst is below a minimum target operating temperature of the catalyst; and

causing the generating of the hydrogen and the combusting of the second combustion mixture based on the determining.

3. The method of any preceding claim, comprising bringing the at least some of the hydrogen and the at least some of the oxygen together at the catalyst.

4. The method of any preceding claim, comprising adsorbing one or both of the at least some of the generated hydrogen and the at least some of the excess oxygen onto a surface in the flow path to facilitate delivery of the at least some of the hydrogen and the at least some of the oxygen to the catalyst.

5. The method of any preceding claim, further comprising controlling the combusting of the first combustion mixture and the second combustion mixture, the controlling comprising manipulating at least one of a valve timing of the internal combustion engine; an operation of one or more fuel injectors or a carburetor of the internal combustion engine; a compression ratio of the internal combustion engine; and a spark timing of the internal combustion engine.

6. The method of any preceding claim, wherein the combusting of the first combustion mixture occurs in a first cylinder of the internal combustion engine.

7. The method of claim 6, wherein the combusting of the second combustion mixture occurs in a second cylinder of the internal combustion engine.

8. The method of claim 7, wherein the second cylinder fires sequentially to the first cylinder.

9. The method of claim 7, wherein the second cylinder fires non-sequentially to the first cylinder.

10. The method of any of claims 1 to 6, wherein the combusting of the first combustion mixture and the combusting of the second combustion mixture occurs in a same engine cylinder.

11. The method of claim 10, wherein the combusting of the first combustion mixture occurs in a first engine cycle and the combusting of the second combustion mixture occurs in a second engine cycle.

12. The method of claim 11, wherein the first and second cycles are sequential.

13. The method of claim 11, wherein the first and second cycles are non-sequential.

14. The method of any of any preceding claim, wherein the internal combustion engine comprises an opposed-piston engine.

15. The method of claim 10, wherein the combusting of the first combustion mixture and the combusting of the second combustion mixture occur at a temporal separation within an engine cycle.

16. The method of claim 15, wherein the generating hydrogen comprises injecting a first quantity of fuel after combusting the second combustion mixture within the engine cycle.

17. The method of claim 16, wherein the injecting of the first quantity of fuel occurs during an expansion stroke of the engine cycle and preferably towards an end of the expansion stroke.

18. The method of claim 16 or claim 17, wherein the first quantity of fuel comprises approximately 20% of a second quantity of fuel present in the second combustion mixture.

19. The method of any of claims 15 to 18, wherein the combusting of the second combustion mixture comprises providing approximately 20% excess air relative to a stoichiometric air-fuel ratio for the second quantity of fuel.

20. An internal combustion engine configured to operate according to the method of any preceding claim.

21. An internal combustion engine comprising:

a combustion mixture delivery system;

a controller configured to control the combustion mixture delivery system to provide a first combustion mixture having a first air-fuel ratio, the first air-fuel ratio comprising an excess of fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during combustion of the first combustion mixture to generate hydrogen in first exhaust gases, the controller being further configured to provide a second combustion mixture having a second air-fuel ratio, the second air-fuel ratio comprising an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture; and

an exhaust system that delivers the first and second exhaust gases to a catalyst such that at least some of the delivered hydrogen reacts with at least some of the delivered oxygen, thereby heating the catalyst.

22. A system comprising the internal combustion engine of claim 21 and a catalyst arranged to receive the first and second exhaust gases.

23. The system of claim 22, further comprising one or more temperature sensors for sensing catalyst temperature and wherein the controller is configured to determine the catalyst

temperature using an output from the one or more sensors and to control the combustion mixture delivery system based on determining that the measured temperature is below a minimum target operating temperature of the catalyst.

24. A vehicle comprising the system of claim 22 or claim 23.

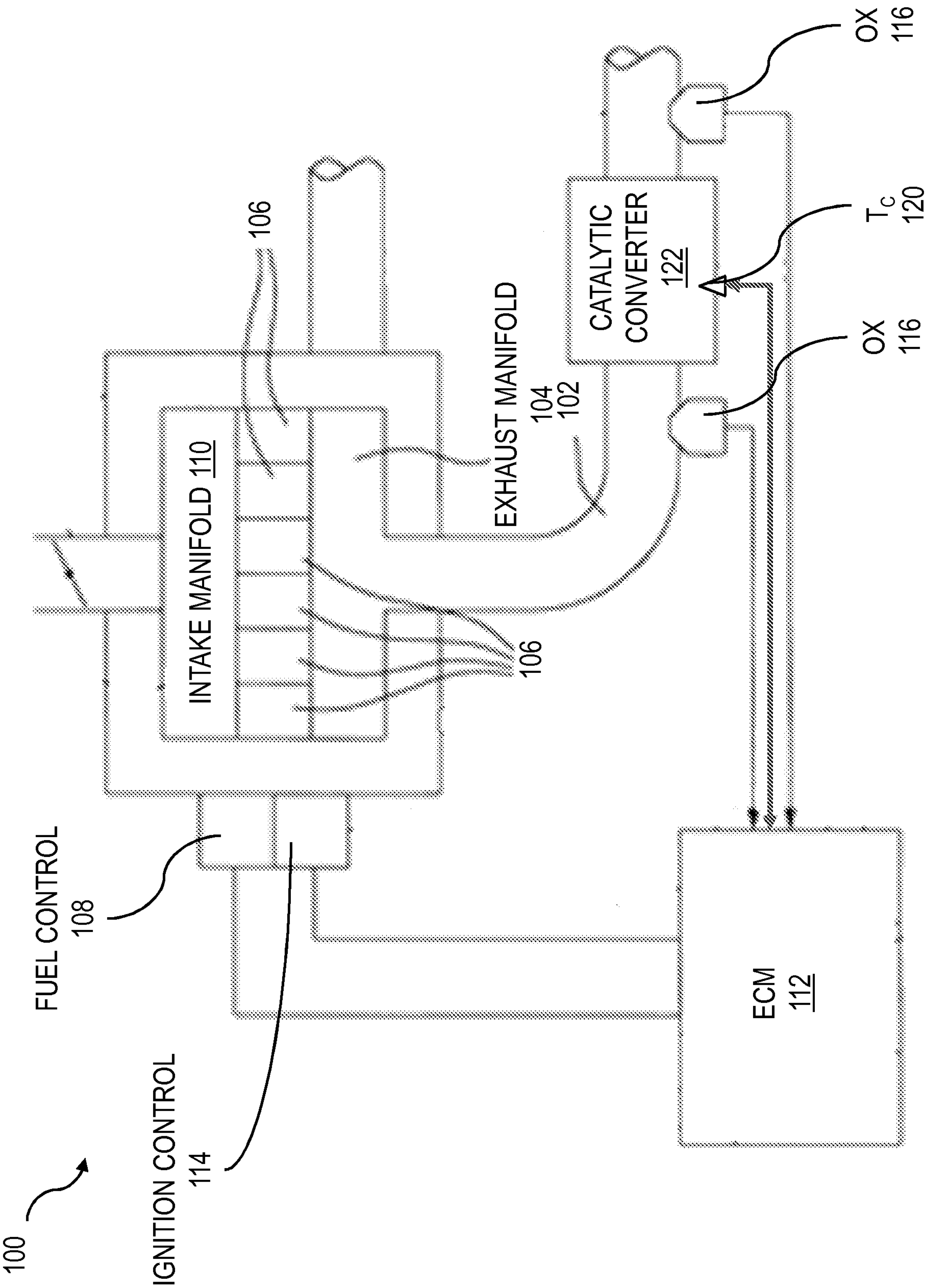
25. An engine management system comprising computer hardware configured to perform operations comprising:

controlling a combustion mixture delivery system of an internal combustion engine to provide a first combustion mixture having a first air-fuel ratio, the first air-fuel ratio comprising an excess of fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during combustion of the first combustion mixture to generate hydrogen in first exhaust gases, and to provide a second combustion mixture having a second air-fuel ratio, the second air-fuel ratio comprising an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture,

wherein the engine management system performs the controlling based on determining that a measured temperature of the catalyst is below a minimum target operating temperature of the catalyst.

26. A computer program product comprising a computer-readable storage medium storing instructions that, when executed by a computing system comprising at least one programmable processor, cause the computing system to perform operations comprising: controlling a combustion mixture delivery system of the engine to provide a first combustion mixture having a first air-fuel ratio, the first air-fuel ratio comprising an excess of fuel relative to a stoichiometric air-fuel ratio, such that a reforming reaction occurs during combustion of the

first combustion mixture to generate hydrogen in first exhaust gases, and to provide a second combustion mixture having a second air-fuel ratio, the second air-fuel ratio comprising an excess of oxygen relative to the stoichiometric air-fuel ratio such that oxygen remains in second exhaust gases after the combusting of the second combustion mixture.


100
IGNITION CONTROL
114
FUEL CONTROL
108
INTAKE MANIFOLD 110
106
106
EXHAUST MANIFOLD
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CATALYTIC
CONVERTER
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OX
116
OX
116
T C
120
ECM
112

FIG. 1

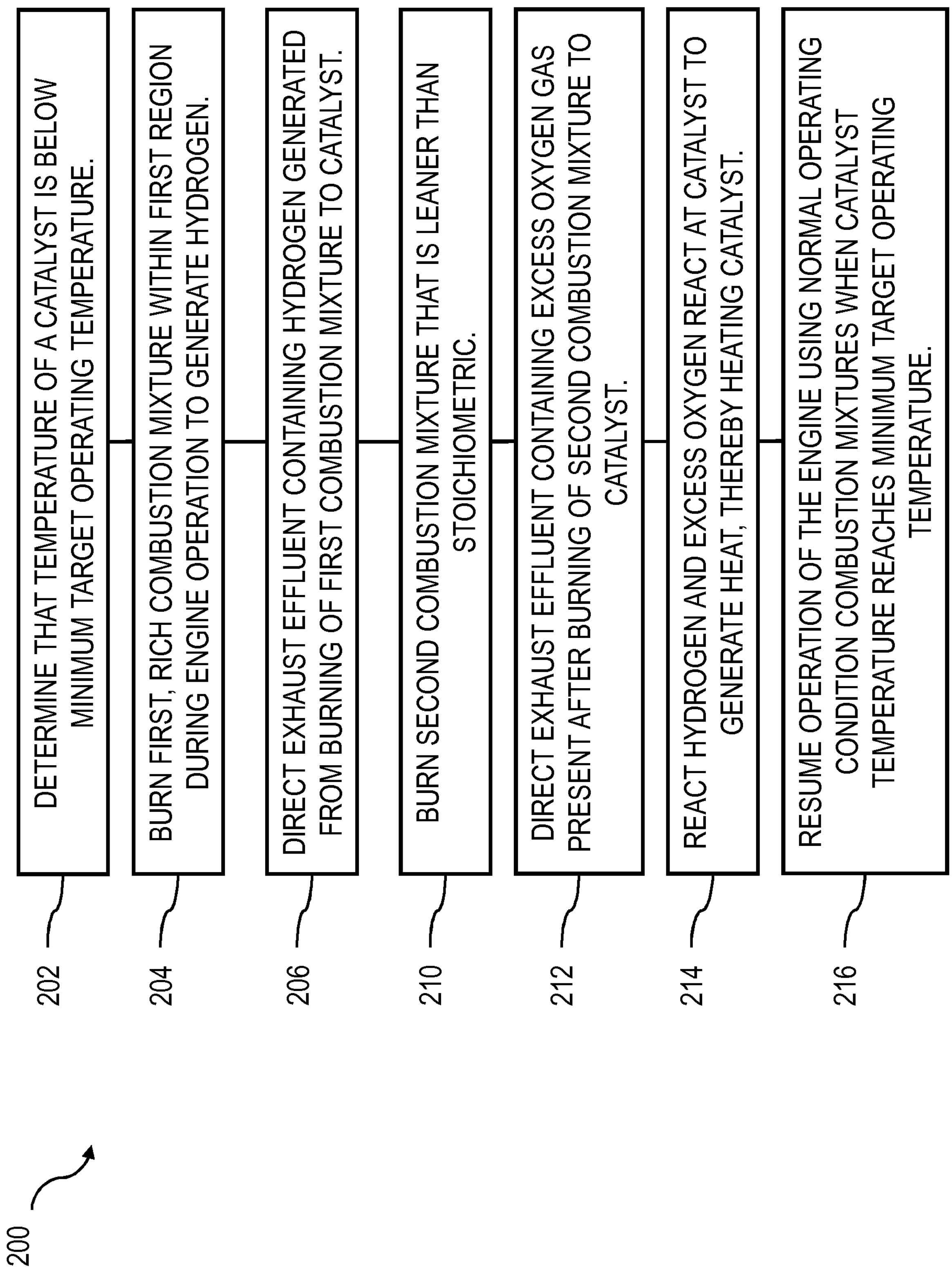
200
202
DETERMINE THAT TEMPERATURE OF A CATALYST IS BELOW MINIMUM TARGET OPERATING TEMPERATURE.
204
BURN FIRST, RICH COMBUSTION MIXTURE WITHIN FIRST REGION DURING ENGINE OPERATION TO GENERATE HYDROGEN.
206
DIRECT EXHAUST EFFLUENT CONTAINING HYDROGEN GENERATED FROM BURNING OF FIRST COMBUSTION MIXTURE TO CATALYST.
210
BURN SECOND COMBUSTION MIXTURE THAT IS LEANER THAN STOICHIOMETRIC.
212
DIRECT EXHAUST EFFLUENT CONTAINING EXCESS OXYGEN GAS PRESENT AFTER BURNING OF SECOND COMBUSTION MIXTURE TO CATALYST.
214
REACT HYDROGEN AND EXCESS OXYGEN REACT AT CATALYST TO GENERATE HEAT, THEREBY HEATING CATALYST.
216
RESUME OPERATION OF THE ENGINE USING NORMAL OPERATING CONDITION COMBUSTION MIXTURES WHEN CATALYST TEMPERATURE REACHES MINIMUM TARGET OPERATING TEMPERATURE.

FIG. 2

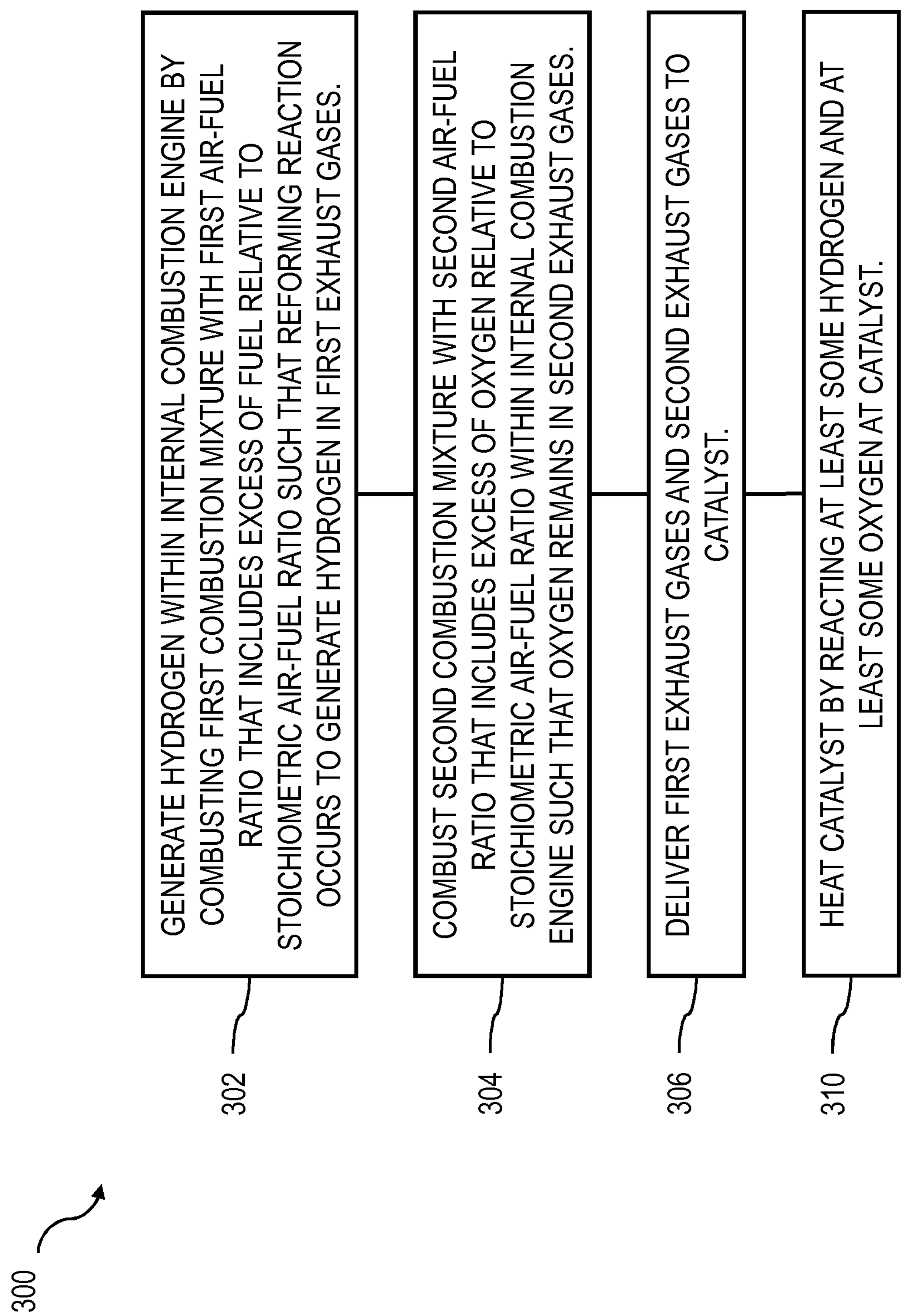
300
302
GENERATE HYDROGEN WITHIN INTERNAL COMBUSTION ENGINE BY COMBUSTING FIRST COMBUSTION MIXTURE WITH FIRST AIR-FUEL RATIO THAT INCLUDES EXCESS OF FUEL RELATIVE TO STOICHIOMETRIC AIR-FUEL RATIO SUCH THAT REFORMING REACTION OCCURS TO GENERATE HYDROGEN IN FIRST EXHAUST GASES.
304
COMBUST SECOND COMBUSTION MIXTURE WITH SECOND AIR-FUEL RATIO THAT INCLUDES EXCESS OF OXYGEN RELATIVE TO STOICHIOMETRIC AIR-FUEL RATIO WITHIN INTERNAL COMBUSTION ENGINE SUCH THAT OXYGEN REMAINS IN SECOND EXHAUST GASES.
306
DELIVER FIRST EXHAUST GASES AND SECOND EXHAUST GASES TO CATALYST.
310
HEAT CATALYST BY REACTING AT LEAST SOME HYDROGEN AND AT LEAST SOME OXYGEN AT CATALYST.

FIG. 3

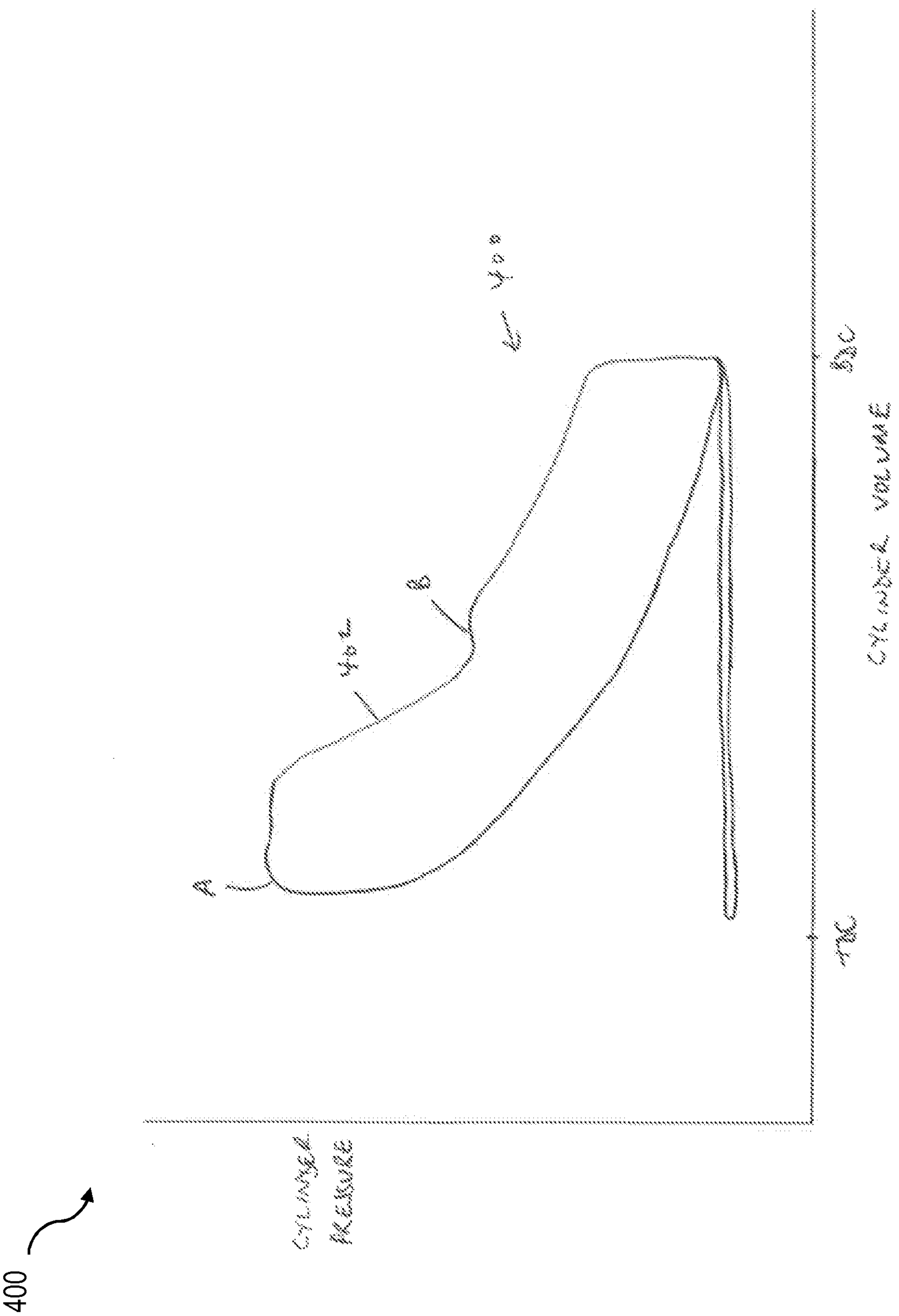

FIG. 4

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2014/037544

A. CLASSIFICATION OF SUBJECT MATTER
INV. F01N3/20 F02D41/O0 F02D41/02
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F01N F02D

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal , WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 7 886 523 BI (LEGARE JOSEPH E [US]) 15 February 2011 (2011-02-15)	1-9, 11, 20-26
Y	column 18, line 9 - line 40; figures l-8b -----	10, 12-19
Y	FR 2 854 659 AI (BOSCH GMBH ROBERT [DE]) 12 November 2004 (2004-11-12) page 3; figures 1-7 -----	10, 12-19
X	US 2006/162321 AI (ZILLMER MICHAEL [DE] ET AL) 27 July 2006 (2006-07-27) paragraph [0014]; figures 1-5 -----	1,20-26
X	W0 2007/016713 A2 (AVL LIST GMBH [AT]; MEYERDIERKS DIETRICH [DE]; K0ESKEMEIER FRIEDRICH [ ]) 15 February 2007 (2007-02-15)	1,20-26
Y	abstract; figures 1-18 -----	10, 12-19

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
1 October 2014	10/10/2014

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Morales Gonzalez, M

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2014/037544

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			US	2006162321	AI	27-07-2006
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