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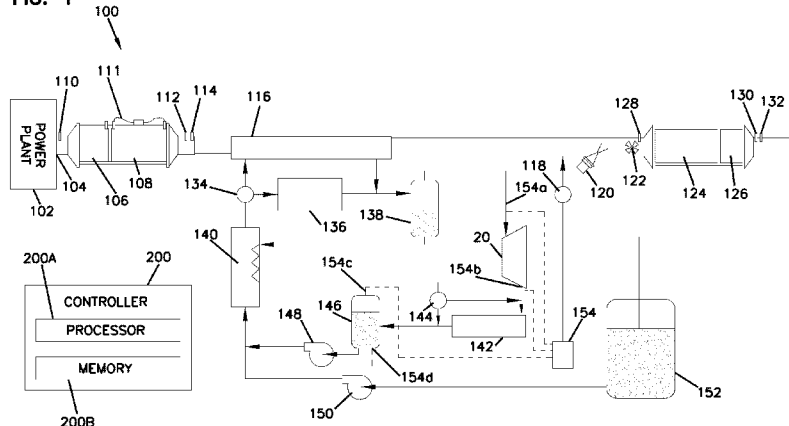
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(54) Title: WASTE HEAT RECOVERY SYSTEM WITH UREA-BASED EXHAUST AFTERTREATMENT

FIG. 1



(57) Abstract: An advanced aftertreatment concept is presented that utilizes gaseous NH_3 injection and a waste heat recovery system having volumetric expander which captures waste heat energy from an internal combustion engine via a working fluid. The NH_3 comes from the waste heat recovery system's working fluid and is immediately available without the need for a warm-up period on cold start. The consumed NH_3 is automatically re-charged in the waste heat recovery system by on-board DEF. The proposed WHR uses $\text{NH}_3\text{-H}_2\text{O}$ as the working fluid. $\text{NH}_3\text{-H}_2\text{O}$ has very favorable thermodynamics for a waste heat recovery application. A method of control is also presented that maintains an appropriate ammonia level and concentration in the system.

**WASTE HEAT RECOVERY SYSTEM WITH UREA-BASED EXHAUST
AFTERTREATMENT**

Cross-Reference to Related Applications

[0001] This application is being filed on February 3, 2017 as a PCT International Patent Application and claims the benefit of U.S. Patent Application Serial No. 62/291,903, filed on February 5, 2016, and claims the benefit of U.S. Patent Application Serial No. 62/313,994, filed on March 28, 2016, the disclosures of which are incorporated herein by reference in their entireties.

Technical Field

[0002] This application relates to engine systems. More specifically, the application is directed to optimized control of waste heat recovery and exhaust aftertreatment systems associated with a power plant.

Background

[0003] Today's on-road heavy-duty diesel engines meet EPA 2010 NO_x emissions regulations (0.20 g/bhp-hr) with the use of DEF-SCR (diesel exhaust fluid – selective catalytic reduction) aftertreatment systems. The current DEF-SCR system is ineffective at the low exhaust temperatures that occur during cold start, extended idling, and low speed operations because the urea in DEF has issues with fully decomposing and hydrolyzing into ammonia (NH₃) at exhaust gas temperatures below 200°C. Furthermore, if DEF is injected at exhaust gas temperatures below 200°C, solid deposits, such as ammonium nitrate and/or ammonium sulfate, are formed over the catalyst and exhaust system. The solid deposits degrade the NO_x conversion efficiency. Alternative sources of NH₃ that could enable SCR conversion at temperatures below 200°C include solid NH₃ precursors and heated NH₃ generation from DEF. Both of these alternatives require a cold start warm-up period before being able to deliver gaseous NH₃. Neither of these alternatives have become widely adopted.

[0004] Recently developed WHR systems for heavy duty vehicle applications have demonstrated 3 to 8% fuel economy improvement and are differentiated by the expander technology and working fluid. Those expanders have focused on turbine, scrolls and piston devices. Although turbine expanders are mature and can be highly efficient in a narrow operating range, they require additional cost and weight for a speed reduction gear

box and hydraulic dampeners to accommodate their turbines higher operating speeds (~100,000 rpm). Scroll and piston expanders are lower speed devices but are more costly and have higher parasitic losses. Working fluid evaluations have focused on refrigerants, alcohols, and hydrocarbons. Despite having good thermodynamic efficiencies, hydrocarbons and alcohols have fallen out of favor due to flammability concerns. Refrigerants appear to be the favored working fluid but they high global warming potential so their use could be limited or banned in the near future.

[0005] Additionally, future Heavy Duty (HD) vehicle regulations are expected to establish allowable Green House Gas (GHG) emissions. These GHG regulations essentially set CO₂ emissions limits which translate to fuel economy requirements. Waste Heat Recovery (WHR) is one of the technologies that can help engine and vehicle original equipment manufacturers (OEMs) meet these targets. However, the incremental cost of the WHR systems can be high and the corresponding pay-back period may be too long for the end-user to justify the purchase of the WHR system. Additionally, there is a general concern that the WHR systems will make cold start and low speed, low load operating exhaust gas conditions even more challenging for DEF-SCR systems to meet NO_x emissions standard.

Summary

[0006] The teachings presented herein propose to integrate the WHR system with a urea Selective Catalytic Reduction (SCR) aftertreatment system to provide the end-user with the WHR fuel economy benefit while lowering the incremental WHR cost (through Aftertreatment cost reduction). This approach has the potential to improve the pay-back period to further justify the installation of WHR systems and further reducing tailpipe NO_x emissions. .

[0007] The present teachings include a systems approach combining advanced aftertreatment with engine exhaust waste heat recovery (WHR) to simultaneously reduce NO_x and GHG emissions from heavy duty diesel vehicles. The advanced aftertreatment system will use gaseous ammonia (NH₃) injection with low temperature selective catalytic reduction (SCR) catalysts and thermal management to reduce NO_x emissions during cold start and low load, low speed operations and diesel exhaust fluid (DEF) augmented with aqueous ammonia (NH₃) injection to maintain high SCR conversion efficiency at high speed-high temperature operation. The NH₃ is sourced from the Kalina Cycle WHR

system using ammonia-water ($\text{NH}_3\text{-H}_2\text{O}$) as the working fluid and a Roots-type or volumetric expander. The $\text{NH}_3\text{-H}_2\text{O}$ working fluid charge is maintained by automatically re-charging the WHR system with on-board DEF. The DEF (a solution of 32.5% urea and 67.5% de-ionized water) will thermal decompose to NH_3 , H_2O and carbon dioxide (CO_2) when heated above 135°C within the WHR system. The working fluid mixture of $\text{NH}_3\text{-H}_2\text{O}$ offers excellent thermodynamic efficiencies in the Kalina Cycle. The Roots expander is ideally matched the high volumetric flow and “wet” working fluid conditions. The low speed Roots expander is coupled to the engine’s crank, or optionally to a motor/generator, where the recovered energy is realized, improving fuel economy and reducing GHG emissions.

[0008] The present teachings aim to reduce NO_x emissions from an EPA 2010 compliant on-road heavy-duty diesel engine by 90% from 0.20 grams per brake horsepower-hour (g/bhp-hr) to 0.02 g/bhp-hr. A majority of this reduction will be achieved by significantly reducing NO_x emissions during cold start and during low load, low speed operations where today’s DEF-SCR systems are ineffective because the exhaust temperature is too low (less than 200°C) to inject DEF. The proposed concept will use gaseous NH_3 injection, thermal management, and various combinations of high porosity/high cell density catalyst structures, closed coupled catalysts, NO_x storage on the catalyst, NH_3 storage on the catalyst and new generation copper-zeolite SCR catalysts to significantly reduce NO_x at low temperatures (down to 150°C). Testing has shown that the current state SCR catalyst technology is capable of higher NO_x conversion during the cold FTP cycle if NH_3 is present during the early stages of the cycle.

[0009] The present teachings also aim to improve the fuel economy of MY2014 on-road heavy-duty diesel engine. Simple 1D simulations of a typical engine operating at B50 conditions predicts the proposed WHR system will improve fuel economy to a noteworthy extent even though predictive calculations are conservative in that they do not account for or take advantage of the non-azeotropic characteristics of $\text{NH}_3\text{-H}_2\text{O}$.

[0010] Additional objects and advantages will be set forth in part in the description which follows, and in part will be obvious from the description, or may be learned by practice of the teachings presented herein. The objects and advantages will also be realized and attained by means of the elements and combinations particularly pointed out in the appended claims. It is to be understood that both the foregoing general description

and the following detailed description are exemplary and explanatory only and are not restrictive of the claimed invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] Figure 1 is a schematic view of a power generation system, which is an example in accordance with aspects of the invention.

[0012] Figure 2 is a schematic view of a variation of the power generation system of Figure 1, wherein a single heat exchanger with diverter valves is used in the exhaust.

[0013] Figure 3 is a schematic view of a variation of the power generation system of Figure 1, wherein two heat exchangers is used in the exhaust.

[0014] Figure 4 is a schematic side view of an expander usable in the power generation system shown in Figure 1.

[0015] Figure 5 is a schematic perspective view of the expander shown in Figure 3.

[0016] Figure 6 is a schematic of a process flow diagram for operating the system of Figures 1, 2 or 3.

DETAILED DESCRIPTION

[0017] Reference will now be made in detail to the examples which are illustrated in the accompanying drawings. Wherever possible, the same reference numbers will be used throughout the drawings to refer to the same or like parts.

[0018] The proposed advanced aftertreatment concept will utilize gaseous NH_3 injection, thermal management, and various combinations of high porosity/high cell density catalyst structures, closed coupled catalysts, NO_x storage on the catalyst, NH_3 storage on the catalyst and new generation copper-zeolite SCR catalysts to address the low temperature ineffectiveness of today's DEF-SCR systems. The NH_3 comes from the WHR system's working fluid and is immediately available without the need for a warm-up period on cold start. The consumed NH_3 is automatically re-charged in the WHR system by on-board DEF. The proposed WHR uses $\text{NH}_3\text{-H}_2\text{O}$ as the working fluid. $\text{NH}_3\text{-H}_2\text{O}$ has very favorable thermodynamics for this WHR application. Furthermore, the WHR system employs a low speed volumetric expander that does not require complex or costly speed

reduction gearboxes or hydraulic dampeners. The expander's wide performance map and compatibility with "wet" working fluid conditions enables a more robust system that can better leverage the favorable thermodynamics of the $\text{NH}_3\text{-H}_2\text{O}$ working fluid and maximize the fuel economy improvement.

General System Architecture

[0019] Referring to Figure 1, a power generation system or engine system 100 is shown. In one aspect, the power generation system includes a power plant 102. The power plant 102 may be an internal combustion engine, for example a diesel or fuel engine. In the example shown, the power plant 102 is a diesel engine. The power plant develops an exhaust gas stream at an exhaust outlet pipe 104. The exhaust gas stream can be received by a diesel oxide catalyst (DOC) 106 and a diesel particulate filter (DPF) 108. A temperature sensor 110 may be provided upstream of the DOC 106 and the DPF 108 while a temperature sensor 112 may be provided downstream of the DOC 106 and the DPF 108. A NO_x sensor 114 may also be placed downstream of the DOC 106 and the DPF 108. A differential pressure sensor 111 may also be provided to monitor the status of the DPF filter 108. Further downstream in the exhaust outlet pipe 104 a heat exchanger or tail-pipe boiler 116 may be provided. The boiler 116 is utilized to extract heat from the exhaust gas stream, as is explained in further detail below. Downstream of the boiler 116 is an ammonia injector 118, a diesel exhaust fluid (DEF) injector 120, and a mixer 122. The configuration and operation of these components is discussed in further detail below. Further downstream emissions components are provided in the form of a selective catalytic reduction (SCR) converter 124 and an ammonia oxidation catalyst (AOC) converter 126. Temperature sensors 128, 130 and a second NO_x sensor 132 can also be provided, as shown.

[0020] The heat extracted from the exhaust gas stream at the boiler 116 can be utilized to drive a Kalina cycle utilizing an ammonia and water mixture as the working fluid. The use of an ammonia-water working fluid is advantageous in that the fluid can be simultaneously utilized as a working fluid for recovering waste heat from the exhaust system and as a fluid for exhaust aftertreatment. Starting at a diverter valve 134, the working fluid can be selectively delivered to either the boiler 116 or to an EGR boiler 136 to raise the temperature of the working fluid. In some examples, only the EGR boiler 136 is provided without the use of the boiler 116. In other examples, only the boiler 116 is

provided without the use of the EGR boiler 136. As shown, the system utilizes both the EGR boiler 136 and the tailpipe boiler 116. Downstream of the boilers 116, 136, the working fluid is combined and directed to a separator 138 wherein the liquid phase working fluid is delivered to a recuperator 140 to preheat the working fluid delivered to the diverter valve 134 and wherein the gas phase working fluid is delivered to an expander 20. The phase separator 138 is utilized to vary and control the ratio of gas to liquid phase entering the expander 20, getting just enough liquid to act as a sealing agent in the expander without adding excessive friction. Optionally, a portion of the liquid from the separator 138 (lean in ammonia) can be mixed with the expander outlet working fluid. The resulting stream is condensed in the condenser 142. Lowering the mass fraction of ammonia in the working fluid before the condenser 142 lowers the condensing pressure of the working fluid and allows the expander to be expanded to a lower pressure. In this manner, the use of the separator 138 can help the expander match the operating speed of the engine by controlling the volume of gas feeding the volumetric expander.

[0021] The expander 20 extracts energy from the working fluid and converts the energy to rotational power which can be utilized to drive a motor/generator or to deliver power directly back into the engine 102, such as through the engine front end accessory drive. Further details regarding the expander 20 are shown at Figures 4 and 5 and described in a following section.

[0022] From the expander 20, the working fluid is delivered to a condenser 142 to fully transition the working fluid to a liquid state. Downstream of the condenser 142, the working fluid is combined with the working fluid leaving the recuperator 140 that had been fed from the separator 138. A splitter valve 144 can be provided to divert some of the working fluid from the recuperator 140 to upstream of the condenser 142. By delivering an amount of liquid working fluid to the expander exit, the pressure in the system can be lowered to increase the output of the expander 20. In other arrangements, the splitter valve 144 can direct liquid working fluid to the expander inlet. In yet another arrangement, the splitter valve 144 can direct liquid working fluid (lean in ammonia) to the ammonia collection manifold 154. The combined working fluid after the condenser 142 is delivered to a storage tank 146. From the storage tank 146, the working fluid is delivered to the recuperator 140 via a pump 148. The pumped working fluid in the recuperator 140, which is a liquid-to-liquid heat exchanger, is heated by the working fluid

and delivered to the recuperator 140 from the separator 138 and then directed to the diverter valve 134 to complete the cycle.

[0023] The system 100 is also shown as including a diesel exhaust fluid (DEF) storage tank 152, which holds a DEF fluid. In one example, the DEF fluid is an aqueous urea solution made with 32.5% urea and 67.5% deionized water. The DEF fluid can be pumped from the tank to the DEF injector 120 such that the DEF fluid is introduced directly into the exhaust gas stream. The DEF fluid is also shown as being pumped from the tank 152 via a pump 150 that is in parallel to the working fluid pump 148 such that pumped fluid from the pumps 148, 150 is combined upstream of the recuperator 140. The DEF fluid from the pump 150 is used to charge and recharge the system 100 such that the working fluid level is maintained. The DEF fluid will decompose to NH_3 , CO_2 , and H_2O in the system 100 and will operate as an ammonia/water working fluid.

[0024] An ammonia collection manifold 154 is also shown as being provided in the system 100 and can be configured to receive ammonia from numerous locations (e.g. 154a, 154b, 154c, 154d, 154e) within the system 100, for example, from the upper and lower regions of the tank 146 and from upstream and downstream of the expander 20. The system can be configured to utilize all or some of the depicted collection points. Depending on the chosen location of the collection points, a gas based ammonia doser or a liquid based ammonia doser can be utilized. In one example, collection points 154a, 154b at the inlet and outlet of the expander 20 and the collection point 154c at the head of the tank 146 can feed a gas based doser while the collection point 154d depicted at the bottom of the tank 146 and the collection point 154e depicted at the splitter valve 144 can utilize a liquid based doser. The ammonia gases and/or liquid collected at the ammonia collection manifold 154 can be delivered to the ammonia injector 118 and subsequently injected into the exhaust gas stream.

Waste Heat Recovery Device 20

[0025] Referring to Figures 4 and 5, further aspects of the waste heat recovery device or expander 20 are shown. While some details of the expander 20 are discussed in this subsection, additional structural and operational aspects can be found in Patent Cooperation Treaty (PCT) International Publication Number WO 2014/144701 and in United States Patent Application Publication US 2014/0260245, the entireties of which are incorporated herein by reference.

[0026] In general, the volumetric energy recovery device or expander 20 relies upon the kinetic energy and static pressure of a working fluid to rotate an output shaft 38. With continued reference to Figures 4 and 5, it can be seen that the expander 20 has a housing 22 with a fluid inlet 24 and a fluid outlet 26 through which the working fluid 12-1 undergoes a pressure drop to transfer energy to the output shaft 38. The output shaft 38 is driven by synchronously connected first and second interleaved counter-rotating rotors 30, 32 which are disposed in a cavity 28 of the housing 22. Each of the rotors 30, 32 has lobes that are twisted or helically disposed along the length of the rotors 30, 32. Upon rotation of the rotors 30, 32, the lobes at least partially seal the working fluid 12-1 against an interior side of the housing at which point expansion of the working fluid 12-1 only occurs to the extent allowed by leakage which represents an inefficiency in the system. In contrast to some expanders that change the volume of the working fluid when the fluid is sealed, the volume defined between the lobes and the interior side of the housing 22 of device 20 is constant as the working fluid 12-1 traverses the length of the rotors 30, 32. Accordingly, the expander 20 may be referred to as a “volumetric device” as the sealed or partially sealed working fluid volume does not change.

[0027] In the particular example shown at Figures 4 and 5, the expander 20 inlets and outlets are configured for use with a relatively low pressure working fluid, such as an ammonia and water mixture. However, the following description is generally applicable for use with any type of a working fluid. The expander 20 includes a housing 22. The housing 22 includes an inlet port 24 configured to admit relatively high-pressure working fluid 12-1 from the heat exchangers 116/136. The housing 22 also includes an outlet port 26 configured to discharge working fluid 12-2 to the condenser 142. It is noted that the working fluid discharging from the outlet 26 is at a relatively higher pressure than the pressure of the working fluid at the condenser 142.

[0028] As additionally shown in Figure 5, each rotor 30, 32 has four lobes, 30-1, 30-2, 30-3, and 30-4 in the case of the rotor 30, and 32-1, 32-2, 32-3, and 32-4 in the case of the rotor 32. Although four lobes are shown for each rotor 30 and 32, each of the two rotors may have any number of lobes that is equal to or greater than two, as long as the number of lobes is the same for both rotors. Accordingly, when one lobe of the rotor 30, such as the lobe 30-1 is leading with respect to the inlet port 24, a lobe of the rotor 32,

such as the lobe 30-2, is trailing with respect to the inlet port 24, and, therefore with respect to a stream of the high-pressure 12-1.

[0029] As shown, the first and second rotors 30 and 32 are fixed to respective rotor shafts, the first rotor being fixed to an output shaft 38 and the second rotor being fixed to a shaft 40. Each of the rotor shafts 38, 40 is mounted for rotation on a set of bearings (not shown) about an axis X1, X2, respectively. It is noted that axes X1 and X2 are generally parallel to each other. The first and second rotors 30 and 32 are interleaved and continuously meshed for unitary rotation with each other. With renewed reference to Figure 4, the expander 20 also includes meshed timing gears 42 and 44, wherein the timing gear 42 is fixed for rotation with the rotor 30, while the timing gear 44 is fixed for rotation with the rotor 32. The timing gears 42, 44 are configured to retain specified position of the rotors 30, 32 and prevent contact between the rotors during operation of the expander 20.

[0030] The output shaft 38 is rotated by the working fluid 12 as the working fluid under goes expansion from the relatively high-pressure working fluid 12-1 to the relatively low-pressure working fluid 12-2. As may additionally be seen in both Figures 4 and 6, the output shaft 38 extends beyond the boundary of the housing 22. Accordingly, the output shaft 38 is configured to capture the work or power generated by the expander 20 during the expansion of the working fluid 12 that takes place in the rotor cavity 28 between the inlet port 24 and the outlet port 26 and transfer such work as output torque from the expander 20. Although the output shaft 38 is shown as being operatively connected to the first rotor 30, in the alternative the output shaft 38 may be operatively connected to the second rotor 32. In one aspect, the expander 20 can also be operated as a high volumetric efficiency positive displacement pump when driven by a motor/generator.

[0031] As the disclosed expander 20 is configured for use with an ammonia based working fluid, appropriate material selection for the expander 20 is important. Low-chromium metals may be preferred for the housing, rotors, shafts, bearings, and seals as ammonia can leach chromium out of certain materials. As such, low chromium steel, ductile iron, coated aluminum, and composites may be preferable materials for the construction of the components of the expander 20. Some stainless steels may also be utilized.

Controller

[0032] Referring to back to Figure 1, an electronic controller 200 is schematically shown as including a processor 200A and a non-transient storage medium or memory 200B, such as RAM, flash drive or a hard drive. Memory 200B is for storing executable code, the operating parameters, and potential inputs from an operator interface, while processor 200A is for executing the code. Electronic controller 200 is configured to be connected to a number of inputs and outputs that may be used for implementing the bypass operational modes. For example, the electronic controller 200 can receive information from a vehicle control area network (CAN) bus and information from sensors associated with the power generation system 100. For example, and as noted above, temperature sensors 110, 112, 128, 130, NO_x sensors 114, 132 and pressure differential sensors 111 can provide inputs to the controller 200 while the controller 200 can send outputs to the pumps 148, 150, valves 134, 144, and injectors 118, 120. One skilled in the art will understand that many other inputs and outputs can be provided to further implement the methods presented herein, particularly with respect to the waste heat recovery device or expander 20. For example, a level sensor can be placed in the working fluid storage tank and in the DEF tank.

System Operation

[0033] During operation, the ammonia injector 118 and the DEF injector 120 can be selectively operated based on selected system parameters, such as the exhaust gas temperatures. Exhaust temperature can be utilized as an input to the WHR control system. The WHR and aftertreatment controls are integrated to optimize waste heat recovery while efficiently reducing NO_x at low temperature (gas phase NH₃ injection) and maintaining the WHR NH₃ concentration (periodically injecting ammonia lean liquid at high exhaust temperatures).

[0034] Under low exhaust temperature conditions (less than 200°C), the system 100 can be operated such that gas phase NH₃, CO₂ and H₂O can be siphoned off at the ammonia collection manifold 154 to dose the SCR 124 via the injector 118 instead of using the DEF injector. Under high exhaust temperature conditions, the system 100 can be operated to siphon-off liquid phase NH₃, CO₂ and H₂O from the working fluid tank 146 or splitter valve 144. The heat of vaporization of H₂O will help lower the exhaust gas temperature, keeping the SCR catalyst 124 in its optimal, high efficiency temperature

window. This will also balance the gas phase NH_3 , CO_2 and H_2O removal and keep the ammonia concentration in the working fluid within a target range.

[0035] In one operational strategy, the tailpipe boiler 116 is utilized as much as possible to lower SCR inlet temperature, keeping the SCR catalyst 124 in its optimal, high efficiency temperature window.

[0036] Referring to Figure 6, a schematic is shown detailing an exemplary control strategy. The disclosed control strategy addresses the circumstance of the concentration of ammonia in the gas phase being richer than the concentration of ammonia in the liquid phase. If the ammonia gas phase is preferentially siphoned off, then the ammonia concentration in the WHR can become more and more lean over time. The method of Figure 6 described in the following paragraphs operates to control the usage of ammonia gas versus ammonia liquid for NO_x reduction whereby the ammonia concentration in the WHR working fluid can be maintained over time.

[0037] Starting with input parameters from the engine ECU (1) and aftertreatment sensors (2), the ammonia demand calculation (3) determines the mass of ammonia (NH_3) required to reduce the NO_x in exhaust flow. Calculations in (3) can be based on exhaust flow from the engine's speed/torque map within the engine ECU (1), exhaust temperature from the aftertreatment sensors (2) and NO_x concentration from either or both the engine ECU (1) and/or aftertreatment sensors (2). It is known that the ideal NH_3 to NO_x ratio is 1 but this ratio can be adjusted via input (4) to a lower value for example to minimize ammonia slip at the tailpipe or a higher value for example to maximize NO_x reduction. This ratio can also be adjusted to account for the NO/NO_2 ratio characteristics of a particular engine.

[0038] The mass of ammonia (NH_3) from (3) feeds into gaseous ammonia dosage calculation (5) and liquid ammonia dosage calculation (6). Gaseous ammonia dosage calculation (5) takes the mass ammonia demand, WHR working fluid temperature and pressure in the ammonia tank from the ammonia tank sensors (7) and the nominal ammonia concentration from the ammonia tank monitor (8) and determines appropriate amount of gaseous ammonia that needs to be dosed. Similarly, liquid ammonia dosage calculation (6) takes the mass ammonia demand, WHR working fluid temperature and pressure in the ammonia tank from ammonia tank sensors (7) and the nominal ammonia

concentration from the ammonia tank monitor (8) and determines appropriate amount of liquid ammonia that needs to be dosed.

[0039] With the required gaseous ammonia and liquid ammonia that needs to be dosed, the control determines to dose either gaseous or liquid or a combination of the two in (9) based on the nominal ammonia concentration from the ammonia tank monitor (8) and exhaust temperature from the aftertreatment sensors (2). For example, if the exhaust temperature is less than a threshold temperature, say 230°C, the control (9) will elect to dose gaseous ammonia. If the exhaust temperature is greater than the threshold temperature of 230°C, then the control (9) could elect to dose gaseous or liquid ammonia (or a combination of the two) depending on the nominal concentration in the ammonia tank from the ammonia tank monitor (8). Say for example the nominal ammonia concentration was lean due to high usage of gaseous ammonia for low exhaust temperature operation. Then control (9) will elect to dose the liquid ammonia. Since liquid ammonia is leaner than gaseous ammonia, this would increase the nominal ammonia concentration in the working fluid. If the nominal ammonia concentration was rich due to high usage of liquid ammonia for high exhaust temperature operation, the control (9) will elect to dose gaseous ammonia. Since the gaseous ammonia is richer than liquid ammonia, this would decrease the nominal ammonia concentration in the working fluid.

[0040] The output of control (9) feeds an ammonia doser (10) which can be calibrated for gaseous and liquid injection. The doser would open to provide the required gaseous or liquid ammonia.

[0041] Ammonia tank monitor (8) is a continuous mass balance calculation of ammonia tank level (charge of working fluid) and nominal ammonia concentration. This continuous calculation starts by assuming a nominal ammonia concentration based on the urea-water thermal decomposition and hydrolysis from DEF. Then the monitor (8) accounts for the gaseous and liquid ammonia dosed and the dosed amount impact on nominal ammonia concentration. The monitor (8) also determines when the WHR needs to be refilled, primarily based on the ammonia tank level versus the desired working fluid charge. Any refilled DEF is also accounted for by the monitor. The monitor may be periodically calibrated against a sensor in the tank, such as a liquid level sensor.

[0042] The WHR working fluid refill demand signal from ammonia tank monitor (8) feeds decision box (11). Decision box (11) determines when to turn on the DEF refill pump to add more urea-water to the WHR. Several key inputs are required before allowing the DEF pump to turn on. For example, the DEF tank sensors (12) are needed to determine if there is sufficient DEF in the tank and if the tank is frozen or thawed. Also, the decision box (11) considers the WHR conditions such as working fluid flow rate and temperature from WHR sensors (13) where the urea thermal decomposition and hydrolysis will take place in the WHR loop. A hydrolysis catalyst may be included to help ensure complete hydrolysis to ammonia. The intent is to avoid low temperature conditions where only the urea only partially decomposes or hydrolyzes and start forming solids on the cooler surfaces within the WHR loop.

Design Variations

[0043] Referring to Figure 2, a design variation of the system 100 is shown including a diesel oxidation catalyst DOC, a diesel particulate filter DPF, a selective catalytic reduction catalytic converter SCR, and an ammonia oxidation catalyst AOC. In this variant, there is a single heat exchanger HX with diverter valves V1, V2 in the exhaust. During low exhaust temperature conditions (cold start, low-speed/load operation), the valves V1, V2 will be positioned so that the gas exiting the DPF flows directly to the SCR where ammonia (NH₃) and/or DEF can be injected into the exhaust. The heat exchanger HX will capture heat from downstream of the AOC and transfer the heat to the working fluid WF. During high exhaust temperature conditions (high-speed/load operation), the valves will be positioned so that the gas exiting the DPF flows through the heat exchanger before entering the SCR. The working fluid flow rate will dictate the heat removed from the exhaust and thereby manage the temperature entering the SCR, keeping the SCR near its optimal NO_x conversion efficiency temperature.

[0044] Referring to Figure 3, a design variation of the system 100 is shown including a diesel oxidation catalyst DOC, a diesel particulate filter DPF, a selective catalytic reduction catalytic converter SCR, and an ammonia oxidation catalyst AOC. In this variant, there are two heat exchangers HX1, HX2 in the exhaust. HX1 is a relatively small heat exchanger between the DPF and SCR and HX2 is a relatively larger heat exchanger downstream of the AOC. During low exhaust temperature conditions (cold start, low-speed/load operation), the all the working fluid WF flow will be directed to HX2

to capture waste heat and no working fluid flow will be directed to HX1 so that the gas exiting the DPF conserves as much heat as possible before entering the SCR. During high exhaust temperature conditions (high-speed/load operation), a high working fluid flow will be directed to HX1 to remove heat from the exhaust before entering the SCR and thereby manage the temperature entering the SCR, keeping the SCR near its optimal NO_x conversion efficiency temperature. Working fluid may be directed to heat exchanger HX2 as well.

[0045] The system 100 can also include variations on the types of catalyst (NO_x storage catalysis, ammonia storage catalyst, diesel particulate filter coated with NO_x SCR catalyst, etc.) utilized and variations on system configurations (close coupling of catalyst near the engine, multiple dosing locations for ammonia and/or DEF, supplemental exhaust heating with a burner or electrically heated catalyst, etc.). Those skilled in the art of exhaust aftertreatment understand there are multiple pathways to reducing NO_x in the engine's exhaust gas.

Summary

[0046] Benefits of the above described system are numerous. For example, an ammonia-water WHR working fluid has excellent thermodynamics with a temperature glide that can be manipulated for optimal performance. Also, the use of a phase separator can optimize Roots expander efficiency (controlling the amount of liquid phase to provide the optimum sealing benefit). The combined benefits of the teachings herein can result in a predicted 3 to 5% fuel economy improvement from waste heat recovery. Additionally, enabling low temperature NO_x reduction in the SCR by using ammonia reduces (or eliminates) the exhaust hydrolysis catalyst and lower aftertreatment cost. The use of a tailpipe boiler will lower peak exhaust temperatures at high NO_x flux points (C100, C75) and thereby reduce SCR size and lower aftertreatment cost. Other benefits exist as well.

[0047] The proposed concept offers a systems level approach to address the traditional NO_x/GHG trade-off design issue. Heavy-duty diesel engines will not be limited to increasing GHGs to achieve lower NO_x emissions or higher NO_x emissions to achieve lower GHGs. The NH₃-H₂O working fluid and expander WHR system will deliver significant improved fuel economy (lowering GHG emissions) that will help meet EPA's Phase 2 GHG emissions standards. The advanced aftertreatment system with 90% lower tailpipe NO_x emissions will enable OEMs to certify engines to 0.02 g/bhp-hr (at the

tailpipe), a level that the California Air Resources Board is recommending to the EPA. This performance can be achieved by the disclosed systems and methods, at least in part, through the generation and use of gas phase ammonia during engine cold start.

[0048] Other implementations will be apparent to those skilled in the art from consideration of the specification and practice of the examples and teachings presented herein. It is intended that the specification and examples be considered as exemplary only, with the true scope of the invention being indicated by the following claims.

WHAT IS CLAIMED IS:

1. A power generation system comprising:
 - a. a power plant having an exhaust outlet;
 - b. a waste heat recovery circuit having an ammonia-water working fluid, the waste heat recovery circuit including:
 - i. a heat exchanger in fluid communication with the exhaust outlet;
 - ii. a volumetric expander receiving and generating rotational power from the working fluid from the heat exchanger;
 - iii. a condenser receiving the working fluid from the expander, the condenser converting the working fluid to a liquid state;
 - iv. a first pump for delivering the liquid working fluid to the heat exchanger; and
 - c. an ammonia injector in fluid communication with the exhaust outlet and in fluid communication with the waste heat recovery circuit, the ammonia injector being adapted to inject gaseous phase ammonia collected from the waste heat recovery circuit.
2. The power generation system of any of the other claims, further including a separator in the waste heat recovery circuit.
3. The power generation system of any of the other claims, wherein the ammonia injector is adapted to inject either gaseous ammonia or liquid phase ammonia.
4. The power generation system of any of the other claims, wherein the ammonia injector is located at one of a first location upstream of a diesel oxide catalyst, between the diesel oxide catalyst and a diesel particulate filter, and downstream of the diesel particulate filter.
5. The power generation system of any of the other claims, wherein gaseous ammonia is preferentially injected at an exhaust temperature below a predefined setpoint associated with at least one of a cold start, a low speed, and a low load.

6. The power generation system of any of the other claims, wherein liquid phase ammonia is preferentially injected at an exhaust temperature above a predefined setpoint associated with a high engine speed and/or high engine load.
7. The power generation system of claim 6, wherein the predefined setpoint is about 300°C.
8. The power generation system of any of the other claims, wherein combined liquid ammonia and urea dosing occurs at an exhaust temperature setpoint.
9. The power generation system of any of the other claims, wherein the system is recharged with urea solution based on a working fluid level sensor in a working fluid storage tank.
10. The power generation system of any of the other claims, further including a urea solution storage tank and a second pump, the second pump delivering urea solution from the storage tank to the waste heat recovery circuit.
11. The power generation system of any of the other claims, further including a urea injector in fluid communication with the urea solution storage tank and in fluid communication with the exhaust outlet, the urea injector being separate from the ammonia injector.
12. A power generation system comprising:
 - a. a power plant having an exhaust outlet;
 - b. a waste heat recovery circuit having an ammonia-water working fluid, the waste heat recovery circuit including:
 - i. a heat exchanger in fluid communication with the exhaust outlet;
 - ii. a volumetric expander receiving and generating rotational power from the working fluid from the heat exchanger;
 - iii. a condenser receiving the working fluid from the expander, the condenser converting the working fluid to a liquid state;
 - iv. a first pump for delivering the liquid working fluid to the heat exchanger; and

- c. a urea solution storage tank and a second pump, the second pump delivering urea solution from the storage tank to the waste heat recovery circuit;
- d. an ammonia collection manifold in fluid communication with the waste heat recovery circuit, the ammonia collection manifold being configured to collect gas and liquid phase ammonia from at least one location within the waste heat recovery circuit; and
- e. an ammonia injector in fluid communication with the exhaust outlet and in fluid communication with the ammonia collection manifold.

13. The power generation system of claim 12, further including a separator in the waste heat recovery circuit.

14. The power generation system of claim 12 or 13, wherein the ammonia injector is adapted to inject either gaseous ammonia or liquid phase ammonia.

15. The power generation system of any of claims 12 to 14, wherein the ammonia injector is located at one of a first location upstream of a diesel oxide catalyst, between the diesel oxide catalyst and a diesel particulate filter, and downstream of the diesel particulate filter.

16. The power generation system of any of claims 12 to 15, wherein gaseous ammonia is preferentially injected at an exhaust temperature below a predefined setpoint associated with at least one of a cold start, a low speed, and a low load.

17. The power generation system of claim 12 or 16, wherein liquid phase ammonia is preferentially injected at an exhaust temperature above a predefined setpoint associated with a high engine speed and/or high engine load.

18. The power generation system of claim 16 or 17, wherein the predefined setpoint is about 300°C.

19. The power generation system of any of claims 12 to 18, wherein combined liquid ammonia and urea dosing occurs at an exhaust temperature setpoint.

20. The power generation system of any of claims 12 to 19, wherein the system is recharged with urea solution based on a working fluid level sensor in a working fluid storage tank.
21. The power generation system of any of claims 12 to 20, further including a urea solution storage tank and a second pump, the second pump delivering urea solution from the storage tank to the waste heat recovery circuit.
22. The power generation system of any of claims 12 to 21, further including a urea injector in fluid communication with the urea solution storage tank and in fluid communication with the exhaust outlet, the urea injector being separate from the ammonia injector.
23. A method of maintaining ammonia concentration in a waste heat recovery working fluid that is utilized in an expander and that is utilized to reduce NO_x levels in an exhaust gas stream associated with a power plant, the method comprising:
- a. determining a mass of ammonia working fluid required to be injected into the exhaust gas stream;
 - b. calculating a liquid ammonia working fluid dosage and a gaseous ammonia working fluid dosage;
 - c. determining whether to dose liquid ammonia, gaseous ammonia, or a combination of liquid and gaseous ammonia into the exhaust gas stream;
 - d. dosing the ammonia working fluid into the exhaust;
 - e. calculating a nominal ammonia working fluid concentration and level in an ammonia storage tank taking into account the ammonia phase and amount injected into the exhaust; and
 - f. adding a urea solution to the ammonia working fluid to maintain the nominal ammonia working fluid concentration and level.
24. The method of claim 23, further including the step of collecting ammonia from the waste heat recovery working fluid and delivering the collected ammonia to an ammonia injector.

25. The method of claim 23, wherein the step of adding a urea solution to the ammonia working fluid includes pumping urea solution from a storage tank into a waste heat recovery circuit within which the ammonia working fluid resides.

26. The method of any of claims 23 to 25, wherein gaseous ammonia is preferentially dosed at an exhaust temperature below a predefined setpoint associated with at least one of a cold start, a low speed, and a low load.

27. The method of any of claims 23 to 26, wherein liquid phase ammonia is preferentially dosed at an exhaust temperature above a predefined setpoint associated with a high engine speed and/or high engine load.

28. The method of claim 26 or 27, wherein the predefined setpoint is about 300°C.

29. A method of reducing NOX levels in an exhaust gas stream associated with a power plant having a waste heat recovery circuit utilizing an ammonia-based working fluid, the method comprising:

- a. heating the ammonia-based working fluid with heat from the exhaust gas stream at a heat exchanger;
- b. passing the ammonia-based working fluid through the expander to generate useful work at an output shaft of the expander;
- c. condensing the ammonia-based working fluid at a condenser;
- d. pumping the ammonia-based working fluid to the heat exchanger;
- e. collecting gas phase ammonia from the waste heat recovery circuit; and
- f. injecting the gas phase ammonia into the exhaust gas stream with a first injector.

30. The method of claim 29, wherein the step of collecting gas phase ammonia includes collecting the ammonia at a location between the heat exchanger and the expander.

31. The method of claim 29 or 30, wherein the step of collecting gas phase ammonia includes collecting the ammonia at a location between the expander and the condenser.

32. The method of any of claims 29 to 31, wherein the step of collecting gas phase ammonia includes collecting the ammonia at a location between the condenser and the heat exchanger.

33. The method of claim 29, further including pumping a urea solution into the waste heat recovery circuit to make up for the amount of ammonia-based working fluid injected into the exhaust gas stream.

34. The method of claim 33, wherein the step of pumping the urea solution is accomplished with a first pump that is separate from a second pump that pumps the ammonia-based working fluid.

35. The method of any of claims 29 to 34, further including the step of injecting a urea solution into the exhaust gas stream with a second injector, the second injector being separate from the first injector.

36. A method of reducing NOX levels in an exhaust gas stream associated with a power plant having a waste heat recovery circuit utilizing an ammonia-based working fluid, the method comprising:

- a. heating the ammonia-based working fluid with heat from the exhaust gas stream at a heat exchanger;
- b. passing the ammonia-based working fluid through the expander to generate useful work at an output shaft of the expander;
- c. condensing the ammonia-based working fluid at a condenser;
- d. pumping the ammonia-based working fluid to the heat exchanger;
- e. collecting liquid phase ammonia from the waste heat recovery circuit at a location between the heat exchanger and the expander; and
- f. injecting the liquid phase ammonia into the exhaust gas stream with a first injector.

37. The method of claim 36, wherein the step of collecting liquid phase ammonia includes collecting the ammonia at a location between the condenser and a working fluid storage tank.

38. The method of claim 36 or 37, wherein the step of collecting liquid phase ammonia includes collecting the ammonia at a location between a splitter valve and a recuperator of the waste heat recovery circuit.

FIG. 1

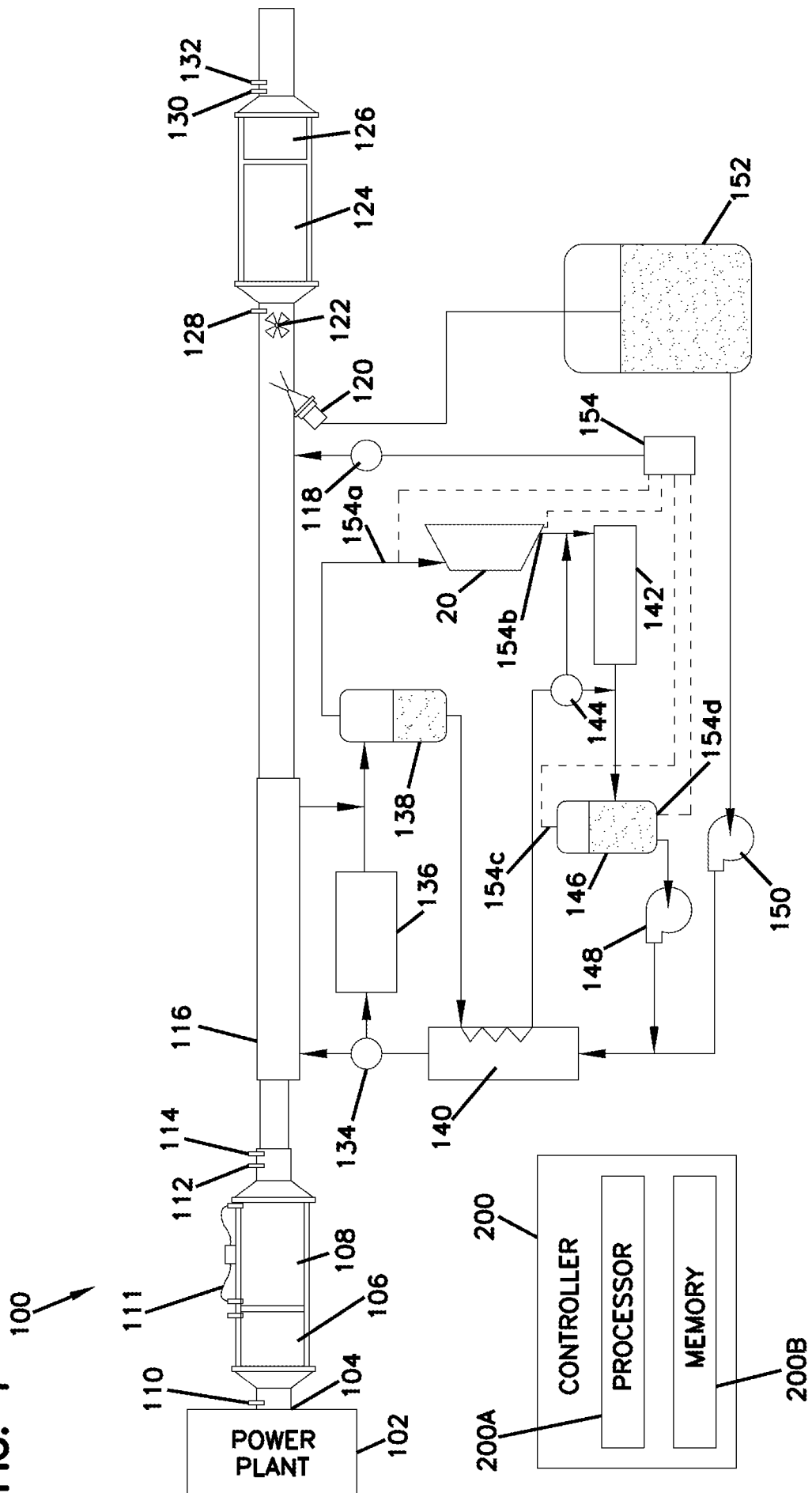


FIG. 2

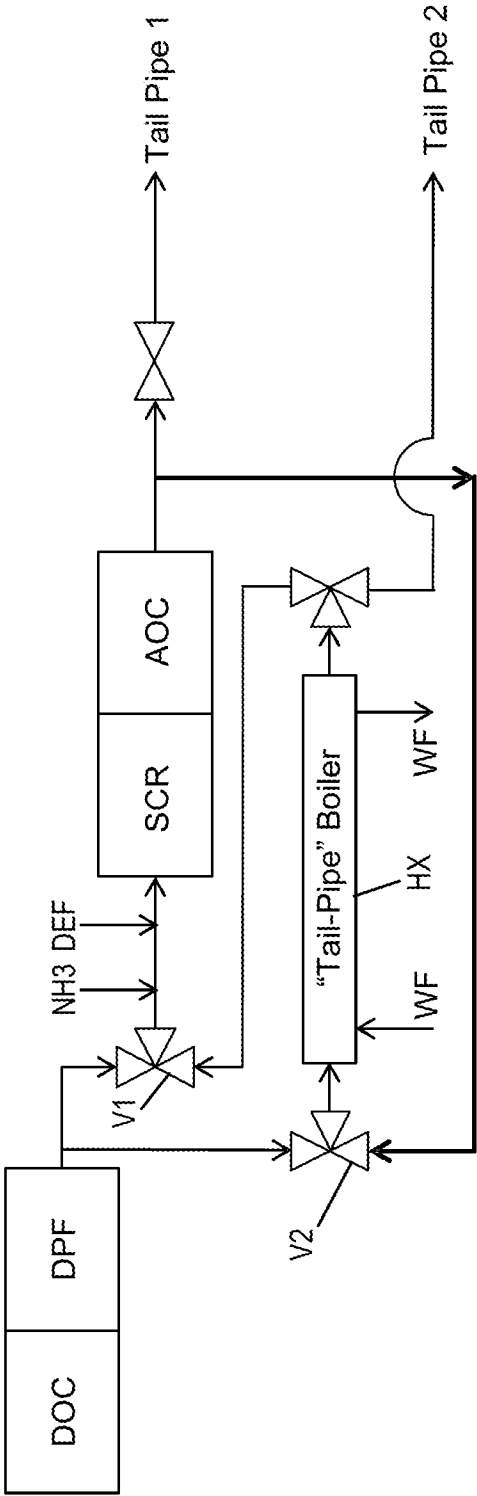


FIG. 3

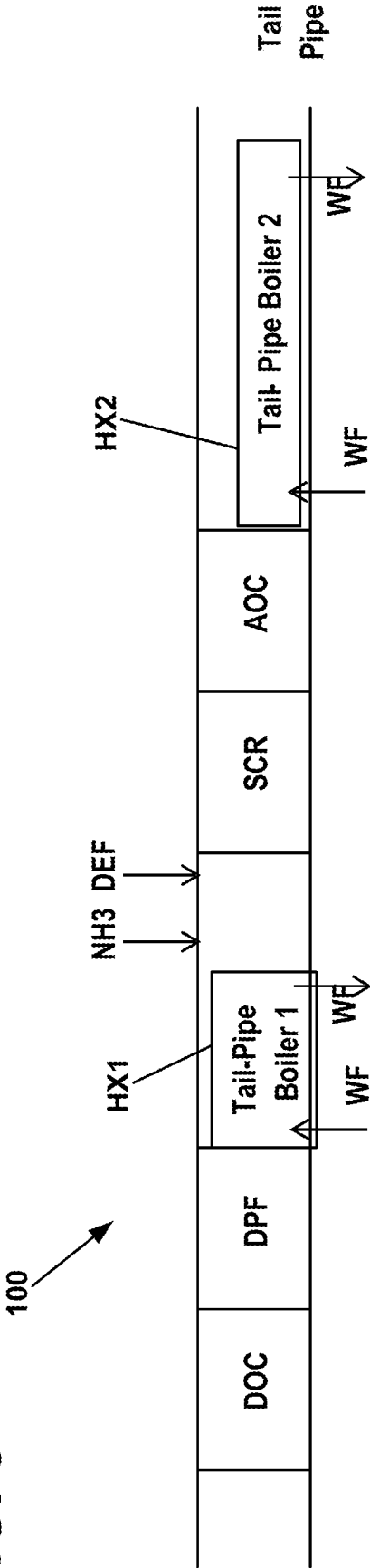
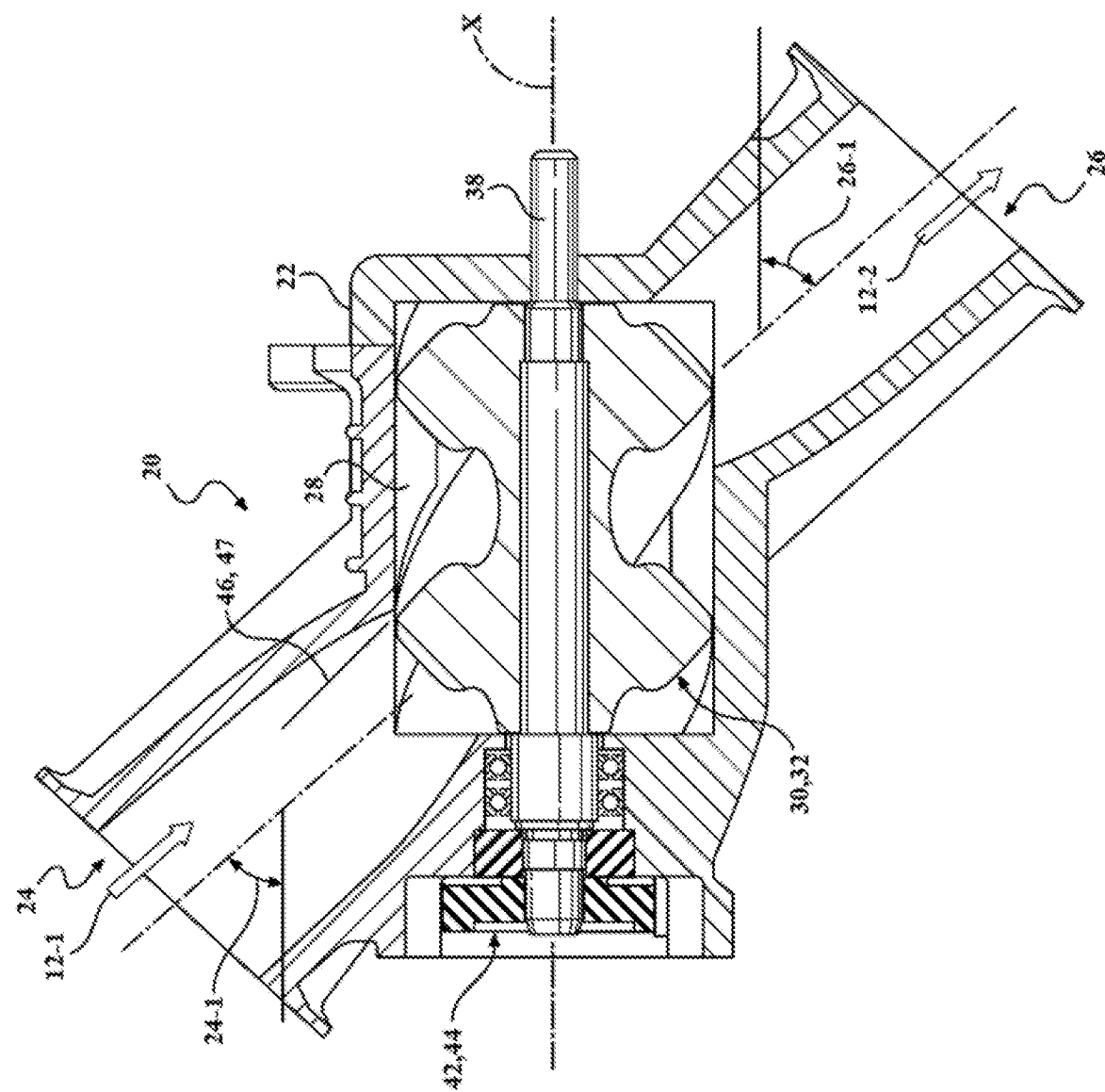


FIG. 4



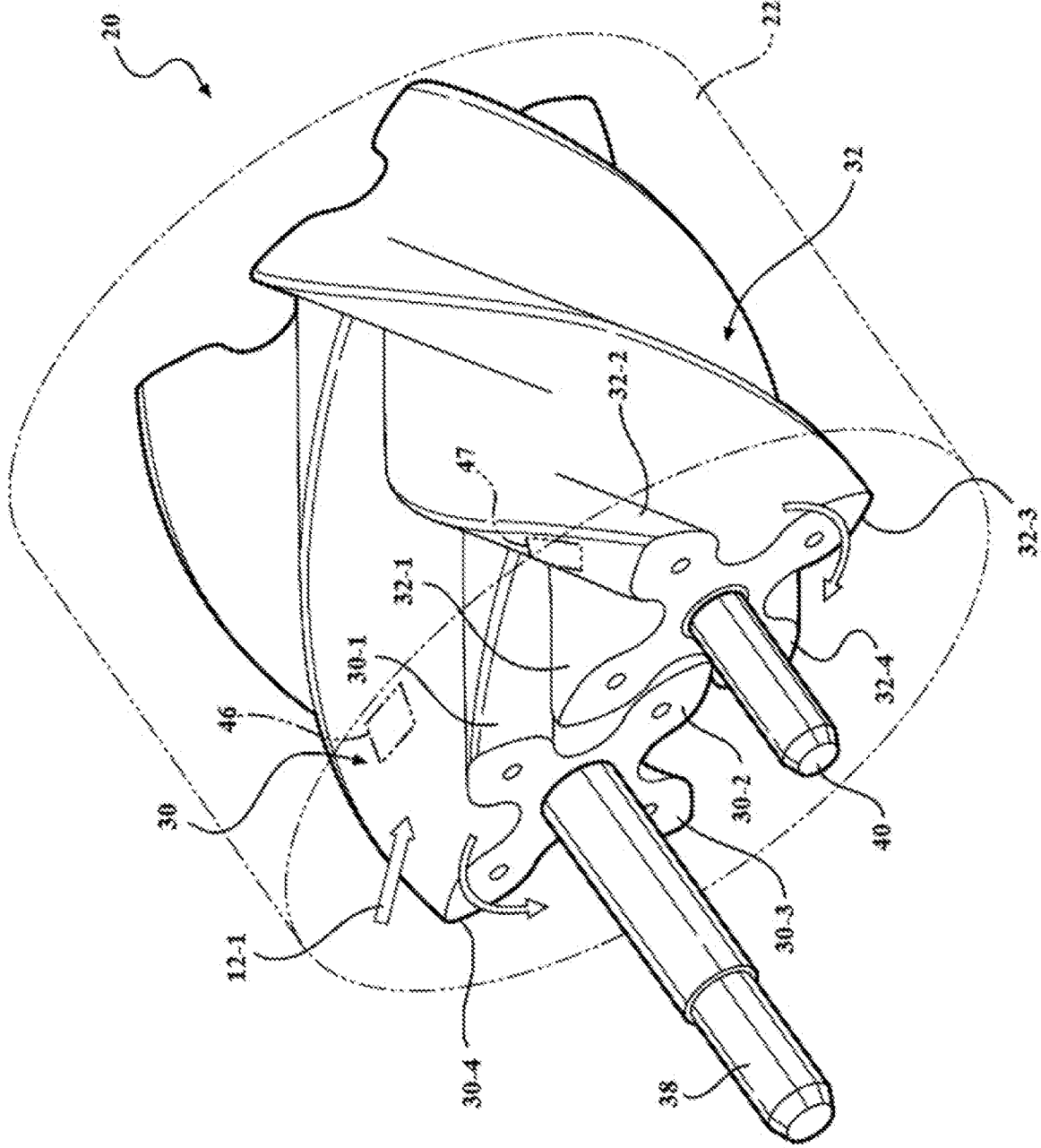
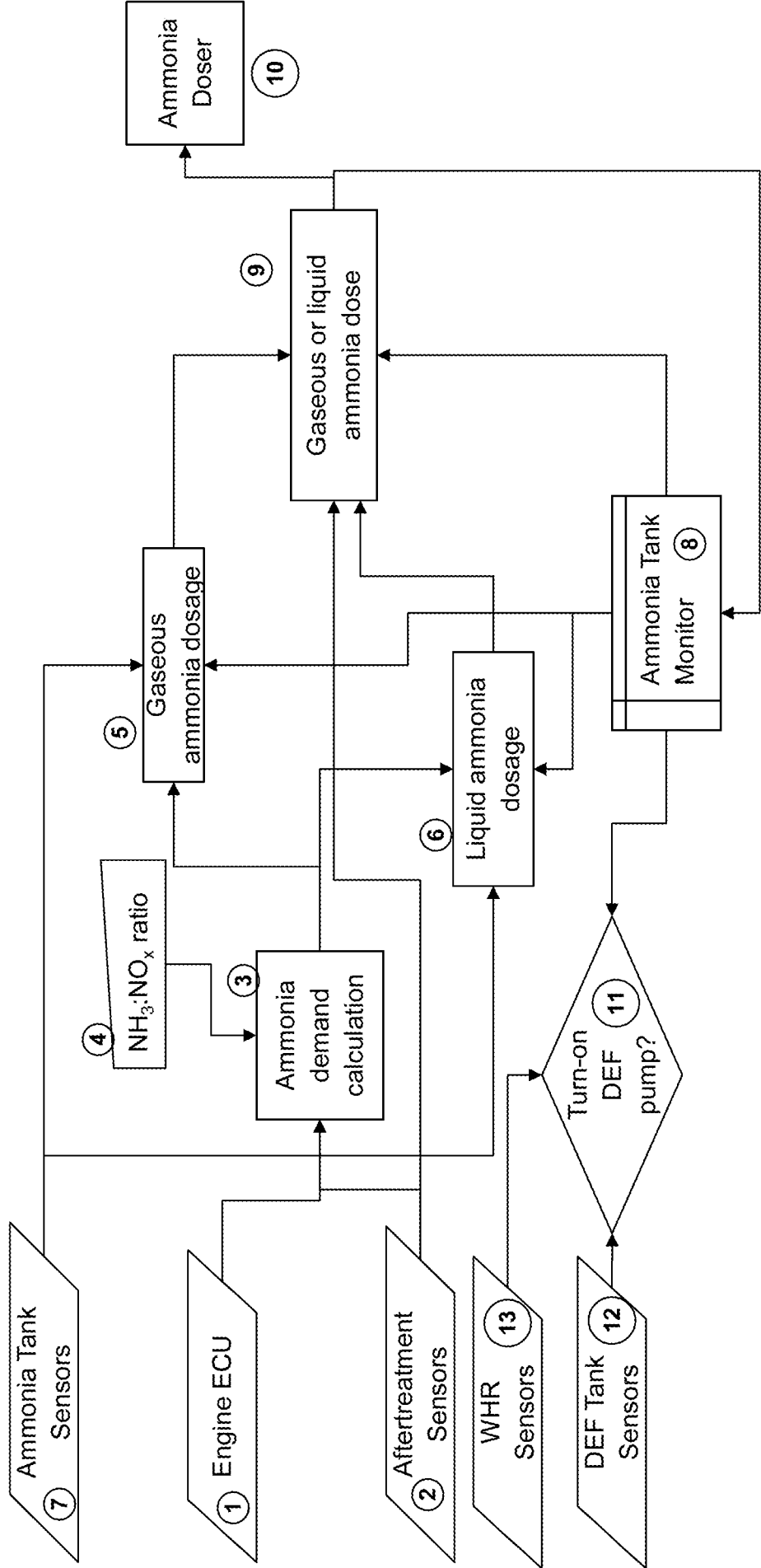


FIG. 5

FIG. 6



A. CLASSIFICATION OF SUBJECT MATTER**F01K 25/10(2006.01)i, F01N 3/20(2006.01)i, F01N 5/02(2006.01)i, F02G 5/02(2006.01)i, F01N 3/021(2006.01)i**

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)

F01K 25/10; B01D 53/86; F01K 25/08; F01N 3/28; F01K 13/00; F01N 3/08; F01K 23/10; F02G 5/02; F01N 3/04; F01K 25/00; F01N 3/20; F01N 5/02; F01N 3/021

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

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

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

eKOMPASS(KIPO internal) & keywords: engine, exhaust, waste heat, ammonia-water, working fluid, injector, gaseous ammonia, separator, and urea

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 2789818 A1 (LIEBHERR MACHINES BULLE S.A.) 14 October 2014 See paragraphs [0039]-[0060], claims 1-12, and figure 1.	1, 29-31, 36-38
Y		12-14, 33-34
A		23-26
Y	WO 2012-025776 A1 (RENAULT TRUCKS et al.) 01 March 2012 See page 6, line 4 - page 8, line 6 and figure 1.	12-14, 33-34
Y	EP 2503113 A1 (CATERPILLAR MOTOREN GMBH & CO., KG.) 26 September 2012 See abstract and figure 3.	13
A	JP 2009-103013 A (DENSO CORP.) 14 May 2009 See abstract and figures 1-2.	1, 12-14, 23-26 , 29-31, 33-34, 36-38
A	US 6732525 B2 (ENDO et al.) 11 May 2004 See column 3, lines 20-45 and figures 1-2.	1, 12-14, 23-26 , 29-31, 33-34, 36-38



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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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

18 May 2017 (18.05.2017)

Date of mailing of the international search report

19 May 2017 (19.05.2017)

Name and mailing address of the ISA/KR

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INTERNATIONAL SEARCH REPORTInternational application No.
PCT/US2017/016522**Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)**

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☒ Claims Nos.: 7
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claim 7 is regarded to be unclear because it refers to multiple dependent claim 6 which does not comply with PCT Rule 6.4(a).
3. ☒ Claims Nos.: 2-6,8-11,15-22,27-28,32,35
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2017/016522

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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