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— *as to the identity of the inventor (Rule 4.17(i))*

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

**Published**:

— *with international search report (Art. 21(3))*

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# (54) Title: HEAT RECOVERY TURBINE WITH MULTIPLE HEAT SOURCES

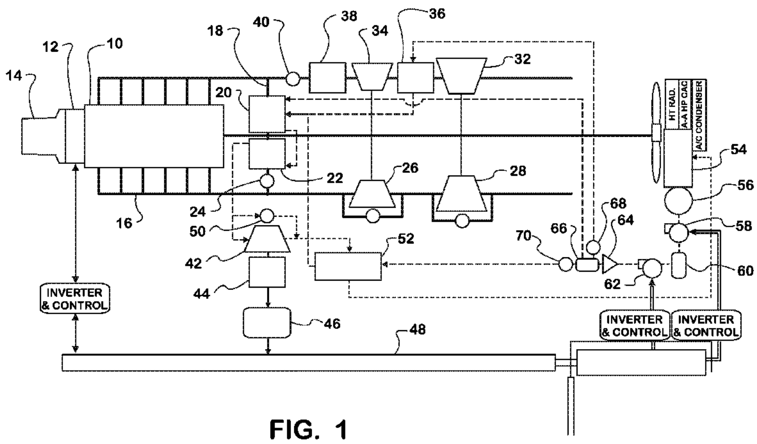


FIG. 1

(57) **Abstract**: A cooling system for an exhaust gas recirculation assembly comprises a first exhaust gas recirculation cooler, a second exhaust gas recirculation cooler, a heat recovery turbine, a first coolant pump, a second coolant pump and a pressure regulator. The second exhaust gas recirculation cooler is upstream in the exhaust system of the first exhaust gas recirculation cooler, and receives the coolant from the first exhaust gas recirculation cooler. The heat recovery turbine is in fluid communication with coolant from the second exhaust gas recirculation cooler. The first coolant pump controls flow through the first exhaust gas recirculation cooler. The second coolant pump controls flow through the second exhaust gas recirculation cooler and the heat recovery turbine. The pressure regulator is disposed downstream of the first cooler and upstream of the second coolant pump. A portion of the coolant supplied to the second coolant pump passes through the first coolant pump.

# HEAT RECOVERY TURBINE WITH MULTIPLE HEAT SOURCES

DESCRIPTION

## TECHNICAL FIELD

**[0001]** The present disclosure relates to a Rankine cycle waste heat recovery system and method of controlling the same on an internal combustion engine. More particularly, the present disclosure relates to a Rankine cycle heat waste recovery system utilizing coolant from an exhaust gas recirculation cooler and a method of controlling the same.

## BACKGROUND

**[0002]** Many modern diesel engines utilize exhaust gas recirculation ("EGR") in order to reduce certain emissions in the exhaust, particularly nitrogen oxides ("$NO_X$"). In order to maintain engine power outputs that are acceptable to users, most engines have an EGR cooler, where the exhaust gas in the EGR system is cooled before it is mixed with intake air and provided to the engine for use in combustion. The cooling fluid used in the EGR cooler receives a large amount of heat from the exhaust gas, and may vaporize the cooling fluid. Therefore, this heat within the cooling fluid may be utilized in a Rankine cycle waste heat recovery system to generate useable energy, such as electrical energy, or mechanical energy. Thus vaporized cooling fluid may in turn pass through a turbine where the fluid is allowed to expand, thus causing the turbine to rotate. The rotation of the turbine may typically generate electrical power. Therefore, useable energy is reclaimed from the heat of the coolant passed through the EGR cooler.

**[0003]** However, in certain operating conditions, such as soon after engine starting, engine operations in a cold ambient temperature, or when EGR rates are low, insufficient heat may be transferred to the coolant passing through the EGR cooler to vaporize the coolant. If the coolant in the EGR cooler does not vaporize, liquid in the coolant may damage the turbine. Therefore, a need exists for a Rankine cycle waste heat recovery system that controls a flow of EGR coolant to the turbine.

## SUMMARY

According to one embodiment, an internal combustion engine comprises an exhaust system, an air intake system, and exhaust gas recirculation portion, a heat recovery turbine, a first coolant pump, and a second coolant pump. The exhaust gas recirculation portion has a first cooler, a second cooler, and an exhaust gas recirculation valve. The exhaust gas

recirculation portion is disposed in fluid communication with the exhaust system and the air intake system. The heat recovery turbine is disposed in fluid communication with coolant passing through the first cooler and the second cooler of the exhaust gas recirculation portion. The first coolant pump is disposed in fluid communication with the first cooler and controls fluid flow through the first cooler. The second coolant pump is disposed in fluid communication with the second cooler and controls fluid flow through the second cooler and the heat recovery turbine. Coolant supplied to the second coolant pump passes through the first coolant pump prior to entry into the second coolant pump.

**[0004]** According to another embodiment, an exhaust gas recirculation system comprises an exhaust gas recirculation valve, a first exhaust gas recirculation cooler, a second exhaust gas recirculation cooler, a heat recovery turbine, a first coolant pump, and a second coolant pump. The exhaust gas recirculation valve is disposed in fluid communication with an exhaust system and an intake system. The first exhaust gas recirculation cooler receives a coolant. The second exhaust gas recirculation cooler is disposed upstream in the exhaust system of the first exhaust gas recirculation cooler, and receives the coolant from the first exhaust gas recirculation cooler. The heat recovery turbine is disposed in fluid communication with coolant from the second exhaust gas recirculation cooler. The first coolant pump is disposed in fluid communication with the first exhaust gas recirculation cooler and controls fluid flow through the first exhaust gas recirculation cooler. The second coolant pump is disposed in fluid communication with the second exhaust gas recirculation cooler and controls fluid flow through the second exhaust gas recirculation cooler and the heat recovery turbine. At least a portion of the coolant supplied to the second coolant pump has passed through the first coolant pump.

**[0005]** According to a further embodiment, a cooling system for an exhaust gas recirculation assembly comprises a first exhaust gas recirculation cooler, a second exhaust gas recirculation cooler, a heat recovery turbine, a first coolant pump, a second coolant pump and a pressure regulator. The first exhaust gas recirculation cooler receives a coolant. The second exhaust gas recirculation cooler is disposed upstream in the exhaust system of the first exhaust gas recirculation cooler, and receives the coolant from the first exhaust gas recirculation cooler. The heat recovery turbine is disposed in fluid communication with coolant from the second exhaust gas recirculation cooler. The first coolant pump is disposed in fluid communication with the first exhaust gas recirculation cooler and controls fluid flow through the first exhaust gas recirculation cooler. The second coolant pump is disposed in fluid communication with the second exhaust gas recirculation cooler and controls fluid flow through the second exhaust gas recirculation cooler and the heat recovery turbine. The pressure regulator is disposed in fluid communication with the first cooler and the second cooler. The pressure regulator is disposed downstream of the first cooler and upstream of the second coolant pump. At least a portion of the coolant supplied to the second coolant pump has passed through the first coolant pump.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0006]** FIG. 1 is a schematic diagram showing an engine having a waste heat recovery system according to one embodiment

**[0007]** FIG. 2 is a schematic diagram showing a portion of an engine having a waste heat recovery system according to another embodiment.

**[0008]** FIG 3. is a schematic diagram showing a portion of an engine having a waste heat recovery system according to a further embodiment.

**[0009]** FIG. 4 is a schematic diagram showing a portion of an engine having a waste heat recovery system according to yet another embodiment.

## DETAILED DESCRIPTION

**[0010]** FIG. 1 shows an engine 10 connected to an electric motor and generator 12 and a transmission 14. The engine 10 has an exhaust system 16. The exhaust system 16 has an exhaust gas recirculation (“EGR”) portion 18. The EGR portion 18 has a first EGR cooler 20, a second EGR cooler 22 and an EGR valve 24. The first and second EGR coolers 20, 22 reduce the temperature of exhaust gas within the EGR portion 18. The exhaust system 16 additionally is shown as having a high pressure turbocharger turbine 26 and a low pressure turbocharger turbine 28. The EGR valve 24 controls the flow of exhaust gas within the EGR portion 18.

**[0011]** The engine 10 additionally has an air intake system 30. The air intake system 30 has a low pressure turbocharger compressor 32 and a high pressure turbocharger compressor 34. A low pressure charge air cooler 36 is provided to cool intake air within the air intake system 30 following the low pressure turbocharger compressor 32, and a high pressure charge air cooler 38 is provided after the high pressure turbocharger compressor 34. A throttle valve 40 is also disposed within the air intake system 30. The low pressure turbocharger turbine 28 and the low pressure turbocharger compressor 32 form a first turbocharger and the high pressure turbocharger turbine 26 and the high pressure turbocharger compressor 34 form a second turbocharger. It is contemplated that the first turbocharger and the second turbocharger may be variable geometry turbochargers.

**[0012]** Coolant from the second EGR cooler 22 flows to a heat recovery turbine 42. The heat recovery turbine uses the Rankine cycle in order to allow the heat recovery turbine to rotate and generate torque used to turn a heat recovery generator 44 that generates electrical energy. An inverter and voltage controller 46 control the output of the heat recovery generator 44 and allow the electrical energy to be passed to a high voltage bus 48 of a vehicle containing the engine 10.

**[0013]** A bypass valve 50 is provided between the second EGR cooler 22 and the heat recovery turbine 42. The bypass valve 50 allows at least a portion of the coolant from the second EGR cooler 22 to bypass the heat recovery turbine 42 when the bypass valve 50 is positioned in at least a partially open position. When the bypass valve 50 is in a fully open position, all of the coolant from the second EGR cooler 22 bypasses the heat recovery turbine 42, and when the bypass valve 50 is in a fully closed position, all of the coolant from the second EGR cooler 22 flows through the heat recovery turbine 42. It is contemplated that the bypass valve 50 may include an orifice to reduce the pressure of flow through the bypass valve 50.

**[0014]** Coolant that has passed through the heat recovery turbine 42 or the bypass valve 50 is delivered to a recuperator 52. The recuperator 52 allows coolant to be pre-heated before being provided to the first EGR cooler 20, depending on operating conditions of the engine 10.

**[0015]** Coolant exiting the recuperator 52 is provided to a heat exchanger assembly 54. The heat exchanger assembly 54 ay include a condenser and a radiator in order to lower the temperature of the coolant. Next, coolant is delivered to an accumulator 56. The accumulator is in fluid communication with a low pressure pump 58. The low pressure pump 58 is contemplated to raise the pressure of the coolant to a range from about one bar to about four bar (1-4 bar). The low pressure pump 58 is in fluid communication with a filter 60 that removes foreign materials from the coolant. A high pressure pump 62 receives coolant from the filter 60. The high pressure pump 62 is contemplated to raise the pressure of the coolant to a range from about fifteen bar to about twenty five bar (15-25 bar). Coolant exiting the high pressure pump 62 flows through a check valve 64 and to a distributor 66. The check valve 64 prevents backflow within the coolant system.

**[0016]** The distributor 66 has a plurality of outlets that allow coolant to flow to various components. For example, coolant may be provided to the first EGR cooler 20, to the low pressure charge air cooler 36, or to the recuperator 52. A charge air cooler valve 68 controls the flow of coolant from the distributor 66 to the low pressure charge air cooler 36. Similarly, a recuperator valve 70 controls the flow of coolant from the distributor 66 to the recuperator 52. Coolant that flows to the recuperator 52 is heated by the coolant that has left the heat recovery turbine 42 or passed through the bypass valve 50, before being provided to the first EGR cooler 20. Thus, the recuperator 52 allows the coolant entering the first EGR cooler 20 to be at a higher temperature than coolant that does not pass through the recuperator 52. Thus, in certain operating conditions, the recuperator 52 allows the heat recovery turbine 42 to be used when it otherwise would not, as the coolant is at a sufficient temperature to be in a vapor state.

**[0017]** Turning now to FIG. 2, a schematic view of another embodiment of an engine 110 is shown. It is contemplated that the engine 110 has an air intake system and an exhaust system that are generally identical to those shown in FIG. 1. The engine 110 is connected to an electric motor and generator 112 and a transmission 114.

**[0018]** The engine 110 has an EGR portion 118. The EGR portion 118 has a first EGR cooler 120, and a second EGR cooler 122. Coolant from an accumulator 156 or a condenser 158 is supplied to the first EGR cooler 120. A first coolant pump 172 is disposed in fluid communication with the condenser 158, the accumulator 156, and the first EGR cooler 120. The first coolant pump 172 controls a flow of coolant to the first EGR cooler 120. An interstage cooler 176 may be provided downstream of the first EGR cooler 120. The interstage cooler 176 may receive intake air that has passed through a first turbocharger to cool the air before it passes through a second turbocharger. The first coolant pump 172 additionally controls the flow of coolant through the interstage cooler 176.

**[0019]** Coolant that has passed through the interstage cooler 176 is provided to a second coolant pump 174. A bypass valve 150 is provided upstream of the second coolant pump 174 to allow pressure within the coolant to be regulated. For instance, if it is determined that pressure is too high within the EGR coolant system, the bypass valve 150 may be opened to regulate the pressure. Similarly, it is also contemplated that if temperature within the second EGR cooler 122 is too low, the bypass valve 150 may be opened to reduce an amount of coolant available to flow through the second EGR cooler 122. The second coolant pump 174 is provided to control coolant flow through the second EGR cooler 122. The second coolant pump 174 may alter the flow rate of coolant in order to control the temperature and pressure of the coolant.

**[0020]** Fluid that passes through the second EGR cooler 122 is provided to a heat recovery turbine 142. The heat recovery turbine 142 is adapted to receive coolant in a vapor state. The coolant expands as it passes through the heat recovery turbine 142. Rotation of the heat recovery turbine 142 turns a generator 144 to produce electrical energy. The generator 144 is connected to an inverter 146 to regulate the electrical energy generated by the generator 144. Coolant that has passed through the heat recovery turbine 142 is provided to a condenser 158 where it is cooled.

**[0021]** FIG. 3 shows a similar engine 210 to that shown in FIG. 2, however a charge air cooler 236 with a charge air cooler pump 278 is also present, otherwise the engine 210 is generally identical to the engine 110. Coolant from the condenser 258 or the accumulator may also be provided to the charge air cooler pump 278. The charge air cooler pump 278 control the flow of coolant through the charger air cooler 236. Coolant from the charge air cooler 236 is then provided to upstream of a second coolant pump 274 and a bypass valve 250 where the coolant from the charge air cooler 236 mixes with coolant that has passed through a first coolant pump 272, a first EGR cooler 220 and an interstage cooler 276. The coolant then is supplied to second coolant pump 274 to control the flow of coolant through the second EGR cooler 222 and the heat recovery turbine 242.

**[0022]** FIG. 4 shows a further embodiment of an engine 310 that us similar to the embodiments shown in FIGs. 2 and 3, however, a recuperator 352 is also provided, otherwise the engine 310 is generally identical to the other engines 110, 210. The recuperator 352 receives coolant from a heat recovery turbine 342 that has not passed through a condenser 358 and uses heat from this coolant to raise the temperature of coolant from the condenser 358 or the accumulator 356 before it is provided to a first coolant pump 372 or a charge air cooler pump 378. The recuperator enables a cooling system to operate at higher temperatures, where greater amounts of heat transfer may occur.

**[0023]** It will be understood that a control system may be implemented in hardware to effectuate the method. The control system can be implemented with any or a combination of the following technologies, which are each well known in the art: a discrete logic circuit(s) having logic gates for implementing logic functions upon data signals, an application specific integrated circuit (ASIC) having appropriate combinational logic gates, a programmable gate array(s) (PGA), a field programmable gate array (FPGA), etc.

**[0024]** When the control system is implemented in software, it should be noted that the control system can be stored on any computer readable medium for use by or in connection with any computer related system or method. In the context of this document, a "computer-readable medium" can be any medium that can store, communicate, propagate, or transport the program for use by or in connection with the instruction execution system, apparatus, or device. The computer readable medium can be, for example, but is not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or propagation medium. More specific examples (a non-exhaustive list) of the computer-readable medium would include the following: an electrical connection (electronic) having one or more wires, a portable computer diskette (magnetic), a random access memory (RAM) (electronic), a read-only memory (ROM) (electronic), an erasable programmable read-only memory (EPROM, EEPROM, or Flash memory) (electronic), an optical fiber (optical) and a portable compact disc read-only memory (CDROM) (optical). The control system can be embodied in any computer-readable medium for use by or in connection with an instruction execution system, apparatus, or device, such as a computer-based system, processor-containing system, or other system that can fetch the instructions from the instruction execution system, apparatus, or device and execute the instructions.

## CLAIMS

What is claimed is:

1. An internal combustion engine comprising:

an exhaust system;

an air intake system;

an exhaust gas recirculation portion having a first cooler, a second cooler, and an exhaust gas recirculation valve, the exhaust gas recirculation portion being disposed in fluid communication with the exhaust system and the air intake system;

a heat recovery turbine being disposed in fluid communication with coolant passing through the first cooler and the second cooler of the exhaust gas recirculation portion;

a first coolant pump being disposed in fluid communication with the first cooler and controlling fluid flow through the first cooler; and

a second coolant pump being disposed in fluid communication with the second cooler and controlling fluid flow through the second cooler and the heat recovery turbine, wherein coolant supplied to the second coolant pump passes through the first coolant pump prior to entry into the second coolant pump.

2. The internal combustion engine of claim 1, wherein the first coolant pump is a low pressure pump.

3. The internal combustion engine of claim 1, wherein the second coolant pump is a high pressure pump.

4. The internal combustion engine of claim 1, further comprising an interstage cooler, the interstage cooler disposed in fluid communication with the first cooler and the second cooler, the interstage cooler being disposed downstream of the first cooler and upstream of the second cooler.

5. The internal combustion engine of claim 4, wherein the interstage cooler is disposed upstream of the second coolant pump.

6. The internal combustion engine of claim 1, further comprising a pressure regulator, the pressure regulator in fluid communication with the first cooler and the second cooler, the pressure regulator being disposed downstream of the first cooler and upstream of the second coolant pump.

7. The internal combustion engine of claim 6, further comprising a condenser disposed in fluid communication with the heat recovery turbine and the pressure regulator and disposed downstream of both the heat recovery turbine and the pressure regulator.

8. The internal combustion engine of claim 1, further comprising a charge air cooler system having a charge air cooler and a charge air cooler coolant pump, the charge air cooler coolant pump being in fluid communication with a condenser, the condenser being in fluid communication with the first coolant pump and the second coolant pump.

9. The internal combustion engine of claim 1, further comprising a recuperator, the recuperator being in fluid communication with a condenser and the heat recovery turbine, the condenser being in fluid communication with the first coolant pump and the second coolant pump.

10. An exhaust gas recirculation system comprising:

an exhaust gas recirculation valve disposed in fluid communication with an exhaust system and an intake system;

a first exhaust gas recirculation cooler receiving a coolant;

a second exhaust gas recirculation cooler, the second exhaust gas recirculation cooler being disposed upstream in the exhaust system of the first exhaust gas recirculation cooler, and receiving the coolant from the first exhaust gas recirculation cooler;

a heat recovery turbine disposed in fluid communication with coolant from the second exhaust gas recirculation cooler; and

a first coolant pump being disposed in fluid communication with the first exhaust gas recirculation cooler and controlling fluid flow through the first exhaust gas recirculation cooler; and

a second coolant pump being disposed in fluid communication with the second exhaust gas recirculation cooler and controlling fluid flow through the second exhaust gas recirculation cooler and the heat recovery turbine,

wherein at least a portion of the coolant supplied to the second coolant pump has passed through the first coolant pump.

11. The exhaust gas recirculation system of claim 10, wherein the first coolant pump is a low pressure pump.

12. The exhaust gas recirculation system of claim 10, wherein the second coolant pump is a high pressure pump.

13. The exhaust gas recirculation system of claim 10, further comprising further comprising an interstage cooler, the interstage cooler disposed in fluid communication with the first cooler and the second cooler, the interstage cooler being disposed downstream of the first cooler and upstream of the second cooler.

14. The exhaust gas recirculation system of claim 15, wherein the interstage cooler is disposed upstream of the second coolant pump.

15. The exhaust gas recirculation system of claim 10, further comprising a pressure regulator, the pressure regulator in fluid communication with the first cooler and the second cooler, the pressure regulator being disposed downstream of the first cooler and upstream of the second coolant pump.

16. The exhaust gas recirculation system of claim 15, further comprising a condenser disposed in fluid communication with the heat recovery turbine and the pressure regulator and disposed downstream of both the heat recovery turbine and the pressure regulator.

17. The exhaust gas recirculation system of claim 10, further comprising a recuperator, the recuperator being in fluid communication with a condenser and the heat recovery turbine, the condenser being in fluid communication with the first coolant pump and the second coolant pump.

18. A cooling system for an exhaust gas recirculation assembly comprising:

a first exhaust gas recirculation cooler receiving a coolant;

a second exhaust gas recirculation cooler, the second exhaust gas recirculation cooler being disposed upstream in the exhaust system of the first exhaust gas recirculation cooler, and receiving the coolant from the first exhaust gas recirculation cooler;

a heat recovery turbine disposed in fluid communication with coolant from the second exhaust gas recirculation cooler;

a first coolant pump being disposed in fluid communication with the first exhaust gas recirculation cooler and controlling fluid flow through the first exhaust gas recirculation cooler;

a second coolant pump being disposed in fluid communication with the second exhaust gas recirculation cooler and controlling fluid flow through the second exhaust gas recirculation cooler and the heat recovery turbine; and

a pressure regulator disposed in fluid communication with the first cooler and the second cooler, the pressure regulator being disposed downstream of the first cooler and upstream of the second coolant pump, wherein at least a portion of the coolant supplied to the second coolant pump has passed through the first coolant pump.

19. The cooling system for an exhaust gas recirculation assembly of claim 18, further comprising a condenser disposed in fluid communication with the heat recovery turbine and the pressure regulator and disposed downstream of both the heat recovery turbine and the pressure regulator.

20. The cooling system for an exhaust gas recirculation assembly of claim 18, further comprising a recuperator, the recuperator being in fluid communication with a condenser and the heat recovery turbine, the condenser being in fluid communication with the first coolant pump and the second coolant pump.

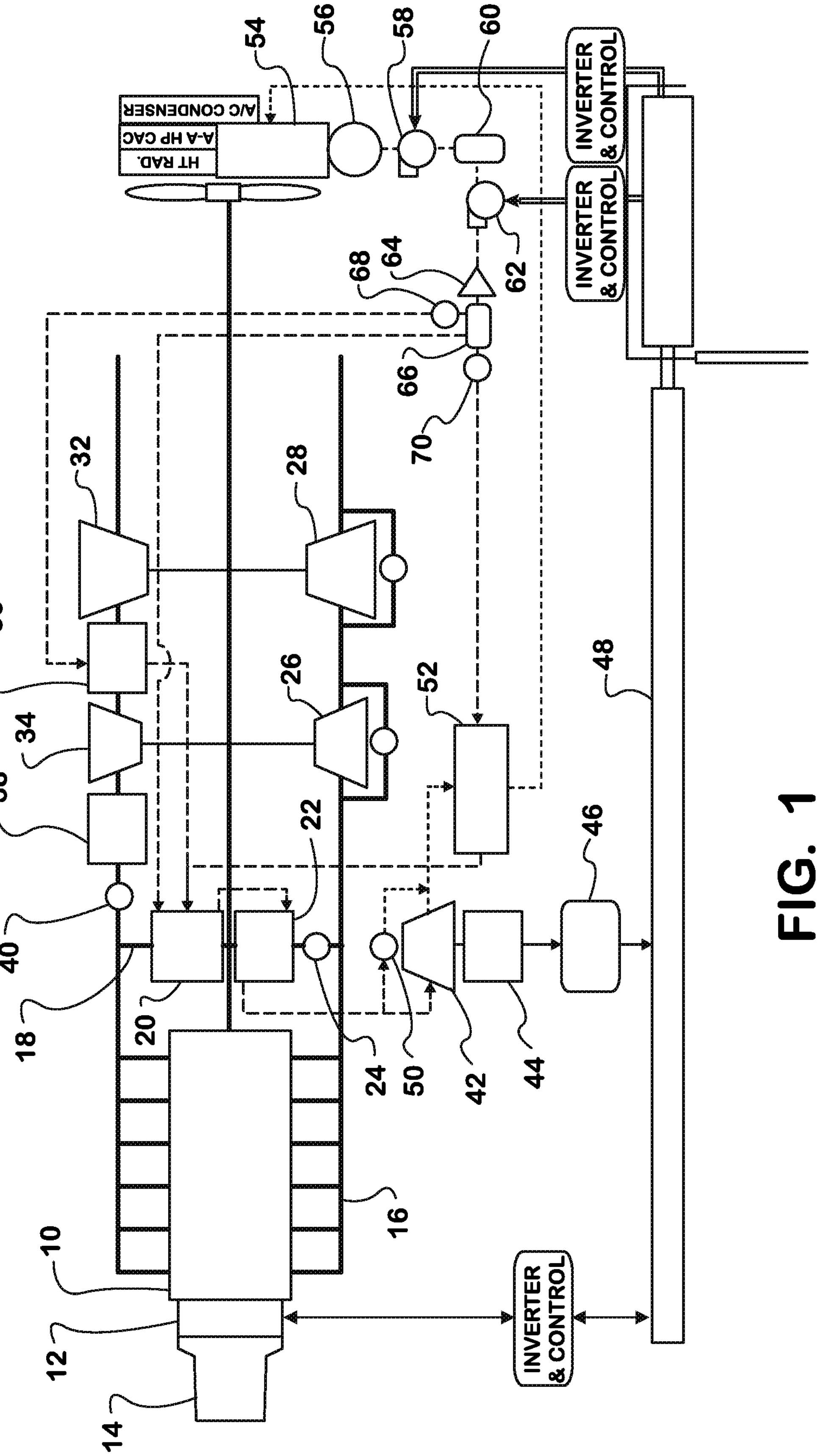
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FIG. 1

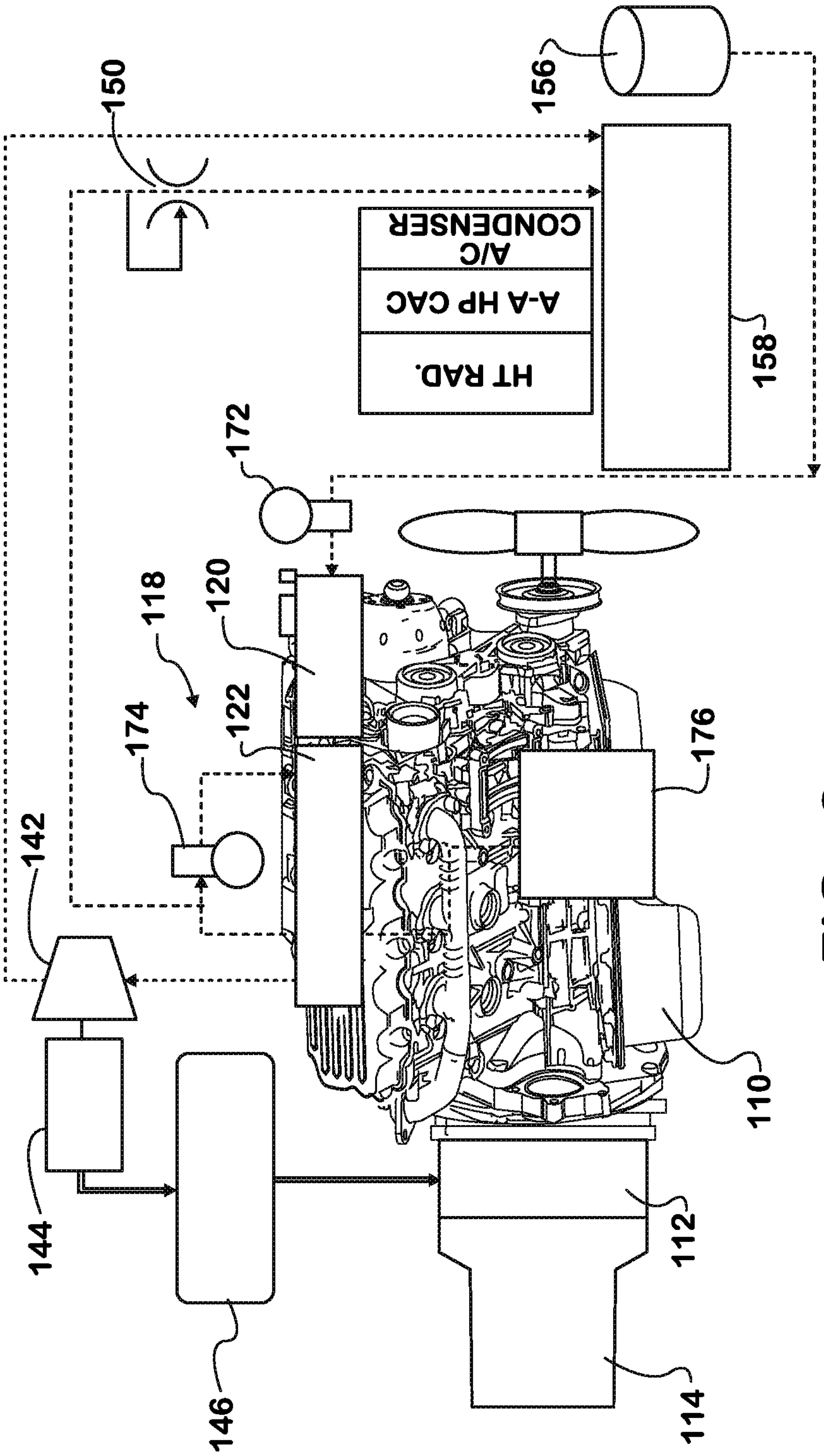
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FIG. 2

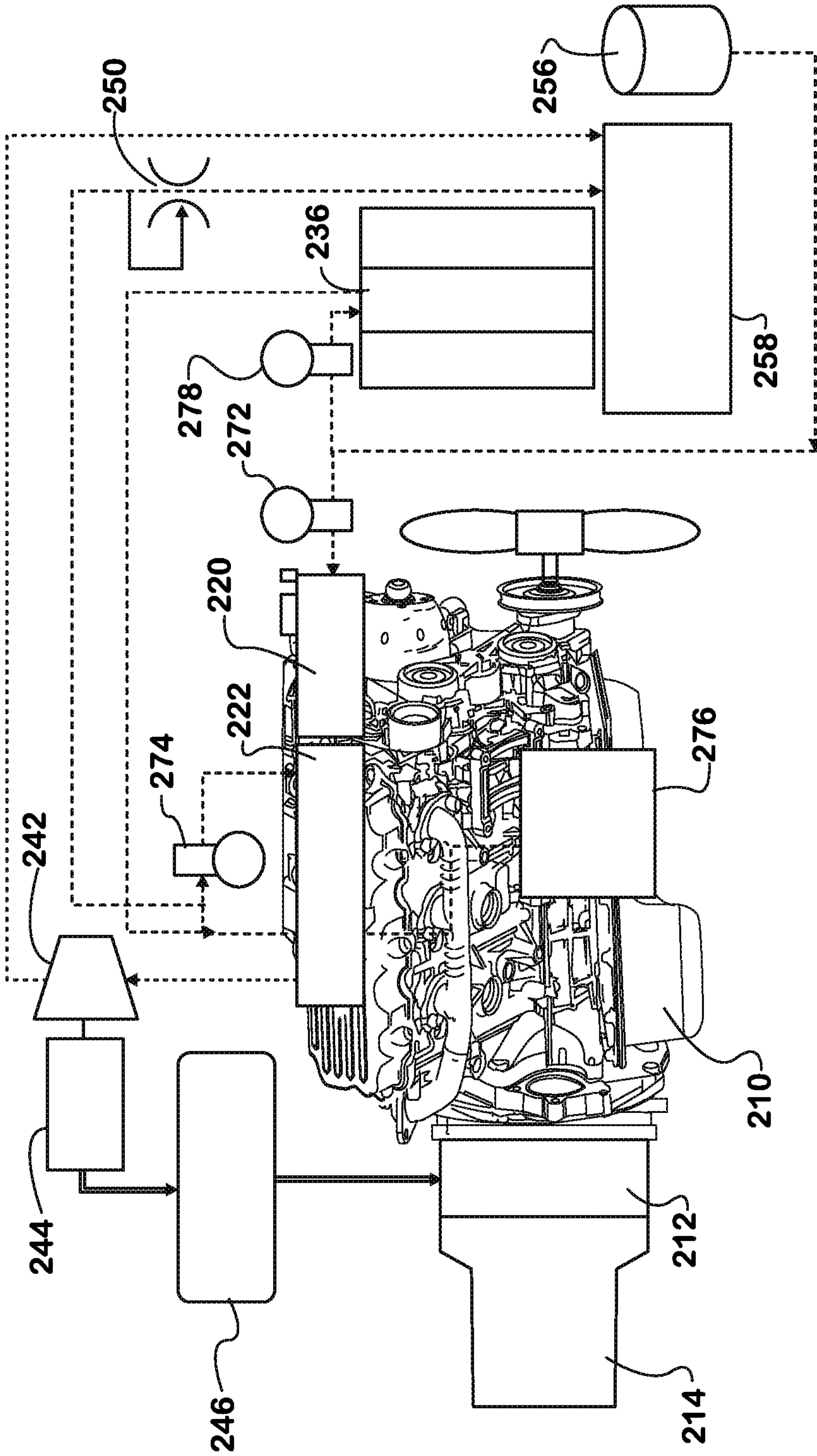


FIG. 3

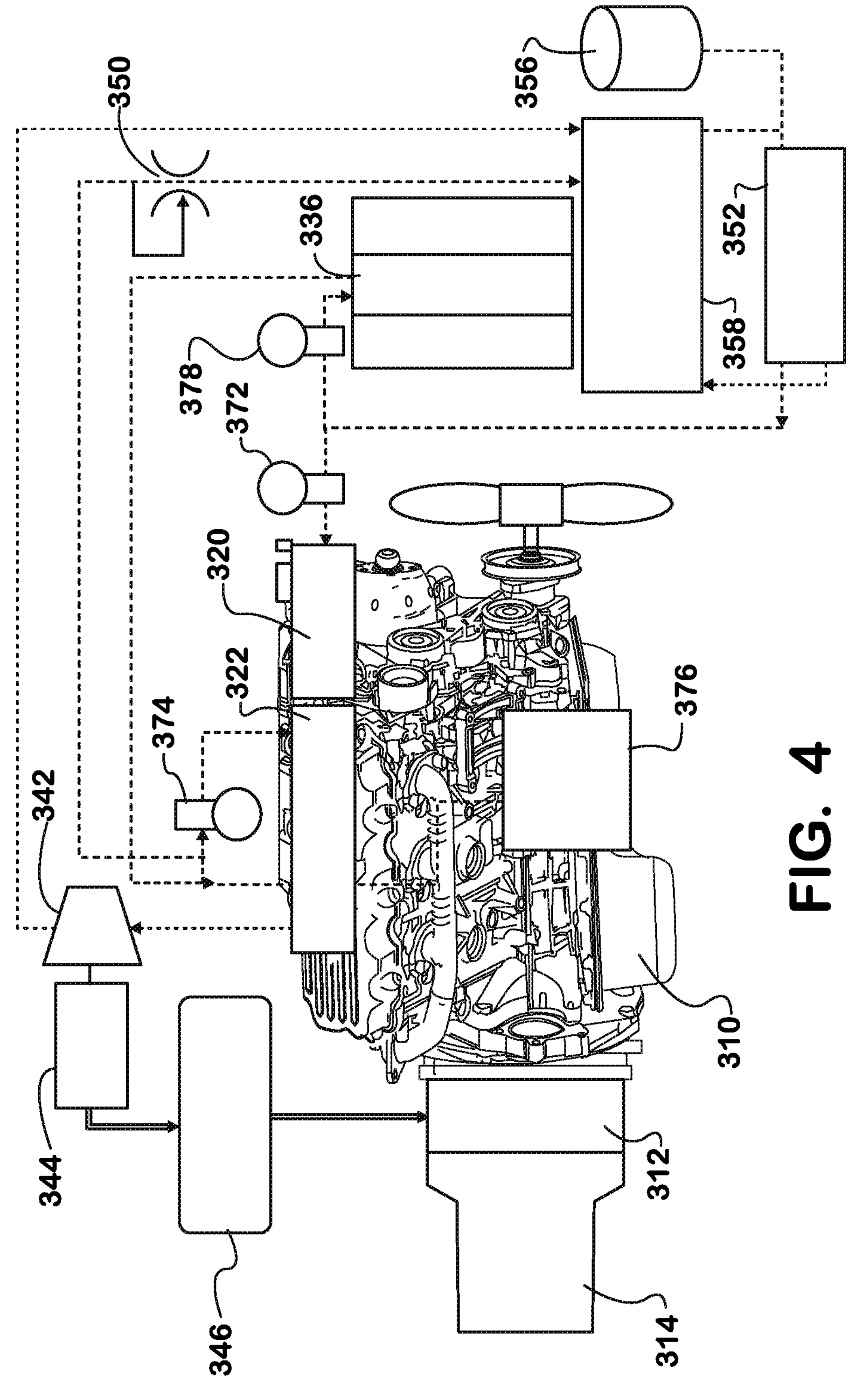
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FIG. 4

# INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 11/28443

**A. CLASSIFICATION OF SUBJECT MATTER**
IPC(8) - F02G 3/00 (2011.01)
USPC - 60/616
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)
IPC(8): F02G 3/00 (2011.01)
USPC: 60/616

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): F02G 3/00 (2011.01) ; USPC: 60/597,613,614,515,616,623 - text limited -

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PubWEST: (PGPB, USPT, EPAB, JPAB); Google Scholar; Google Patent - Search Terms: exhaust gas EGR turbine turbo compressor expander heat thermal coolant pump engine internal combustion spark ignition diesel compression exchang transfer valve pressure intake manifold recuperator intercooler anti-freeze fresh air evaporator etc.

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

| Category* | Citation of document, with indication, where appropriate, of the relevant passages | Relevant to claim No. |
|---|---|---|
| Y | US 2010/0139626 A1 (Raab et al.) 10 June 2010 (10.06.2010) para. [0021] through [0041], Fig. 1-10 | 1-20 |
| Y | US 2006/0213184 A1 (Stewart) 28 September 2006 (28.09.2006) para. [0005] through [0013], Fig. 1, 2 | 1-20 |
| Y | US 2011/0023796 A1 (Cattani et al.) 03 February 2011 (03.02.2011) para. [0033] through [0042], Fig. 1-3 | 8 |
| A | US 2007/0267000 A1 (Raduenz et al.) 22 November 2007 (22.11.2007) entire document | 1-20 |
| A | US 2010/0139267 A1 (Schliesche et al.) 10 June 2010 (10.06.2010) entire document | 1-20 |

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

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

| Date of the actual completion of the international search | Date of mailing of the international search report |
|---|---|
| 02 May 2011 (02.05.2011) | 17 MAY 2011 |


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