

NITROGEN ENRICHED AIR SUPPLY FOR GASOLINE COMPRESSION IGNITION COMBUSTION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to U.S. Patent Application Serial No. 15/475,383 filed March 31, 2017, which is incorporated by reference in this disclosure in its entirety.

[0002] The present disclosure relates generally to a way to improve internal combustion engine operability and more particularly to the use of generating nitrogen enriched combustion air from multiple sources for use in a compression ignition engine that uses gasoline as a fuel source.

BACKGROUND

[0003] Within the realm of internal combustion engines (ICEs) used for vehicular propulsion, the spark ignition (SI) engine and the compression ignition (CI) engine are the ones most commonly in use. In SI engines, a mixture of air and fuel (typically gasoline) is introduced into a cylindrical combustion chamber for ignition via spark plug. As the resulting flame front propagates through the combustion chamber from the initial ignition point, the temperature continues to rise, which in turn leads to high peak combustion temperatures. Common emissions from the SI process include (among others) carbon monoxide (CO), unburned hydrocarbons and nitrogen oxides (NO_x). Modern SI engine vehicles typically employ a three-way catalytic converter for reduction of each of these combustion byproducts. In order to ensure that the catalysts operate at peak performance with regard to NO_x reduction, such engines are operated at or near stoichiometric fuel-to-air ratios as a way to avoid the presence of catalyst-impairing excess oxygen (O₂) in the exhaust gas.

[0004] In CI engines, fuel (typically diesel fuel) is introduced into the combustion chamber where the air is already present in a highly compressed form. The elevated temperature within the chamber that accompanies the increased pressure causes the fuel to auto-ignite. The combustion process follows via mixing of fuel/air through diffusion. Unlike typical SI engines, the direct fuel injection of CI engines eliminates throttle losses and associated fuel pumping losses. The high compression ratio and inherent lean burn of CI engine with less pumping loss

result in higher thermodynamic efficiency than that of SI engine. However, the excess O₂ associated with such lean fuel-to-air ratios makes the use of the SI engine's three way catalyst impractical for NO_x reduction, as such catalysts only operate effectively over a very narrow range (typically between about 0.5% and 1.0%) of O₂ levels. To overcome this limitation, complicated and expensive fuel injection and after-treatment system are included. Examples of known after-treatment approaches include a lean NO_x trap, selective catalytic reduction (SCR) and Exhaust Gas Recirculation (EGR). While useful for their intended purpose, excessive reliance on these approaches can be counterproductive, as lean NO_x traps and SCR require periodic regeneration, while the effectiveness of EGR is limited at high engine power levels.

[0005] Another engine type, known as the homogeneous charge compression ignition (HCCI) engine, attempts to combine features of both diesel-based CI engines and gasoline-based SI engines. In an HCCI engine, the fuel and air is mixed prior to introduction to the combustion chamber in a manner generally similar to traditional SI engines. Like traditional CI engines, combustion is achieved through auto-ignition of the mixture at certain temperature and pressure conditions within the combustion chamber. Under ideal conditions, an HCCI engine achieves a diffuse, flameless combustion along with lower peak pressure and temperature; such combustion is effective in keeping NO_x production low. In reality, however, it has proven extremely difficult to establish precise control over attaining the correct combination of temperature, pressure and composition of the fuel-air mixture over a wide range of engine operating conditions, particularly as it relates to high power output conditions.

[0006] Still another engine type, known as the gasoline compression ignition (GCI) engine (also referred to as the partially premixed compression ignition (PPCI) engine), has received attention as an attractive alternative to traditional diesel CI or gasoline SI engines. In a GCI engine, the fuel is injected in a staged manner late in the compression phase of the engine's four-stroke cycle operation. In this way, the fuel charge may be thought of as having both locally stoichiometric and globally stratified properties. Significantly, gasoline in general (and low-octane gasoline in particular) has a higher volatility and longer ignition delay relative to diesel fuel. By introducing such a fuel relatively late in the compression stroke and taking advantage of the fuel's ignition delay (which helps to promote additional fuel-air mixing), combustion does not commence before the end of the injection. To achieve a desirable degree of stratification, multiple injections may be used. By operating under low temperature combustion (LTC) conditions, GCI engines can have significantly reduced NO_x production and soot emissions

while achieving diesel-like thermal efficiencies. Moreover, refining low-octane gasoline is easier (and less expensive) than processing conventional gasoline and diesel fuels, which in turn reduces the entire well-to-tank emissions of other undesirable substances, such as CO₂.

[0007] One shortcoming with a GCI engine is that the NO_x emission that is low during normal engine operating conditions tends to increase under heavy loads. As such, automobile manufacturers have implemented some of the various techniques mentioned above (i.e., SCR, EGR, etc.) as a way to ensure NO_x compliance under all engine operating conditions. Such corrective measures are expensive and, as mentioned above, can limit engine performance. For example, excessive EGR can lead to combustion instability and associated misfiring, as well as contribute to valve clogging from the carbon deposits that are contained in the recirculated exhaust gas. The excessive reliance on EGR also makes it difficult to control GCI engine transient responses, as the reduction of the intake air charge density may be incompatible with maintaining a continuous combustion flame front within the combustion chamber.

SUMMARY

[0008] According to one embodiment of the present disclosure, a GCI engine with a nitrogen (N₂) enriched air supply for exhaust gas emissions reduction is disclosed. The GCI engine includes numerous combustion chambers, an air inlet in selective fluid communication with each of the combustion chambers, an exhaust gas outlet in selective fluid communication with each of the combustion chambers and an inlet air management system that can prioritize the preparation of a nitrogen enriched air charge. The inlet air management system includes a membrane-based separator, an EGR flowpath, a flow control conduit and a combustion air enrichment controller. The separator is in fluid communication with the air inlet such that air introduced to the separator is split into an oxygen enriched air (OEA) stream and a nitrogen enriched air (NEA) stream. Likewise, the exhaust gas recirculation flowpath is in fluid communication with the exhaust gas outlet to convey a nitrogen enriched combustion product stream that forms when a mixture of air and gasoline is ignited within the combustion chamber. In addition, the flow control conduit is cooperative with the separator and the exhaust gas recirculation flowpath such that one or both of the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath and the nitrogen enriched air stream from the separator are placed in selective fluid communication with the air inlet. Numerous sensors are used to acquire engine operating parameters. The controller is in signal communication with the

sensors such that they—along with the separator, exhaust gas recirculation flowpath and flow control conduit—cooperate to deliver to the air inlet (a) the oxygen enriched air stream from the separator during a cold start and warm-up load on the GCI engine and (b) the nitrogen enriched air stream from the separator and the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath. Significantly, during an increase in engine load not associated with the cold start and warm-up load, the controller provides an instruction set where the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided at least partially by the nitrogen enriched air stream from the separator, as well as increasingly by the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath.

[0009] Within the present context, the various engine operating loads or conditions (for example, low, normal, cold start and high) may correspond to various regimes that may be monitored and operated upon by the controller to ensure that proper management of the air mixture. In a similar manner, the controller—either alone or working in conjunction with another controller—may be used to ensure that proper fuel and associated environmental operating conditions for such modes are being followed.

[0010] By way of example, the disclosed GCI engine using an unleaded regular gasoline with a research octane number (RON) of 91 may experience a relatively long ignition delay for one or more of the various operating conditions: low engine loads; low ambient temperatures and cold start (as well as its attendant early warm-up). In such circumstances, auto-ignition may be too weak, too late or fail altogether. To avoid such conditions, the controller may work with other conduit, valves and a spark plug such that injected fuel starts ignition and combustion on time. In case of SI operation, the OEA stream helps increasing flame speed and combustion rate especially when the cylinder temperature is low. Likewise, for medium-to-high-load operation, cylinder pressure and temperatures are increased; such operating conditions tend to promote early auto-ignition and may lead to higher NO_x emissions and higher combustion noise.

[0011] According to another embodiment of the present disclosure, a vehicle is disclosed. The vehicle includes a platform comprising a wheeled chassis, a guidance apparatus cooperative with the wheeled chassis and a passenger compartment and a GCI engine coupled to the platform to deliver motive power. The GCI engine includes numerous combustion chambers, an air inlet, an exhaust gas outlet and an inlet air management system that includes a membrane-based separator, an EGR flowpath, a flow control conduit, numerous sensors and a combustion

air enrichment controller. Both the air inlet and the exhaust gas outlet are in selective-fluid communication with each of the combustion chambers. Air introduced to the separator is split into at least an OEA stream and an NEA stream, while the EGR flowpath is used to convey a nitrogen enriched combustion product stream back into the air inlet. The flow control conduit is used to route the nitrogen enriched air supply among the various components.

[0012] The various components of the inlet air management system cooperate to deliver to the air inlet OEA and NEA streams. In particular, the OEA stream is carried from the separator during a cold start and warm-up load on the GCI engine, while the NEA stream is carried from both the separator and the EGR flowpath during periods not associated with the cold start and warm-up loads. Moreover, during these periods not associated with the cold start and warm-up loads, the controller provides an instruction set where varying portions of the exhaust gas emissions reduction is provided by the nitrogen enriched combustion product stream from the EGR flowpath and the NEA air stream from the separator.

[0013] According to yet another embodiment of the present disclosure, a method of operating a GCI engine is disclosed. The method includes introducing a gasoline-based fuel to engine combustion chambers and using an inlet air management system to—among other things—help reduce exhaust gas emissions. The inlet air management system includes a membrane-based separator, an exhaust gas recirculation flowpath, flow control conduit cooperative with the separator and the exhaust gas recirculation flowpath, numerous sensors and a combustion air enrichment controller in signal communication with the sensors and the flow control conduit. In use, air introduced into a membrane-based separator for separation into at least an OEA stream and an NEA stream is manipulated by the inlet air management system so that at least a portion of the NEA stream, as well as (depending on the engine load) the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath, is provided to the engine as a way to adjust the rate at which GCI combustion takes place within the engine. In this way, during an increase in engine load not associated with cold start or warm-up operating conditions, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided at least partially by the nitrogen enriched air stream from the separator and in certain circumstances from the nitrogen enriched combustion product stream that is present in the exhaust gas recirculation flowpath.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS

[0014] The following detailed description of specific embodiments of the present disclosure can be best understood when read in conjunction with the following drawings, where like structure is indicated with like reference numerals and in which:

FIG. 1 shows a simplified cutaway view of a GCI engine and a portion of an inlet air management system in accordance with one or more embodiments shown or described herein;

FIG. 2 illustrates a simplified view of various flowpaths associated with the air management system in accordance with one or more embodiments shown or described herein;

FIG. 3 illustrates a variation of the air management system of FIG. 2 where a membrane module is coupled with an air filter for a line-replaceable unit in accordance with one or more embodiments shown or described herein;

FIG. 4 illustrates a normalized comparison of NO_x and soot emission with varying nitrogen enrichment using the air management system in accordance with one or more embodiments shown or described herein; and

FIG. 5 illustrates an exemplary in-cylinder temperature trace during a notional GCI engine combustion process.

DETAILED DESCRIPTION

[0015] The present disclosure relates to a method and system for improving engine performance and reducing NO_x emissions of a GCI engine through intake air control that uses the combined contributions of a membrane and EGR in order to selectively deliver a nitrogen-containing charge to the engine's combustion chambers. While it is generally known to have each of these components operate independently of one another, the authors of the present disclosure take the position that by integrating the two, improvements in overall engine performance may be realized, as well as reduced size, weight or complexity of a resulting air supply system. In particular, under the present disclosure, the incoming air supply is routed through the membrane to separate the input air stream into the OEA stream and NEA stream. The NEA stream is fed to the engine air intake in order to dilute the intake charge and decrease GCI combustion rate, which in turn reduces NO_x emission in a manner generally similar to a

conventional EGR. Likewise, in operating conditions (such as cold start) where GCI may not be possible, the OEA increases the flame propagation combustion rate for quicker warm-up and related engine operability improvements. In an optional form, the excessive OEA can also be fed into the vehicle's passenger compartment to refresh cabin air (that is to say, passenger compartment) quality. The EGR may be used to also dilute the intake charge, and in so doing, can help reduce the size of the membrane to help with its packaging within a vehicular environment. This EGR use is particularly beneficial in high load conditions as a way to supplement the NO_x-reducing performance of the NEA that comes from the membrane. By relying at least in part on the membrane for additional N₂ over numerous GCI engine operating conditions, the reliance on the EGR request may be reduced, which in turn may lead to improvements in GCI transient control response, as well as increased high load limits of the GCI engine.

[0016] Referring first to FIGS. 1 and 2, a diagrammatic illustration of a GCI engine **1** with a nitrogen enriched air supply for use in a vehicle **2** with a passenger compartment **3** is shown. The engine **1** includes an engine block **5** with numerous cylinders **10**, a crankshaft **15** rotatably movable within the block **5**, numerous cams **20** responsive to movement of the crankshaft **15**, a head **25** coupled to the engine block **5** to define numerous combustion chambers **30**. The head **25** includes inlet valves **35** and exhaust valves **40** (only one of each is shown) that in one form may be spring-biased to move in response to the crankshaft **15** through a corresponding one of the cams **20** that are controlled by either a crankshaft-driven chain, crankshaft-actuated pushrods or pneumatic actuators (none of which are shown). An air inlet **45** (which may be part of combustor inlet gas **115_C** that is fluidly coupled to portions of the flow control conduit **115** and intake control **125** that are discussed in more detail in subsequent paragraphs) and an exhaust gas outlet **50** are in selective fluid communication with each of the combustion chambers **30** through a fuel injector **55**, while a piston **60** is received in each respective cylinder **10** and coupled to the crankshaft **15** through a connecting rod **65** so that the reciprocating movement of the piston **60** in response to a compression ignition combustion taking place within the combustion chamber **30** is converted by the pivoting movement of the connecting rod **65** and crankshaft **15** to rotational movement of the crankshaft **15** for subsequent power delivery to the remainder of a powertrain that is made up of the engine **1** and transmission, axles, differentials and wheels (none of which are shown). The combustion associated with the GCI engine **1** can be categorized as having partially premixed compression ignition (PPCI) attributes in that the

timing of the auto-ignition combustion is controlled by manipulating fuel/air ratio levels within the combustion chamber during portions of the compression stroke.

[0017] The supply of air that is used for the combustion process achieves its nitrogen enrichment with an inlet air management system **100**. This system **100** includes a membrane-based separator **105** and an EGR **110**, along with suitable conduit **115** so that air used for the combustion, as well as exhaust gas that is a product of such combustion, may be used to dilute an air intake charge of the engine **1** in order to selectively decrease GCI combustion rate, which in turn leads to a reduction in NO_x emission. Within the present context, the flow control conduit **115** includes not just the pipes, tubes, channels or related fluid-conveying lines, but also any valves (not shown) or related flow control devices that are fluidly disposed in such lines. By using the separator **105**, reliance on the EGR **110** may be reduced, especially for certain engine loads. In other engine operating loads or conditions such as cold starts and associated warm-ups, the separator **105** may be used with a spark ignition device **120** (such as a spark plug) to increase the flame propagation combustion rate. Within the present context, the other operating conditions that are not associated with the cold start or warm-up conditions can be run under the GCI mode of operation discussed herein.

[0018] As shown, an inlet (that is to say, a feed stream) **115_I** of ambient air forms a portion of the flow control conduit **115** and is used to first introduce the air to the separator **105** where an O₂-rich permeate flows through OEA stream **115_{OEA}** and an N₂-rich retentate **105B** flows through NEA stream **115_{NEA}**. Both OEA and NEA streams **115_{OEA}**, **115_{NEA}** are fed to intake control **125** that is in the form of a mixing chamber or the like. In one form, the EGR **110** is in the form of a valve so that it along with the associated portions of flow control conduit **115** form an EGR flowpath **115_{EGR}** that recirculates the exhausted gas that leaves the combustion chamber **30** through exhaust valve **40** into the intake control **125**. The intake control **125**—in response to control signals from a processor-based controller **130** that is discussed in more detail below that is used to adjust valve and bypass flows in various parts of flow control conduit **115**—modulates the performance of separator **105** with feed flow rate and feed/permeate pressure in order to adjust the amount of each gas stream from the three inputs (that is to say, the OEA stream **115_{OEA}**, the NEA stream **115_{NEA}** and the EGR stream **115_{EGR}**) according to the required engine **1** load or related operational conditions. During cold start condition, the OEA stream **115_{OEA}** can be supplied solely to increase the combustion rate; in such cases, no NEA stream **115_{NEA}** is introduced into the combustion chambers **30**. In other operating conditions, the NEA stream

115_{NEA} is supplied for reducing NO_x emissions. At high engine load conditions (such as those associated with elevated mean effective pressure (MEP)) as discussed herein, the EGR stream **115_{EGR}** can be utilized with the NEA stream **115_{NEA}** as a way to avoid having to construct a prohibitively large separator **105** to accommodate the higher volume or surface area needed for such loads. As shown, a portion of either or both of filtered inlet air **115_F** and the OEA stream **115_{OEA}** can be routed to a vehicular passenger compartment or cabin as a way to refresh or otherwise augment the cabin air quality. In one form, the inlet air **115_I** may be pressurized, such as by a turbocharger **135** or other related device. The turbocharger **135** may be driven by excess exhaust gas that is not directed back into the intake control **125**.

[0019] The EGR stream **115_{EGR}** works by recirculating a portion of the exhaust gas back to the turbocharged intake air coming from one or the other of NEA stream **115_{NEA}** and OEA stream **115_{OEA}**. This has the effect of diluting the O₂ being introduced into the combustion chamber **30**, which in turn reduces peak in-cylinder temperatures by providing inert gases like N₂ and H₂O that with their relatively high specific heat are effective absorbing the heat that is generated during the combustion process.

[0020] Instructions for operation of the inlet air management system **100** come from the controller **130** that may be embodied in one or more electronic control units (ECUs). Controller **130** is used to receive data from sensors **S** and provide logic-based instructions to the various parts of the inlet air management system **100**. As will be appreciated by those skilled in the art, controller **130** may be a singular unit, or one of a distributed set of units throughout the vehicle **2**. In one configuration, controller **130** may be configured to have a more discrete set of operational capabilities associated with a smaller number of component functions such as those associated solely with the operation of the inlet air management system **100**, while in another configuration, controller **130** may have a more comprehensive capability such that it acts to control a larger number of components, such as the engine **1**, either in conjunction with or separately from the inlet air management system **100**, and that all such variants, regardless of the construction and range of functions performed by the controller **130**, are deemed to be within the scope of the present disclosure. In one form associated with only performing functions associated with the inlet air management system **100**, the controller **130** may be configured as an application-specific integrated circuit (ASIC). In one form, controller **130** is provided with one or more input/output (I/O) **130A**, microprocessor or central processing unit (CPU) **130B**, read-only memory (ROM) **130C**, random-access memory (RAM) **130D**, which are respectively

connected by a bus **130I** to provide connectivity for a logic circuit for the receipt of signal-based data, as well as the sending of commands or related instructions. Various algorithms and related control logic may be stored in the ROM **130C** or RAM **130D** in manners known to those skilled in the art. Such control logic may be embodied in a preprogrammed algorithm or related program code that can be operated on by controller **130** and then conveyed via I/O **130A** to the inlet air management system **100** as discussed herein. In one form of I/O **130A**, signals from the various sensors **S** are exchanged with controller **130**.

[0021] In situations where the controller **130** is configured to provide control to more than just the inlet air management system **100** (for example, to the operation of one or more of the engine **1**, supply of fuel or other systems within vehicle **2**), other such signals from additional sensors **S** may also be signally provided to controller **130** for suitable processing by the control logic contained therein, including those where combustion data from the engine **1** is provided for control over the mixing or related delivery of combustor inlet gas **115C** that is delivered from the intake control **125**. For example, in a manner consistent with GCI modes of engine **1** operation, controller **130** may be programmed with a fuel injector driver **130E**, an EGR driver **130F**, engine valve control **130G** and flow valve control **130H** (for any valves disposed in the flow conduit **115**) to provide a multiple late-injection, stratified-mixture, low-temperature combustion process as a way to promote smooth operation and low NO_x emissions of engine **1** over a substantial entirety of its load-speed range. Such control is particularly beneficial for the multiple late-injection strategy used for the delivery of fuel in the GCI engine **1** as such delivery is optimized when it coincides with various sequences in the compression stroke that can be measured by sensors **S** that detect crank angle degree (CAD) from the crankshaft **15** to help control when auto-ignition occurs. Within the present context, the position of the piston **60** within the cylinder **10** is typically described with reference to CAD before or after the top dead center (TDC) position of piston **60**. The controller **130** may also base such delivery strategies on other engine **1** operating parameters such as load and engine speed, as well as the number of times such injection is contemplated. For example, CAD from 0° to 180° corresponds to the power stroke, with 0° representing TDC and 180° representing bottom dead center (BDC). Likewise, CAD from 180° to 360° represents an exhaust stroke with the latter representing TDC. Moreover, CAD from 360° to 540° represents an intake stroke with BDC at the latter. Furthermore, CAD from 540° to 720° represents a compression stroke with TDC at the latter. By way of example, the controller **130**—when used in a 6-cylinder engine—would have ignition

taking place every 120° of crankshaft **15** rotation, that is to say three ignitions per every revolution of engine **1**. Thus, when ignition has taken place each of the six cylinders one time, the crankshaft **15** has rotated twice to traverse 720° of rotary movement. Likewise, if engine **1** were configured as a 4-cylinder engine, the ignition would take place every 180° of crankshaft **15** rotation. In one form, one of the sensors **S** may be a crank sensor to monitor the position or rotational speed of the crankshaft **15**. The data acquired from such a crank sensor is routed to the controller **130** for processing in order to determine fuel injection timing and other engine **1** parameters, including ignition timing for those circumstances (such as cold startup, and the ensuing warm-up) where spark ignition device **120** is being used. Sensors **S** such as the crank sensor may be used in combination with other sensors **S** (such as those associated with valve **20** position) to monitor the relationship between the valves **20** and pistons **60** in engine **1** configurations with variable valve timing.

[0022] The controller **130** may be implemented using model predictive control schemes such as the supervisory model predictive control (SMPC) scheme or its variants, or such as multiple-input and multiple-output (MIMO) protocols, where inputs include numerous values associated with the various post-combustion exhaust gas treatment components discussed herein, sensors **S** (such as exhaust gas temperature sensor, O_2 sensor, NO_x sensor, SO_x sensor or the like), estimated values (such as from the lookup tables or calculated algorithmically) or the like. In that way, an output voltage associated with the one or more sensed values from sensors **S** is received by the controller **130** and then digitized and compared to a predetermined table, map, matrix or algorithmic value so that based on the differences, outputs indicative of a certain operational condition are generated. These outputs can be used for adjustment in the various components within the purview of the controller **130**, such as the remaining components associated with inlet air management system **100**.

[0023] As mentioned above, in one form, controller **130** may be preloaded with various parameters (such as atmospheric pressure, ambient air temperature and flow rate, exhaust gas temperature and flow rate, engine MEP or the like) into a lookup table that can be included in ROM **130C** or RAM **130D**. In another form, controller **130** may include one or more equation- or formula-based algorithms that permit the CPU to generate a suitable logic-based control signal based on inputs from various sensors, while in yet another form, controller **130** may include both lookup table and algorithm features to promote its monitoring and control functions. Regardless of which of these forms of data and computation interaction are

employed, the controller **130**—along with the associated sensors **S**, membrane separator **105**, EGR **110** and associated flow control conduit **115**—cooperate such that as an operating load on the engine **1** increases beyond a cold start or warm-up condition, more of the NEA stream **115_{NEA}** is delivered to the intake control **125** from the separator **105** than from the EGR **110**.

[0024] Referring next to FIG. 3, in one form, the separator **105** may be formed as part of a module **140** in order to have line-replaceable unit (LRU) qualities. In this way, maintenance operations associated with replacement or service of the separator **105** or air filter **145** may be simplified. Such LRUs may be readily stocked for so-called off-the-shelf replacement from readily-available on-site inventories. Because of their modularity, LRUs also can contribute reducing system costs and increase quality, by centralizing development across different models of vehicle **2**. For lower maintenance cost of the vehicle **2**, the separator **105** may be placed with the air filter **145** in such a way that the module **140** forms a combined housing, while in another form, the separator **105** may be formed in its own housing.

[0025] MEP—including its variants indicated mean effective pressure (IMEP), brake mean effective pressure (BMEP) or friction mean effective pressure (FMEP)—provides a value of the ability of a particular engine **1** to do work without regard to the number of cylinders **10** or related engine **1** displacement. Moreover, it provides a measure of the pressure corresponding to the torque produced so that it may be thought of as the average pressure acting on a piston **60** during the different portions of its four cycles (inlet, compression, ignition and exhaust). In fact, MEP is a better parameter than torque to compare engines for design and output because of its independence from engine speed or size. As such, MEP provides a better indicator than other metrics (such as horsepower) for engines in that the torque produced is a function of MEP and displacement only, while horsepower is a function of torque and rpm. Thus, for a given displacement, a higher maximum MEP means that more torque is being generated, while for a given torque, a higher maximum MEP means that it is being achieved from a smaller engine **1**. Likewise, higher maximum MEP may be correlated to higher stresses and temperatures in the engine **1** which in turn provide an indication of either engine **1** life or the degree of additional structural reinforcement in engine **1**. Significantly, extensive dynamometer testing, coupled with suitable analytical predictions, permit MEP to be well-known for modern engine designs. As such, for a CI engine, MEP values of about 7.0 bar to about 9.0 bar are typical at engine speeds that correspond to maximum torque (around 3000 rpm), while for naturally aspirated (that is to say, non-turbocharged) SI engines, MEP values of about 8.5 bar to about 10.5 bar are

common, while for turbocharged SI engines, the MEP might be between about 12.5 bar and about 17.0 bar.

[0026] Likewise, MEP values may be determined for various operating regimes for engine **1**. Such operating regimes may include low power or load (including, for example, engine idling conditions) that is one form corresponds to a MEP of up to about 1.0 bar, in another form of an MEP of up to about 2.0 bar. Likewise, such operating regimes may include normal (or medium) power or load that is one form corresponds to a MEP of between about 2.0 bar to about 5.0 bar, in another form of an MEP of between about 2.0 bar and about 6.0 bar, in another form of an MEP of between about 2.0 bar and about 7.0 bar. Moreover, such operating regimes may include a high power or load that is one form corresponds to a MEP of about 7.0 bar and above, in another form of an MEP of about 8.0 bar and above, in another form of an MEP of about 9.0 bar and above, and in another form of an MEP of about 10.0 bar and above.

[0027] As will be understood, these and other MEP values may be input into a suitably-mapped set of parameters that may be stored in a memory accessible location (such as the lookup tables mentioned above) so that these values may be used to adjust various engine **1** operating parameters, as well as for the controller **130** when acting in its diagnostic capacity. In such case, it may work in conjunction with some of the sensors **S**, including those that can be used to measure cylinder **10** volume (such as through crankshaft **15** angle or the like).

[0028] Referring next to FIGS. 4 and 5, both analytical and experimental studies confirm that using the NEA stream **115_{NEA}** and the EGR stream **115_{EGR}** can dilute the intake charge to decrease GCI combustion rate, and as a result reduce NO_x emission. Because the NEA stream **115_{NEA}** is used over a substantial entirety of the loads that engine **1** is expected to be exposed to, it is beneficial to understand the construction of the separator **105**. In particular, separator **105** can be adjusted such that O₂ penetrates the membrane several times faster than N₂, which impacts the amount of OEA stream **115_{OEA}** being produced on the permeate side **105A**. Penetration speed can be measured in terms of permeance or permeability of the air that is incoming to separator **105**. In the meantime, the NEA stream **115_{NEA}** is continuously produced in the retentate side **105B**. A membrane selectivity or related separation factor is used to compare the separating capacity of a membrane for certain target gases where the selectivity is given by the ratio of their permeability (or permeance). In order to meet the certain requirements of the product air (certain N₂ concentration and flow rate of NEA stream **115_{NEA}**),

the required amount of feed air (that is, feed flow rate), as well as the feed/permeate pressure, can be varied. In addition, the purity of O₂ in the permeate side **105A** stream may also be varied. Likewise, the configuration of the separator **105** may be varied. For example, the separator **105** may be configured as a spiral-wound module, a plate-and-frame module, a hollow fiber membrane module, a hollow fiber module or a capillary module. For instance, in a hollow fiber membrane module, the feed can be introduced inside of the fiber (called ‘inside-out’) or outside of the fiber (called ‘outside-in’). As shown in Table 1 for a hollow fiber membrane module, the highly O₂ selective membrane (material B, with an O₂/N₂ selectivity of 5) is shown to be more effective as the separator **105** than the less O₂ selective membrane (material A, with an O₂/N₂ selectivity of 2) in minimizing the amount of intake air flow required in order to achieve the same N₂ concentration in the NEA stream. Such selectivity (as well as configuration) can thus form a basis for sizing the separator **105** for a given engine **1**.

Production of NEA using hollow fiber membrane module.

Membrane material	Feed configuration	Feed		Permeate		Retentate	
		Flow rate, L/min	N ₂ concentration, vol.%	Flow rate, L/min	O ₂ concentration, vol.%	Flow rate, L/min	N ₂ concentration, vol.%
A	Inside-out	90	79	40	28.5	50	85
B	Inside-out	66		16	39.8		
B	Outside-in	68		18	37.0		

Feed pressure: 3 bar; Permeate pressure: 1.1 bar

Table 1

[0029] As part of the analysis conducted by the authors of the present disclosure, computational fluid dynamics (CFD) were used to simulate the performance and emissions of GCI engine **1** operating in a nitrogen enhanced mode of operation. In such simulation, a single cylinder 4 valve engine with a 14.5:1 geometric compression ratio was analyzed. The combustion chamber received 14 milligrams of light naphtha fuel injected during a single cycle run, where the load was specified at 5 bar MEP at 1500 rpm with 1.1 bar boosted intake pressure. These results are shown where in general, increasing the amount of NO_x-suppressing fluid from the EGR stream **115_{EGR}** is beneficial at idle or related low engine **1** load conditions, but less so at MEPs associated with medium and high loads. For example, EGR **110** should not be used at loads higher than about 7.0 bar BMEP, as at these higher load conditions, the resulting exhaust gas emissions can contain an excessive amount of smoke. By monitoring engine **1** load and determining that such load is less than a threshold (such as that associated

with a defined low load range), appropriate operation of the EGR **110** can be achieved. Moreover, the controller **130** may be used to instruct how much of the N₂ enrichment being provided to the intake control **125** comes from each of the EGR stream **115_{EGR}** and the NEA stream **115_{NEA}** based on factors such as this.

[0030] Referring with particularity to FIG. 4, experiments were conducted on engine **1** as discussed in the previous paragraph as a way to verify the feasibility of N₂ enrichment by using separator **105**. Various parameters were varied, including those associated with feed and permeate flow rate and operating pressure (feed pressure) on the N₂ purity and flow rate. The NO_x emission was normalized to the reference value with a standard atmospheric concentration of 79% (by volume) of N₂. Thus, a relatively modest 6% increase in N₂ to 85% results in about an 80% suppression of the NO_x emission relative to the non-enriched reference case, although soot production does increase by about 25 to 30 percent.

[0031] Referring with particularity to FIG. 5, an in-cylinder temperature trace is shown for a simulated combustion process for the GCI engine **1**. In this regard, the chart represents a rate of heat release versus CAD. The peak in-cylinder temperature decreases with an increasing N₂ composition in the inlet air charge. The NEA stream **115_{NEA}** dilutes the intake charge and decreases GCI engine **1** combustion rate, as a result, reducing peak in-cylinder temperature of the engine **1**. It is known that NO_x emission is produced at high temperature. As such, lowering the in-cylinder temperature results in a dramatically reduced NO_x emission. Significantly, the temperature reduction associated the NO_x reduction permits changes in where during the compression process the injection of fuel takes place. As such, the injection of fuel at a particular CAD to keep such combustion temperatures low depends on various factors associated with a desired multiple late-injection, stratified-mixture, low-temperature combustion process. Such factors may include fuel-to-air ratios, EGR levels, inlet air temperature and pressure or the like. With the GCI engine **1**, the fuel may be injected at different times during on the compression stroke (for example, between about 120° to 90° CAD before TDC in some circumstances, and between about 30° to 10° before TDC in others); the controller **130** may take into consideration differences in the fuel's auto-ignition properties under these various temperature and pressure regimes within the combustion chamber **30** to instruct such injection, as well as NEA or OEA streams **115_{NEA}**, **115_{OEA}**, valve lift timing or the like.

[0032] By injecting the fuel at a particular CAD, emissions in general, and NO_x in particular, may be reduced while still preserving stable, efficient operation. With particular regard to high engine 1 loads (where the MEP is high), it may be difficult to inject all of the fuel at the desired CAD due to the high rotational speed. It is in situations like this where the use of the inlet air management system 100 and its blended reliance on NEA stream 115_{NEA} and EGR stream 115_{EGR} coming from the respective separator 105 and an EGR 110 is most useful. In particular, controller 130 can be used in conjunction with the other components discussed herein to provide an appropriate inlet charge to intake control 125 in order to promote auto-ignition combustion to within a preferred CAD. In fact, depending on the engine 1 load and various input parameters, much (if not all) of the auto-ignition can be made to take place in a narrow CAD after TDC, as shown in the figure. Likewise, the duration of the combustion event can be controlled to achieve desirable peak cylinder temperature and pressure levels that are consistent with NO_x reduction. In a similar way, increasing the OEA stream 115_{OEA} may be used in certain engine 1 operating conditions to advance the initiation of the combustion process (often in conjunction with the spark ignition device 120).

[0033] Having described the subject matter of the present disclosure in detail and by reference to specific embodiments thereof, it is noted that the various details disclosed herein should not be taken to imply that these details relate to elements that are essential components of the various embodiments described herein, even in cases where a particular element is illustrated in each of the drawings that accompany the present description. Further, it will be apparent that modifications and variations are possible without departing from the scope of the present disclosure, including, but not limited to, embodiments defined in the appended claims. More specifically, although some aspects of the present disclosure are identified herein as preferred or particularly advantageous, it is contemplated that the present disclosure is not necessarily limited to these aspects.

[0034] It is noted that one or more of the following claims utilize the term “wherein” as a transitional phrase. For the purposes of defining features discussed in the present disclosure, it is noted that this term is introduced in the claims as an open-ended transitional phrase that is used to introduce a recitation of a series of characteristics of the structure and should be interpreted in like manner as the more commonly used open-ended preamble term “comprising.”

[0035] It is noted that terms like “preferably”, “generally” and “typically” are not utilized herein to limit the scope of the claims or to imply that certain features are critical, essential, or even important to the structures or functions disclosed herein. Rather, these terms are merely intended to highlight alternative or additional features that may or may not be utilized in a particular embodiment of the disclosed subject matter. Likewise, it is noted that the terms “substantially” and “approximately” and their variants are utilized herein to represent the inherent degree of uncertainty that may be attributed to any quantitative comparison, value, measurement or other representation. As such, use of these terms represent the degree by which a quantitative representation may vary from a stated reference without resulting in a change in the basic function of the subject matter at issue.

[0036] It will be apparent to those skilled in the art that various modifications and variations can be made to the embodiments described herein without departing from the spirit and scope of the claimed subject matter. Thus it is intended that the specification cover the modifications and variations of the various embodiments described herein provided such modification and variations come within the scope of the appended claims and their equivalents.

CLAIMS

1. A gasoline compression ignition (GCI) engine with a nitrogen enriched air supply for exhaust gas emissions reduction, the GCI engine comprising:
 - a plurality of combustion chambers each with a piston movably disposed
 - 5 therein;
 - at least one fuel injector in selective fluid communication with each of the combustion chambers;
 - an air inlet in selective fluid communication with each of the combustion chambers;
 - 10 an exhaust gas outlet in selective fluid communication with each of the combustion chambers; and
 - an inlet air management system comprising:
 - a membrane-based separator in fluid communication with the air inlet such that air introduced to the separator is operated thereupon to be split into at least an oxygen
 - 15 enriched air stream and a nitrogen enriched air stream;
 - an exhaust gas recirculation flowpath in fluid communication with the exhaust gas outlet to convey a nitrogen enriched combustion product stream that forms when a mixture of air and a gasoline-based fuel is ignited within the combustion chamber;
 - flow control conduit cooperative with the separator and the exhaust gas
 - 20 recirculation flowpath such that the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath, the nitrogen enriched air stream from the separator, or both, are placed in selective fluid communication with the air inlet;
 - a plurality of sensors configured to acquire engine operating parameters; and

a combustion air enrichment controller in signal communication with the sensors such that (i) during compression of air within each combustion chamber, gasoline-based fuel is selectively introduced in a staged manner to give a mixture of fuel and air that has both locally stoichiometric and globally stratified properties for compression
5 ignition and (ii) the separator, exhaust gas recirculation flowpath, flow control conduit, sensors and controller cooperate to deliver to the air inlet (a) the oxygen enriched air stream from the separator during a cold start and warm-up load on the GCI engine and (b) the nitrogen enriched air stream from the separator and the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath, wherein during
10 an increase in engine load not associated with the engine cold start and warm-up loads, the controller provides an instruction set where the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided at least partially by the nitrogen enriched air stream from the separator and increasingly the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath.

15

2. The GCI engine of claim 1, wherein the inlet air management system is configured such that the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is never exclusively provided by the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath.

20

3. The GCI engine of claim 1, wherein when the increase in engine load not associated with the cold start and warm-up load corresponds to an engine mean effective pressure of below about two bar, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided substantially exclusively by the

separator.

4. The GCI engine of claim 1, wherein when the increase in engine load not associated with the cold start and warm-up load corresponds to an engine mean
5 effective pressure of between about two bar and about seven bar, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided primarily by the separator.

5. The GCI engine of claim 1, wherein when the increase in engine load not
10 associated with the cold start and warm-up load corresponds to an engine mean effective pressure of greater than about seven bar, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided by both the separator and exhaust gas recirculation flowpath.

15 6. The GCI engine of claim 1, further comprising a spark igniter disposed within the head for selectively igniting a mixture of air and a gasoline-based fuel that is introduced into the combustion chamber, the spark igniter configured such that the selectively igniting only during the cold start or warm-up loads on the engine.

20 7. The GCI engine of claim 6, wherein the controller is configured such that no nitrogen enriched air stream is delivered to the air inlet during the cold start or warm-up loads on the engine.

8. The GCI engine of claim 1, wherein the flow control conduit comprises at least

one valve disposed therein, the at least one valve configured to be actuated by a control signal from the controller.

9. The GCI engine of claim 1, wherein the separator is disposed within the inlet air
5 management system as a line-replaceable unit.

10. The GCI engine of claim 9, wherein the line-replaceable unit forms a modular assembly that contains the separator and an air filter.

10 11. The GCI engine of claim 1, further comprising:
an engine block defining a plurality of cylinders each of which define a volumetric space of a respective one of the combustion chambers;
a crankshaft rotatably movable within the block and coupled to the pistons each of which are disposed within a respective one of the cylinders such that upon
15 compression ignition of the mixture, a resulting reciprocating motion of the pistons imparts rotational motion to the crankshaft;
a plurality of cams responsive to movement of the crankshaft;
a head coupled to the engine block to define the plurality of combustion chambers, the head comprising at least one inlet valve and at least one exhaust valve
20 disposed therein such that each of the valves are movably responsive to the crankshaft through a corresponding one of the cams; and
a fuel inlet in selective fluid communication with each of the combustion chambers through the fuel injector.

12. A vehicle comprising:
- a platform comprising a wheeled chassis that defines a passenger compartment therein; and
 - 5 a gasoline compression ignition (GCI) engine coupled to the platform to deliver motive power thereto, the GCI engine comprising:
 - a plurality of combustion chambers each with a piston movably disposed therein;
 - at least one fuel injector in selective fluid communication with each of the
 - 10 combustion chambers;
 - an air inlet in selective fluid communication with each of the combustion chambers;
 - an exhaust gas outlet in selective fluid communication with each of the combustion chambers; and
 - 15 an inlet air management system comprising:
 - a membrane-based separator in fluid communication with the air inlet such that air introduced to the separator is operated thereupon to be split into at least an oxygen enriched air stream and a nitrogen enriched air stream;
 - an exhaust gas recirculation flowpath in fluid communication with the exhaust
 - 20 gas outlet to convey a nitrogen enriched combustion product stream that forms when a mixture of air and a gasoline-based fuel is ignited within the combustion chamber;
 - flow control conduit cooperative with the separator and the exhaust gas recirculation flowpath such that the nitrogen enriched combustion product stream from

the exhaust gas recirculation flowpath, the nitrogen enriched air stream from the separator, or both, are placed in selective fluid communication with the air inlet;

a plurality of sensors configured to acquire engine operating parameters; and

a combustion air enrichment controller in signal communication with the sensors

5 such that (i) during compression of air within each combustion chamber, the fuel is selectively introduced in a staged manner to give a mixture of fuel and air that has both locally stoichiometric and globally stratified properties for compression ignition and (ii) the separator, exhaust gas recirculation flowpath, flow control conduit, sensors and controller cooperate to deliver to the air inlet (a) the oxygen enriched air stream from
10 the separator during a cold start and warm-up load on the GCI engine and (b) the nitrogen enriched air stream from the separator and the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath, wherein during an increase in engine load not associated with the engine cold start and warm-up loads, the controller provides an instruction set where varying portions of the exhaust gas
15 emissions reduction is provided by the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath and the nitrogen enriched air stream from the separator.

13. The vehicle of claim 12, wherein a portion of the flow control conduit is in
20 selective fluid communication with the passenger compartment to deliver at least a portion of the oxygen enriched air stream is conveyed to the passenger compartment.

14. The vehicle of claim 13, wherein the oxygen enriched air stream is conveyed to

the passenger compartment during all engine loads not associated with the engine cold start and warm-up loads.

15. The vehicle of claim 12, wherein the varying portions of the exhaust gas
5 emissions reduction is determined by the controller based on an engine mean effective pressure such that:

in a first engine mean effective pressure range, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided substantially exclusively by the separator;

10 in a second engine mean effective pressure range, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided primarily by the separator; and

in a third engine mean effective pressure range, the nitrogen enriched air supply that is used for the exhaust gas emissions reduction is provided by both the separator
15 and exhaust gas recirculation flowpath.

16. The vehicle of claim 12, wherein the inlet air management system is further configured such that the oxygen enriched air stream is delivered to the air inlet only during the cold start or warm-up loads on the engine.

20

17. A method of operating a GCI engine, the method comprising:

introducing a gasoline-based fuel to a plurality of combustion chambers within the GCI engine, wherein each of the combustion chambers are defined at least in part by a cylinder with a piston movably disposed therein; and

providing an inlet air management system comprising:

a membrane-based separator;

an exhaust gas recirculation flowpath;

flow control conduit cooperative with the separator and the exhaust gas

5 recirculation flowpath;

a plurality of sensors configured to acquire engine operating parameters; and

a combustion air enrichment controller in signal communication with the sensors

and the flow control conduit;

using the inlet air management system to introduce air into a membrane-based

10 separator;

separating the introduced air into at least an oxygen enriched air stream and a

nitrogen enriched air stream;

compressing at least a portion of one of the oxygen enriched air stream and the

nitrogen enriched air stream within each combustion chamber and selectively

15 introducing the fuel in a staged manner to give a mixture of fuel and air that has both

locally stoichiometric and globally stratified properties for compression ignition; and

adjusting a combustion rate within the GCI engine by delivering at least a

portion of the nitrogen enriched air stream from the separator and a nitrogen enriched
combustion product stream from the exhaust gas recirculation flowpath to the plurality

20 of combustion chambers, wherein during an increase in engine load not associated with

a cold start or warm-up load, the controller provides an instruction set where the

nitrogen enriched air supply that is used for the exhaust gas emissions reduction is

provided at least partially by the nitrogen enriched air stream from the separator and

increasingly the nitrogen enriched combustion product stream from the exhaust gas recirculation flowpath.

18. The method of claim 17, wherein during an increase in engine load that is
5 associated with a cold start or warm-up load, the controller provides an instruction set where the oxygen enriched air stream from the separator is provided to the plurality of combustion chambers.

19. The method of claim 18, wherein during the increase in engine load that is
10 associated with a cold start or warm-up load, the controller provides an instruction set where no nitrogen enriched air stream is provided to the plurality of combustion chambers.

20. The method of claim 17, wherein the oxygen enriched air stream is supplied by
15 the separator to increase a flame propagation combustion rate within the combustion chamber during at least one of GCI engine cold start and GCI engine warm-up.

21. The method of claim 17, wherein the emissions reduction of an exhaust gas comprises a NO_x emission reduction.
20

22. The method of claim 17, wherein the adjusting a combustion rate within the GCI engine comprises diluting an air intake charge into the combustion chambers.

23. The method of claim 17, wherein the adjusting a combustion rate within the GCI engine comprises speeding up the transient control response of the GCI engine.