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(54) NOx generation quantity estimation method for internal combustion engine

(57) In an NO_x generation quantity estimation method for an internal combustion engine, the concentration of a gas contained in intake gas and serving as a material for generation of NO_x, (intake-gas oxygen concentration), a load index value indicating the load of the engine (fuel injection quantity), an atomization index value indicating the degree of atomization of fuel within the combustion chamber (fuel injection pressure), and the highest flame temperature are selected as peripheral condition quantities in relation to gas mixture which affect the quantity of NO_x generated in a combustion region as a result of combustion. A combustion-generated NO_x quantity per unit fuel quantity (combustion-generated NO_x ratio) is obtained on the basis of the four peripheral condition quantities and a predetermined empirical formula which defines the relation between the four peripheral condition quantities and the combustion-generated NO_x ratio. Subsequently, the quantity of generated NO_x is estimated through multiplication of the combustion-generated NO_x ratio by the fuel injection quantity.

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Description

BACKGROUND OF THE INVENTION

Field of the Invention

[0001] The present invention relates to an NO_x generation quantity estimation method for estimating the quantity of NO_x which is generated in a combustion chamber of an internal combustion engine as a result of combustion of gas mixture containing fuel and air (the quantity of NO_x generated in such a manner will be called "combustion-generated NO_x quantity").

Description of the Related Art

[0002] In an internal combustion engine such as a spark-ignition engine or a diesel engine, the quantity of NO_x contained in exhaust gas discharged from an exhaust passage to the outside (hereinafter may be referred to as "NO_x discharge quantity") must be reduced, and this necessitates reduction of combustion-generated NO_x quantity; i.e., the quantity of NO_x which is generated in a combustion chamber as a result of combustion of gas mixture atomized through injection and containing fuel and air. An effective way of reducing the combustion-generated NO_x quantity is lowering the highest flame temperature (highest combustion temperature) through, for example, increasing the quantity of EGR gas circulated by means of an EGR apparatus, or delaying fuel injection timing.

[0003] However, when the quantity of EGR gas is increased in order to reduce the combustion-generated NO_x quantity, in the case of a diesel engine, the generation quantity of particulate matter (PM) increases. When fuel injection timing is delayed in order to reduce the combustion-generated NO_x quantity, fuel efficiency deteriorates.

[0004] Accordingly, in order to minimize the combustion-generated NO_x quantity in consideration of suppression of an increase in the discharge quantity of particulate matter (PM) and suppression of deterioration in fuel efficiency, the combustion-generated NO_x quantity is desirably controlled to a predetermined target value corresponding to the operating conditions of the engine. Meanwhile, direct measurement of the combustion-generated NO_x quantity is considerably difficult. Therefore, in order to accurately control the combustion-generated NO_x quantity to a predetermined target value, the combustion-generated NO_x quantity must be accurately estimated.

[0005] For such accurate estimation, a control apparatus for an internal combustion engine disclosed in Japanese Patent Application Laid-Open (*kokai*) No. 2002-371893 detects combustion pressure and intake-gas oxygen concentration by use of a cylinder pressure sensor and an intake-gas oxygen concentration sensor, and estimates the above-mentioned combustion-generated NO_x quantity on the basis of combustion temperature and gas mixture concentration calculated on the basis of the combustion pressure and the intake-gas oxygen concentration, wherein the estimation is performed by use of the extended Zeldovich mechanism, which is a typical known combustion model. Then, EGR gas quantity, fuel injection timing, or the like is controlled so that the estimated combustion-generated NO_x quantity coincides with the predetermined target value.

[0006] Incidentally, the actual quantity of NO_x generated in a combustion chamber as a result of combustion of gas mixture greatly depends on peripheral condition quantities in relation to gas mixture, such as load exerted on the engine (drive torque) and the atomization level of fuel which constitutes gas mixture to be combusted. However, the above-mentioned conventional apparatus does not take such peripheral condition quantities in relation to gas mixture into consideration for estimation of the combustion-generated NO_x quantity. Therefore, the conventional apparatus has a drawback in that the above-mentioned combustion-generated NO_x quantity cannot be accurately estimated, and thus, the above-mentioned (actual) combustion-generated NO_x quantity cannot be accurately controlled to a predetermined target value.

SUMMARY OF THE INVENTION

[0007] In view of the foregoing, an object of the present invention is to provide an NO_x generation quantity estimation method for estimating combustion-generated NO_x quantity; i.e., the quantity of NO_x which is generated in a combustion chamber of an internal combustion engine as a result of combustion of gas mixture containing fuel and air, in consideration of peripheral condition quantities in relation to the gas mixture.

[0008] In order to achieve the above object, the present invention provides an NO_x generation quantity estimation method for an internal combustion engine which estimates the above-mentioned combustion-generated NO_x quantity on the basis of a peripheral condition quantity in relation to gas mixture which affects the combustion-generated NO_x quantity. Since the combustion-generated NO_x quantity can be estimated in consideration of a peripheral condition quantity in relation to gas mixture which affects the combustion-generated NO_x quantity, the combustion-generated NO_x quantity can be accurately estimated.

[0009] In this case, the combustion-generated NO_x quantity is preferably estimated on the basis of at least a load index value which represents the degree of load of the engine and serves as the peripheral condition quantity. Examples of the load index value, which represents the degree of load of the engine, include fuel injection quantity (per operation cycle), drive torque of the engine, and temperature of the inner wall surface of a combustion chamber.

[0010] The greater the load of the engine, the greater the amount of expansion energy to be produced in a combustion chamber against the load. As a result, the temperature of the inner wall surface of the combustion chamber increases, and gas mixture before combustion is heated more by means of radiant heat from the inner wall surface. Accordingly, the greater the load of the engine, the higher the highest flame temperature (the highest combustion temperature), with a resultant increase in the combustion-generated NO_x quantity.

[0011] Accordingly, through employment of the above-described method in which the combustion-generated NO_x quantity is estimated on the basis of at least the load index value, the combustion-generated NO_x quantity can be estimated in such a manner that the combustion-generated NO_x quantity increases with the load represented by the load index value. As a result, the combustion-generated NO_x quantity can be accurately estimated.

[0012] In the NO_x generation quantity estimation method of the present invention, the combustion-generated NO_x quantity is preferably estimated on the basis of at least an atomization index value which represents the degree of atomization of (injected) fuel within the combustion chamber and serves as the peripheral condition quantity. Examples of the atomization index value, which represents the degree of atomization of fuel within the combustion chamber, include fuel injection pressure, swirl ratio, and excess air ratio in a region where combustion occurs.

[0013] The greater the degree of atomization of injected fuel, the higher the ratio, to the quantity of the injected fuel, of the quantity of air which is mixed with the fuel to produce a gas mixture. Accordingly, the greater the degree of atomization of injected fuel, the higher the excess air ratio in a region occupied by the gas mixture (i.e., the region where combustion occurs (combustion region)), with a resultant increase in the combustion-generated NO_x quantity. Accordingly, through employment of the above-described method in which the combustion-generated NO_x quantity is estimated on the basis of at least the atomization index value, the combustion-generated NO_x quantity can be estimated in such a manner that the combustion-generated NO_x quantity increases with the degree of atomization represented by the atomization index value. As a result, the combustion-generated NO_x quantity can be accurately estimated.

[0014] The present invention also provides an NO_x discharge quantity estimation method for an internal combustion engine in which the quantity of NO_x contained in exhaust gas discharged from the exhaust passage of the engine to the outside (hereinafter referred to as "NO_x discharge quantity") is estimated by use of the above-described NO_x generation quantity estimation method of the present invention. The NO_x discharge quantity estimation method comprises the steps of: estimating a combustion region, the combustion region being a portion of the combustion chamber in which combustion of the gas mixture occurs; estimating, by use of the NO_x generation quantity estimation method of the present invention, a quantity of NO_x generated in the combustion region as a result of the combustion of the gas mixture; estimating a quantity of NO_x in a non-combustion region, the non-combustion region being the remaining portion of the combustion chamber; and estimating the NO_x discharge quantity on the basis of the combustion-generated NO_x quantity and the quantity of NO_x in the non-combustion region.

[0015] In an internal combustion engine equipped with an EGR apparatus for circulating to the intake passage a portion of exhaust gas flowing through the exhaust passage, No_x contained in EGR gas is circulated into the combustion chamber via the EGR apparatus. In addition, the above-mentioned combustion-generated NO_x quantity is the quantity of NO_x generated in the region (the above-mentioned combustion region) which is a portion of the combustion chamber and in which combustion occurs. Accordingly, in the remaining portion of the combustion chamber (hereinafter referred to as the "non-combustion region"), the circulated NO_x remains even after combustion. Therefore, in order to accurately estimate the quantity of NO_x contained in exhaust gas discharged from the exhaust passage to the outside, not only the combustion-generated NO_x quantity but also the "quantity of NO_x remaining in the non-combustion region" must be taken into consideration.

[0016] On the basis of the above knowledge, in the present invention, the NO_x discharge quantity is estimated in consideration of not only the quantity of NO_x generated in the estimated combustion region as a result of combustion but also the quantity of NO_x in the non-combustion region (after combustion); i.e., the above-mentioned "quantity of NO_x remaining in the non-combustion region." Thus, the NO_x discharge quantity can be accurately estimated.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017]

FIG. 1 a schematic diagram showing the overall configuration of a system in which an engine control apparatus, which performs an NO_x generation quantity estimation method for an internal combustion engine according to an embodiment of the present invention, is applied to a four-cylinder internal combustion engine (diesel engine);

FIG. 2 is a diagram schematically showing a state in which gas is taken from an intake manifold to a certain cylinder and is then discharged to an exhaust manifold;

FIG. 3 is a flowchart showing a routine which the CPU shown in FIG. 1 executes so as to control fuel injection quantity, etc;

FIG. 4 is a table for determining a fuel injection quantity, to which the CPU shown in FIG. 1 refers during execution of the routine shown in FIG. 3;

FIG. 5 is a table for determining a base fuel injection timing, to which the CPU shown in FIG. 1 refers during execution of the routine shown in FIG. 3;

FIG. 6 is a table for determining a base fuel injection pressure, to which the CPU shown in FIG. 1 refers during execution of the routine shown in FIG. 3;

FIG. 7 is a table for determining a target NO_x discharge quantity, to which the CPU shown in FIG. 1 refers during execution of the routine shown in FIG. 3;

FIG. 8 is a table for determining an injection-timing correction value, to which the CPU shown in FIG. 1 refers during execution of the routine shown in FIG. 3;

FIG. 9 is a flowchart showing a routine which the CPU shown in FIG. 1 executes so as to compute an NO_x discharge quantity (actual NO_x discharge quantity); and

FIG. 10 is a flowchart showing a routine which the CPU shown in FIG. 1 executes so as to compute a combustion-generated NO_x ratio.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0018] With reference to the drawings, there will now be described an control apparatus of an internal combustion engine (diesel engine), which apparatus performs an NOx generation quantity estimation method and an NOx discharge quantity estimation method according to an embodiment of the present invention.

[0019] FIG. 1 schematically shows the entire configuration of a system in which such an engine control apparatus is applied to a four-cylinder internal combustion engine (diesel engine) 10. This system comprises an engine main body 20 including a fuel supply system; an intake system 30 for introducing gas to combustion chambers (cylinder interiors) of individual cylinders of the engine main body 20; an exhaust system 40 for discharging exhaust gas from the engine main body 20; an EGR apparatus 50 for performing exhaust circulation; and an electronic control apparatus 60.

[0020] Fuel injection valves (injection valves, injectors) 21 are disposed above the individual cylinders of the engine main body 20. The fuel injection valves 21 are connected via a fuel line 23 to a fuel injection pump 22 connected to an unillustrated fuel tank. The fuel injection pump 22 is electrically connected to the electronic control apparatus 60. In accordance with a drive signal from the electronic control apparatus 60 (an instruction signal corresponding to an (instruction) base fuel injection pressure Pcrbase to be described later), the fuel injection pump 22 pressurizes fuel in such a manner that the actual injection pressure (discharge pressure) of fuel becomes equal to the instruction base fuel injection pressure Pcrbase.

[0021] Thus, fuel pressurized to the base fuel injection pressure Pcrbase is supplied from the fuel injection pump 22 to the fuel injection valves 21. Moreover, the fuel injection valves 21 are electrically connected to the electronic control apparatus 60. In accordance with a drive signal (an instruction signal corresponding to an (instruction) fuel injection quantity qfin to be described later) from the electronic control apparatus 60, each of the fuel injection valves 21 opens for a predetermined period of time so as to inject, directly to the combustion chamber of the corresponding cylinder, the fuel pressurized to the instruction base fuel injection pressure Pcrbase, in the instruction fuel injection quantity qfin.

[0022] The intake system 30 includes an intake manifold 31, which is connected to the respective combustion chambers of the individual cylinders of the engine main body 20; an intake pipe 32, which is connected to an upstream-side branching portion of the intake manifold 31 and constitutes an intake passage in cooperation with the intake manifold 31; a throttle valve 33, which is rotatably held within the intake pipe 32; a throttle valve actuator 33a for rotating the throttle valve 33 in accordance with a drive signal from the electronic control apparatus 60; an intercooler 34, which is interposed in the intake pipe 32 to be located on the upstream side of the throttle valve 33; a compressor 35a of a turbocharger 35, which is interposed in the intake pipe 32 to be located on the upstream side of the intercooler 34; and an air cleaner 36, which is disposed at a distal end portion of the intake pipe 32.

[0023] The exhaust system 40 includes an exhaust manifold 41, which is connected to the individual cylinders of the engine main body 20; an exhaust pipe 42, which is connected to a downstream-side merging portion of the exhaust manifold 41; a turbine 35b of the turbocharger 35 interposed in the exhaust pipe 42; and a diesel particulate filter (hereinafter referred to as "DPNR") 43, which is interposed in the exhaust pipe 42. The exhaust manifold 41 and the exhaust pipe 42 constitute an exhaust passage.

[0024] The DPNR 43 is a filter unit which accommodates a filter 43a formed of a porous material such as cordierite and which collects, by means of a porous surface, the particulate matter contained in exhaust gas passing through the filter. In the DPNR 43, at least one metal element selected from alkaline metals such as potassium K, sodium Na, lithium Li, and cesium Cs; alkaline-earth metals such as barium Ba and calcium Ca; and rare-earth metals such as lanthanum La and yttrium Y is carried, together with platinum, on alumina serving as a carrier. Thus, the DPNR 43 also serves as a storage-reduction-type NO_x catalyst unit which, after absorption of NO_x, releases the absorbed NO_x and reduces it.

[0025] The EGR apparatus 50 includes an exhaust circulation pipe 51, which forms a passage (EGR passage) for circulation of exhaust gas; an EGR control valve 52, which is interposed in the exhaust circulation pipe 51; and an EGR cooler 53. The exhaust circulation pipe 51 establishes communication between an exhaust passage (the exhaust manifold 41) located on the upstream side of the turbine 35b, and an intake passage (the intake manifold 31) located on the downstream side of the throttle valve 33. The EGR control valve 52 responds to a drive signal from the electronic control apparatus 60 so as to change the quantity of exhaust gas to be circulated (exhaust-gas circulation quantity, EGR-gas flow rate).

[0026] The electronic control apparatus 60 is a microcomputer which includes a CPU 61, ROM 62, RAM 63, backup RAM 64, an interface 65, etc., which are connected to one another by means of a bus. The ROM 62 stores a program to be executed by the CPU 61, tables (lookup tables, maps), constants, etc. The RAM 63 allows the CPU 61 to temporarily store data when necessary. The backup RAM 64 stores data in a state in which the power supply is on, and holds the stored data even after the power supply is shut off. The interface 65 contains A/D converters.

[0027] The interface 65 is connected to a hot-wire-type airflow meter 71, which serves as air flow rate (new air flow rate) measurement means, and is disposed in the intake pipe 32; an intake gas temperature sensor 72, which is provided in the intake passage to be located downstream of the throttle valve 33 and downstream of a point where the exhaust circulation pipe 51 is connected to the intake passage; an intake pipe pressure sensor 73, which is provided in the intake passage to be located downstream of the throttle valve 33 and downstream of the point where the exhaust circulation pipe 51 is connected to the intake passage; a crank position sensor 74; an accelerator opening sensor 75; and an intake-gas oxygen concentration sensor 76 provided in the intake passage to be located downstream of the throttle valve 33 and downstream of the point where the exhaust circulation pipe 51 is connected to the intake passage. The interface 65 receives respective signals from these sensors, and supplies the received signals to the CPU 61. Further, the interface 65 is connected to the fuel injection valves 21, the fuel injection pump 22, the throttle valve actuator 33a, and the EGR control valve 52; and outputs corresponding drive signals to these components in accordance with instructions from the CPU 61.

[0028] The hot-wire-type airflow meter 71 measures the mass flow rate of intake air (new air) passing through the intake passage (intake new air quantity per unit time), and generates a signal indicating the mass flow rate Ga (intake new air flow rate Ga). The intake gas temperature sensor 72 detects the temperature of the above-mentioned intake gas, and generates a signal representing the intake gas temperature Tb. The intake pipe pressure sensor 73 measures the pressure of intake gas (i.e., intake pipe pressure), and generates a signal representing the intake pipe pressure Pb.

[0029] The crank position sensor 74 detects the absolute crank angle of each cylinder, and generates a signal representing the crank angle CA and engine speed NE; i.e., rotational speed of the engine 10. The accelerator opening sensor 75 detects an amount by which an accelerator pedal AP is operated, and generates a signal representing the accelerator pedal operated amount Accp. The intake-gas oxygen concentration sensor 76 detects the oxygen concentration of intake gas (i.e., intake-gas oxygen concentration), and a signal representing intake-gas oxygen concentration RO2_in.

Outline of NO_x Generation Quantity Estimation Method

[0030] Next, there will be described an outline of an NO_x generation quantity estimation method according to the embodiment of the present invention performed by the control apparatus of the internal combustion engine having the above-described configuration (hereinafter may be referred to as the "present apparatus"). FIG. 2 is a diagram schematically showing a state in which gas (intake gas) is taken from the intake manifold 31 into a certain cylinder (cylinder interior) of the engine 10 and is then discharged to the exhaust manifold 41.

[0031] As shown in FIG. 2, intake gas (accordingly, cylinder interior gas) includes new air taken from the tip end of the intake pipe 32 via the throttle valve 33, and EGR gas (including NO_x) taken from the exhaust circulation pipe 51 via the EGR control valve 52. The mass ratio (i.e., EGR ratio) of the mass of the taken EGR gas (EGR gas mass) to the sum of the mass of the taken new air (new air mass) and the mass of the taken EGR gas (EGR gas mass) changes depending on the opening of the throttle valve 33 and the opening of the EGR control valve 52, which are properly controlled by the electronic control apparatus 60 (CPU 61) in accordance with the operating condition.

[0032] During an intake stroke, the intake gas (i.e., gas composed of the new air and the EGR gas containing NO_x) is taken in the cylinder via an opened intake valve Vin as the piston moves downward, and the thus-produced gas mixture serves as cylinder interior gas. The cylinder interior gas is confined within the cylinder when the intake valve Vin closes upon the piston having reached bottom dead center (hereinafter referred to as "ATDC-180°"), and then compressed in a subsequent compression stroke as the piston moves upward. When the piston reaches top dead center (specifically, when a final fuel injection timing finjfin to be described later comes), the present apparatus opens the corresponding fuel injection valve 21 for a predetermined period of time corresponding to the instruction fuel injection quantity qfin, to thereby inject fuel directly into the cylinder. As a result, the injected fuel disperses in the cylinder with elapse of time, while mixing with the cylinder interior gas to produce a gas mixture. The gas mixture starts combustion by means of self ignition at a predetermined timing.

[0033] In the present embodiment, such combustion is assumed to occur only in a combustion region (hereinafter may be referred to as "region B"; see FIG. 2), which is a portion of the combustion chamber and is estimated as described later, and not to occur in a non-combustion region (hereinafter may be referred to as "region A"; see FIG. 2), which is the remaining portion of the combustion chamber other than the region B. Cylinder interior gas remaining in the combustion chamber after combustion is discharged, as exhaust gas, to the exhaust manifold 41 via the exhaust valve Vout, which is held open during the exhaust stroke, as the piston moves upward. The exhaust gas is then discharged to the outside via the exhaust pipe 42.

[0034] Next, a specific method, performed by the present apparatus, for estimating NO_x generation quantity will be described. In the NO_x generation quantity estimation method, upon arrival of each time when the final fuel injection timing finjfin for a cylinder to which fuel is injected (hereinafter referred to as "fuel injection cylinder"), B-region combustion-generated NO_x quantity NOxB (quantity of NO_x generated as a result of combustion in the region B during the expansion stroke immediately after the final fuel injection timing) is estimated.

[0035] The B-region combustion-generated NO_x quantity NOxB can be determined in accordance with the following Eq. (1), as a value obtained through multiplication of a combustion-generated NO_x quantity per unit fuel quantity (hereinafter referred to as "combustion-generated NO_x ratio RNOx_burn") by an instruction fuel injection quantity qfinc (=qfin) in the present operation cycle.

$$\mathrm{NOxB} = \mathrm{RNOx\_burn} \cdot \mathrm{qfinc} \qquad (1)$$

[0036] Here, the combustion-generated NO_x ratio RNOx_burn in above Eq. (1) is estimated in accordance with the following Eq. (2).

$$\mathrm{RNOx\_burn} = e^{K0} \cdot (\mathrm{RO2c})^{K1} \cdot (\mathrm{qfinc})^{K2} \cdot (\mathrm{Pcrc})^{K3} \cdot e^{(K4/\mathrm{Tflame})} \qquad (2)$$

[0037] In Eq. (2), e is the base of a natural logarithm. RO2c is bottom-dead-center intake-gas oxygen concentration; i.e., intake-gas oxygen concentration RO2_in detected by means of the intake-gas oxygen concentration sensor 76 at the time when the intake valve Vin is closed (i.e., ATDC-180°). qfinc is, as used in Eq. (1), instruction fuel injection quantity (= qfin) in the present operation cycle. Pcrc is instruction fuel injection pressure (= Pcrbase) in the present operation cycle.

[0038] In Eq. (2), Tflame is highest flame temperature in the expansion stroke of the present operation cycle. The highest flame temperature Tflame is a peak value of flame temperature during a period between start of combustion of gas mixture and end of the combustion, and can be estimated on the basis of a predetermined function which uses, as arguments, engine speed NE and instruction fuel injection quantity qfinc in the present operation cycle. K0 to K4 are fitting constants which are determined in the manner described below on the basis of typical known multiple regression analysis.

[0039] That is, Eq. (2) is an empirical formula for obtaining the combustion-generated NO_x ratio RNOx_burn. The combustion-generated NO_x ratio RNOx_burn estimated by Eq. (2) is a function of the bottom-dead-center intake-gas oxygen concentration RO2c, the instruction fuel injection quantity qfinc in the present operation cycle, the instruction fuel injection pressure Pcrc in the present operation cycle, and the highest flame temperature Tflame. More specifically, the combustion-generated NO_x ratio RNOx_burn is calculated on the basis of the product of the power of the bottom-dead-center intake-gas oxygen concentration RO2c, the power of the instruction fuel injection quantity qfinc in the present operation cycle, the power of the instruction fuel injection pressure Pcrc in the present operation cycle, and an exponential function whose exponent is determined in accordance with the highest flame temperature Tflame.

[0040] The fitting constants K0 to K4 can be determined, for example, through performance of an experiment as follows. That is, first, the engine 10 is operated while the EGR control valve 52 is maintained closed, whereby all the exhaust gas (accordingly, NO_x contained in the exhaust gas) discharged via the exhaust valve Vout is discharged to the outside from the exhaust passage. With this operation, the quantity of NO_x contained in the exhaust gas discharged to the outside from the exhaust passage (i.e., the above-mentioned NO_x discharge quantity) becomes equal to the B-region combustion-generated NO_x quantity NOxB, whereby it becomes possible to measure the B-region combustion-generated NO_x quantity NOxB (accordingly, the combustion-generated NO_x ratio RNOx_burn (= NOxB/qfinc)) through measurement of the NO_x discharge quantity on the basis of output of a predetermined NO_x concentration sensor.

[0041] Next, in this state, the values of the bottom-dead-center intake-gas oxygen concentration RO2c, the instruction fuel injection quantity qfinc in the present operation cycle, the instruction fuel injection pressure Pcrc in the present operation cycle, and the highest flame temperature Tflame (that is, the engine speed NE and the instruction fuel injection quantity qfinc in the present operation cycle) are successively changed so that combinations of the respective values are attained in various predetermined patterns. Subsequently, the combustion-generated NO_x ratio RNOx_burn is successively measured for each pattern.

[0042] Subsequently, the predetermined known multiple regression analysis is performed on the basis of a large number of data sets regarding the relationship between measured values of the combustion-generated NO_x ratio RNOx_burn and the combinations of the above-mentioned respective values, which were obtained as a result of such a work (experiment), whereby the above-mentioned fitting constants K0 to K4 can be obtained. Here, at least the fitting constants K1 to K3 are determined to assume positive values, and the fitting constants K4 is determined to assume a negative value.

[0043] Accordingly, as is understood from Eq. (2), the combustion-generated NO_x ratio RNOx_burn (accordingly, B-region combustion-generated NO_x quantity NOxB) calculated and estimated in accordance with Eq. (2) increases with an increase in any one of the bottom-dead-center intake-gas oxygen concentration RO2c, the instruction fuel injection quantity qfinc in the present operation cycle, the instruction fuel injection pressure Pcrc in the present operation cycle, and the highest flame temperature Tflame. This matches the actual phenomena described below.

[0044] First, the B-region combustion-generated NO_x quantity NOxB increases with the intake-gas oxygen concentration RO2_in. This phenomenon occurs because oxygen is a material for generation of NO_x, and an increase in the quantity of oxygen within the combustion chamber naturally facilitates generation of NO_x.

[0045] The B-region combustion-generated NO_x quantity NOxB increases with the fuel injection quantity qfin. This phenomenon occurs as follows. When the fuel injection quantity qfin increases, the load of the engine 10 increases, so that the inner wall temperature of the combustion chamber increases. Therefore, the greater the fuel injection quantity qfin (i.e., the greater the load of the engine), the greater the quantity of NO_x that is generated.

[0046] The B-region combustion-generated NO_x quantity NOxB increases with the fuel injection pressure Pcr. This phenomenon occurs as follows. When the fuel injection pressure Pcr is increased, the injection speed of fuel increases with a resultant increase in the degree of atomization of the fuel, whereby the above-mentioned excess air factor increases. Therefore, the greater the fuel injection pressure Pcr (i.e., the greater the degree of atomization of injected fuel), the greater the quantity of NO_x that is generated.

[0047] Moreover, the B-region combustion-generated NO_x quantity NOxB increases with the highest flame temperature Tflame. This phenomenon occurs because increased gas temperature accelerates a chemical reaction of producing NO_x from nitrogen. As is understood from above, when the combustion-generated NO_x ratio RNOx_burn is calculated in accordance with Eq. (2), the combustion-generated NO_x ratio RNOx_burn be accurately estimated (thus, the B-region combustion-generated NO_x quantity NOxB can be accurately estimated in accordance with Eq. (1)) in such a manner that the estimated values follow at least the above-described four actual phenomena. The above is the outline of the NO_x generation quantity estimation method.

Outline of NO_x Discharge Quantity Estimation Method

[0048] Next, there will be describe a specific method for estimating NO_x discharge quantity applied to the internal combustion engine 10 equipped with the EGR apparatus 50 shown in FIG. 2. In the NO_x discharge quantity estimation method, upon each arrival of the final fuel injection timing finjfin for the fuel injection cylinder, the mass of NO_x contained in exhaust gas (i.e., NO_x discharge quantity, actual NO_x discharge quantity NOxact) is estimated, the exhaust gas being discharged from the fuel injection cylinder to the outside via the exhaust valve Vout and the exhaust passage during the exhaust stroke immediately after the final fuel injection timing.

[0049] In this method, for estimation of the actual NO_x discharge quantity NOxact, the ratio of the mass of NO_x present in the above-described region B before combustion to the total mass of NO_x taken in the combustion chamber (hereinafter referred to as "NO_x quantity ratio RatioNOx"), the mass of NO_x remaining in the above-described region A after the combustion, and the mass of NO_x remaining in the above-described region B after the combustion must be estimated. Therefore, the methods for obtaining these values will be described with reference to FIG. 2.

<Method of Obtaining NO_x Quantity Ratio RatioNOx>

[0050] Each of gas components, including oxygen molecules and NOx, of intake gas taken in the combustion chamber (cylinder interior gas) is assumed to be uniformly distributed over the entire region within the combustion chamber. Further, in this state, all oxygen present within the region B is assumed to be consumed by combustion. In this case, the ratio of the "mass of oxygen consumed by combustion" to the "total mass of oxygen taken in the combustion chamber" (hereinafter referred to as "oxygen quantity ratio") represents the ratio of the volume of the region B to the volume of the combustion chamber, and also represents the ratio of the mass of NO_x present in the region B before combustion to the total mass of NO_x taken in the combustion chamber (accordingly, the above-mentioned NO_x quantity ratio RatioNOx). In other words, the region B can be estimated by use of the oxygen quantity ratio.

[0051] Accordingly, the oxygen quantity ratio is obtained in order to obtain the NO_x quantity ratio RatioNOx, and the "total mass of oxygen taken in the combustion chamber" and the "mass of oxygen consumed by combustion" must be obtained in order to obtain the oxygen quantity ratio.

[0052] The "total mass of oxygen taken in the combustion chamber" can be obtained through multiplication of the total mass of gas taken in the combustion chamber (hereinafter referred to as "cylinder interior total gas quantity Gcyl") by the oxygen concentration of the cylinder interior gas before combustion. The cylinder interior total gas quantity Gcyl can be obtained in accordance with Eq. (3), which is based on the state equation of gas at ATDC-180°.

$$\mathrm{Gcyl} = (\mathrm{Pa0}\cdot\mathrm{Va0})/(\mathrm{R}\cdot\mathrm{Ta0}) \qquad (3)$$

[0053] In Eq. (3), Pa0 is bottom-dead-center cylinder interior gas pressure; i.e., cylinder interior gas pressure at ATDC-180°. At ATDC-180°, the cylinder interior gas pressure is considered to be substantially equal to the intake pipe pressure Pb. Therefore, the bottom-dead-center cylinder interior gas pressure Pa0 can be obtained from the intake pipe pressure Pb detected by means of the intake pipe pressure sensor 73 at ATDC-180°. Va0 is bottom-dead-center combustion chamber volume; i.e., combustion chamber volume at ATDC-180°. The combustion chamber volume Va can be represented as a function of the crank angle CA on the basis of the design specifications of the engine 10. Therefore, the bottom-dead-center combustion chamber volume Va0 can be obtained on the basis of the function. Ta0 is bottom-dead-center cylinder interior gas temperature; i.e., cylinder interior gas temperature at ATDC-180°. At ATDC-180°, the cylinder interior gas temperature is considered to be substantially equal to the intake gas temperature Tb. Therefore, the bottom-dead-center cylinder interior gas temperature Ta0 can be obtained from the intake gas temperature Tb detected by means of the intake gas temperature sensor 72 at ATDC-180°. R is the gas constant of the cylinder interior gas.

[0054] Moreover, the oxygen concentration of the cylinder interior gas before combustion can be considered to be substantially equal to the intake-gas oxygen concentration RO2_in at the time when the intake valve Vin is closed (i.e., at ATDC-180°). Therefore, the oxygen concentration of the cylinder interior gas before combustion can be obtained as the bottom-dead-center intake-gas oxygen concentration RO2c used in Eq. (2). From the above, the "total mass of oxygen taken in the combustion chamber" can be represented as "Gcyl·RO2c."

[0055] Meanwhile, the "mass of oxygen consumed by combustion" can be represented as "K·qfinc" under the assumption that the entirety of injected fuel (i.e., fuel in the above-mentioned fuel injection quantity qfin) burns completely at the stoichiometric air-fuel ratio stoich. K is a coefficient, which is a value obtained through multiplication of the mass ratio (0.23) of oxygen contained in the atmosphere by the stoichiometric air-fuel ratio stoich (e.g., 14.6); i.e., "0.23·stoich." As in the case of Eqs. (1) and (2), qfinc is instruction fuel injection quantity (= qfin) in the present operation cycle. From the above, the NO_x quantity ratio RatioNOx can be obtained in accordance with the following Eq. (4).

$$\mathrm{RatioNOx} = (\mathrm{K}\cdot\mathrm{qfinc})/(\mathrm{Gcyl}\cdot\mathrm{RO2c}) \qquad (4)$$

<Method of Obtaining Mass of NO_x Remaining in the Region A after Combustion>

[0056] As described above, in the present embodiment, combustion within the combustion chamber is assumed to occur only in the region B and not to occur in the region A. Therefore, of the mass of NO_x circulated into the combustion chamber via the EGR apparatus 50, the mass of NO_x present within the region A before combustion (hereinafter referred to as "A-region circulated NO_x quantity NOxA") can be considered to be conserved (held) within the region A as it is, even after combustion. In other words, the A-region circulated NO_x quantity NOxA directly represents the "the mass of NO_x remaining in the region A after combustion."

[0057] The ratio of the mass of NO_x present within the region A before combustion to the total mass of NO_x taken in the combustion chamber can be represented by use of the above-mentioned NO_x quantity ratio RatioNOx; i.e., represented as "1 - RatioNOx." Therefore, the A-region circulated NO_x quantity NOxA can be obtained through multiplication of the cylinder interior total gas quantity Gcyl by the NO_x concentration of the cylinder interior gas before combustion and (1 - RatioNOx). Since the NO_x concentration of the cylinder interior gas before combustion can be considered to be substantially equal to the NO_x concentration of intake gas (intake gas NO_x concentration RNOx_in), the A-region circulated NO_x quantity NOxA can be represented by the following Eq. (5).

$$NOxA = RNOx\_in \cdot (1 - RatioNOx) \cdot Gcyl \quad (5)$$

[0058] In Eq. (5), the intake gas NO_x concentration RNOx_in is the mass ratio of the mass of NO_x contained in the EGR gas circulated from the EGR apparatus 50 to the cylinder interior total gas quantity Gcyl. When the NO_x concentration of EGR gas is assumed to be equal to the below-described exhaust gas NO_x concentration RNOx_ex calculated in the previous operation cycle (at the time of fuel injection), the intake gas NO_x concentration RNOx_in can be obtained in accordance with the following Eq. (6).

$$RNOx\_in = (RNOx\_ex \cdot Gegr)/Gcyl \quad (6)$$

[0059] In Eq. (6), Gegr is the mass of EGR gas which has been taken, as a portion of intake gas, from the EGR apparatus 50 into the combustion chamber during the intake stroke of the present operation cycle, and can be obtained in accordance with the following Eq. (7).

$$Gegr = Gcyl - Gm \quad (7)$$

[0060] In Eq. (7), Gm represents the mass (intake new air quantity) of new air which has been taken, as a portion of intake gas, from the tip end of the intake pipe 32 into the combustion chamber during the intake stroke of the present operation cycle, and is calculated on the basis of the intake new air quantity per unit time (intake new air flow rate Ga) measured by means of the airflow meter 71, the engine speed NE based on the output of the crank position sensor 74, and a function f(Ga, NE) which uses the intake new air flow rate Ga and the engine speed NE, as arguments, so as to obtain quantity of intake new air per intake stroke. A bottom-dead-center intake new air flow rate Ga0 and a bottom-dead-center engine speed NE0, which are detected by the corresponding sensors at ATDC-180°, are used as the intake new air flow rate Ga and the engine speed NE, respectively. As described above, the A-region circulated NO_x quantity NOxA, and thus the "mass of NO_x remaining in the region A after combustion" can be obtained in accordance with the above-described Eq. (5).

<Method of Obtaining Mass of NO_x Remaining in the Region B after Combustion>

[0061] As a result of combustion, NO_x is generated in the region B, and the quantify of the generated NO_x (the B-region combustion-generated NOx quantity NOxB) is estimated by the above-described Eqs. (1) and (2). The thus-estimated B-region combustion-generated NO_x quantity NOxB can be considered to be substantially equal to "the mass of NO_x remaining in the region B after combustion." Therefore, the "mass of NO_x remaining in the region B after combustion" can be obtained as the B-region combustion-generated NO_x quantity NOxB estimated in accordance with the above-described Eqs. (1) and (2).

[0062] Once the A-region circulated NO_x quantity NOxA, which is the "mass of NO_x remaining in the region A after combustion," and the B-region combustion-generated NO_x quantity NOxB, which is the "mass of NO_x remaining in the region B after combustion, are obtained, the total mass of NO_x remaining in the combustion chamber after combustion can be obtained as "NOxA + NOxB." Moreover, the total mass of gas remaining in the combustion chamber after combustion can be obtained as "Gcyl + qfinc."

[0063] Accordingly, the NO_x concentration (exhaust gas NO_x concentration RNOx_ex) of exhaust gas discharged from the combustion chamber to the exhaust passage (exhaust manifold 41) via the exhaust valve Vout during the exhaust stroke is equal to the mass ratio of the "total mass of NO_x remaining in the combustion chamber after combustion" to the "total mass of gas remaining in the combustion chamber after combustion," and can be obtained in accordance with the following Eq. (8).

$$RNOx\_ex = (NOxA + NOxB)/(Gcyl + qfinc) \quad (8)$$

[0064] As described above, the previous value of the exhaust gas NOx concentration RNOx_ex obtained in accordance with Eq. (8) is used in the above-described Eq. (6) for obtaining the intake gas NO_x concentration RNOx_in, under the assumption that the NO_x concentration of exhaust gas flowing through the exhaust passage (exhaust manifold 41) is equal to the NO_x concentration of EGR gas flowing through the exhaust circulation pipe 51.

[0065] When the NO_x concentration of exhaust gas flowing through the exhaust passage (exhaust manifold 41 and exhaust pipe 42) is assumed to be constant over the entire region of the exhaust passage, the exhaust gas NO_x

concentration RNOx_ex becomes equal to the NO_x concentration of exhaust gas discharged to the outside from the exhaust passage (specifically, the end of exhaust pipe 42).

[0066] Moreover, in an ordinary operation state (in particular, in a steady operation state) of the engine 10, the mass per operation cycle (exhaust stroke) of exhaust gas which is discharged to the outside from the exhaust passage (exhaust pipe 42) is substantially equal to the above-mentioned intake new air quantity Gm. As is understood from the above, the mass per operation cycle of NO_x contained in exhaust gas which is discharged to the outside via the exhaust passage (the above-mentioned actual NO_x discharge quantity NOxact) can be obtained in accordance with Eq. (9). Eq. (9) shows that as the EGR gas quantity Gegr increases, the intake new air quantity Gm decreases, whereby the actual NO_x discharge quantity NOxact decreases. Accordingly, the phenomenon that the actual NO_x discharge quantity NOxact decreases as the EGR gas quantity Gegr increases can be accurately expressed.

$$\mathrm{NOxact} = \mathrm{RNOx\_ex} \cdot \mathrm{Gm} \tag{9}$$

[0067] As described above, upon each arrival of the final fuel injection timing finjfin for the fuel injection cylinder, the present apparatus estimates, by use of Eqs. (1) to (9), the actual NO_x discharge quantity NOxact; i.e., the mass of NO_x discharged from the fuel injection cylinder via the exhaust valve Vout in the exhaust stroke immediately after the injection timing. The above is the outline of the NO_x discharge quantity estimation method.

<Outline of Fuel Injection Control>

[0068] The present apparatus, which performs the above-mentioned NO_x discharge quantity estimation method, calculates, at predetermined intervals, a target NO_x discharge quantity per operation cycle NOxt on the basis of the above-mentioned fuel injection quantity qfin and engine speed NE. Subsequently, the present apparatus feedback-controls the final fuel injection start timing finjfin and the opening of the EGR control valve 52 in such a manner that the actual NO_x discharge quantity NOxact estimated in the previous operation cycle coincides with the target NO_x discharge quantity NOxt.

[0069] Specifically, when the actual NO_x discharge quantity NOxact estimated in the previous operation cycle is greater than the target NO_x discharge quantity NOxt, the final fuel injection start timing finjfin to be applied for the fuel injection cylinder in the present operation cycle is delayed from the base fuel injection start timing finjbase by a predetermined amount, and the opening of the EGR control valve 52 is increased from the current degree by a predetermined amount. As a result, the highest flame temperature of the fuel injection cylinder in the present operation cycle is controlled to decrease, whereby the actual NO_x discharge quantity NOxact; i.e., the quantity of NO_x discharged from the fuel injection cylinder to the outside in the present operation cycle, is rendered coincident with the target NO_x discharge quantity NOxt.

[0070] Meanwhile, when the actual NO_x discharge quantity NOxact estimated in the previous operation cycle is smaller than the target NO_x discharge quantity NOxt, the final fuel injection start timing finjfin to be applied for the fuel injection cylinder in the present operation cycle is advanced from the base fuel injection start timing finjbase by a predetermined amount, and the opening of the EGR control valve 52 is decreased from the current degree by a predetermined amount. As a result, the highest flame temperature of the fuel injection cylinder in the present operation cycle is controlled to increase, whereby the actual NO_x discharge quantity NOxact; i.e., the quantity of NO_x discharged from the fuel injection cylinder to the outside in the present operation cycle, is rendered coincident with the target NO_x discharge quantity NOxt. The above is the outline of fuel injection control.

<Actual Method of Calculating Combustion-Generated NO_x Ratio RNOx_burn>

[0071] Calculation of the combustion-generated NO_x Ratio RNOx_burn performed in accordance with Eq. (2) requires calculation of "power" and "multiplication." However, in general, when calculation of "power" is performed by use of a microcomputer, the calculation load tends to increase; and when calculation of "multiplication" is performed by use of a microcomputer, the calculation accuracy tends to decrease. Therefore, in order to avoid calculation of "power" and "multiplication," the present apparatus (CPU 61) calculates the combustion-generated NO_x Ratio RNOx_burn by means of only table search and "addition," while utilizing the following Eq. (10), which is obtained by taking natural logarithms of both sides of Eq. (2).

$$\begin{aligned}\log(\mathrm{RNOx\_burn}) = {} & \mathrm{K0} + \mathrm{K1}\cdot\log(\mathrm{RO2c}) + \mathrm{K2}\cdot\log(\mathrm{qfinc}) + \\ & \mathrm{K3}\cdot\log(\mathrm{Pcrc}) + \mathrm{K4}/\mathrm{Tflame}\end{aligned} \tag{10}$$

[0072] That is, on the basis of tables Maplog1 (RO2c), Maplog2(qfinc), Maplog3(Pcrc), and Mapinvpro(Tflame), which are previously stored in the ROM 62 for obtaining the respective values of the second through fifth terms of the right side of Eq. (10), the present apparatus determines respective table search values dataMap1 (= K1·log(RO2c)), dataMap2 (= K2·log(qfinc)), dataMap3 (= K3·log(Pcrc)), and dataMap4 (= K4/Tflame), and then obtains the value of "log(RNOx_burn)" in accordance with the following Eq. (11), which includes "addition calculation" only.

$$\text{log(RNOx\_burn)} = \text{K0} + \text{dataMap1} + \text{dataMap2} + \text{dataMap3} + \text{dataMap4} \qquad (11)$$

[0073] Subsequently, the present apparatus obtains the combustion-generated NO$_x$ Ratio RNOx_burn on the basis of a table Mapinvlog(log(RNOx_burn)), which is stored in the ROM 62 in order to obtain the combustion-generated NO$_x$ Ratio RNOx_burn from the "log(RNOx_burn)" obtained in accordance with Eq. (11). This calculation procedure reduces the calculation load of the CPU 61 and prevents deterioration of calculation accuracy.

Actual Operation

[0074] Next, actual operations of the control apparatus of the internal combustion engine having the above-described configuration will be described.

<Control of Fuel Injection Quantity, Etc.>

[0075] The CPU 61 repeatedly executes, at predetermined intervals, a routine shown by the flowchart of FIG. 3 and adapted to control fuel injection quantity, etc. Therefore, when a predetermined timing has been reached, the CPU 61 starts the processing from step 300, and then proceeds to step 305 so as to obtain an (instruction) fuel injection quantity qfin from an accelerator opening Accp, an engine speed NE, and a table (map) Mapqfin shown in FIG. 4. The table Mapqfin defines the relation between accelerator opening Accp and engine speed NE, and fuel injection quantity qfin; and is stored in the ROM 62.

[0076] Subsequently, the CPU 61 proceeds to step 310 so as to determine a base fuel injection timing finjbase from the fuel injection quantity qfin, the engine speed NE, and a table Mapfinjbase shown in FIG. 5. The table Mapfinjbase defines the relation between fuel injection quantity qfin and engine speed NE, and base fuel injection timing finjbase; and is stored in the ROM 62.

[0077] Subsequently, the CPU 61 proceeds to step 315 so as to determine a base fuel injection pressure Pcrbase from the fuel injection quantity qfin, the engine speed NE, and a table MapPcrbase shown in FIG. 6. The table MapPcrbase defines the relation between fuel injection quantity qfin and engine speed NE, and base fuel injection pressure Pcrbase; and is stored in the ROM 62.

[0078] Subsequently, the CPU 61 proceeds to step 320 so as to determine a target NO$_x$ discharge quantity NOxt from the fuel injection quantity qfin, the engine speed NE, and a table MapNOxt shown in FIG. 7. The table MapNOxt defines the relation between fuel injection quantity qfin and engine speed NE, and target NOx discharge quantity NOxt; and is stored in the ROM 62.

[0079] Subsequently, the CPU 61 proceeds to step 325 so as to store, as an NO$_x$ discharge quantity deviation ΔNOx, a value obtained through subtraction, from the target NO$_x$ discharge quantity NOxt, of the latest actual NO$_x$ discharge quantity NOxact, which is computed at a fuel injection timing in a previous operation cycle by a routine to be described later.

[0080] Subsequently, the CPU 61 proceeds to step 330 so as to determine an injection-timing correction value Δθ from the NO$_x$ discharge quantity deviation ΔNOx and a table MapΔθ shown in FIG. 8. The table MapΔθ defines the relation between NOx discharge quantity deviation ΔNOx and injection-timing correction value Δθ, and is stored in the ROM 62.

[0081] Next, the CPU 61 proceeds to step 335 so as to correct the base fuel injection timing finjbase by the injection-timing correction value Δθ to thereby obtain a final fuel injection timing finjfin. Thus, the fuel injection timing is corrected in accordance with the NO$_x$ discharge quantity deviation ΔNOx. As is apparent from FIG. 8, when the NO$_x$ discharge quantity deviation ΔNOx is positive, the injection-timing correction value Δθ becomes positive, and its magnitude increases with the magnitude of the NO$_x$ discharge quantity deviation ΔNOx, whereby the final fuel injection timing finjfin is shifted toward the advance side. When the NO$_x$ discharge quantity deviation ΔNOx is negative, the injection-timing correction value Δθ becomes negative, and its magnitude increases with the magnitude of the NO$_x$ discharge quantity deviation ΔNOx, whereby the final fuel injection timing finjfin is shifted toward the retard side.

[0082] Subsequently, the CPU 61 proceeds to step 340 so as to determine whether the injection start timing (i.e., the final fuel injection timing finjfin) is reached for the fuel injection cylinder. When the CPU 61 makes a "No" determination in step 340, the CPU 61 proceeds directly to step 395 so as to end the current execution of the present routine.

[0083] In contrast, when the CPU 61 makes a "Yes" determination in step 340, the CPU 61 proceeds to step 345 so as to inject fuel in an amount of the (instruction) fuel injection quantity qfin into the fuel injection cylinder from the fuel injection valve 21 at the base fuel injection pressure Pcrbase. In the subsequent step 350, the CPU 61 determines whether the NO_x discharge quantity deviation ΔNOx is positive. When the CPU 61 makes a "Yes" determination in step 350, the CPU 61 proceeds to step 355 so as to reduce the opening of the EGR control valve 52 from the current degree by a predetermined amount. Subsequently, the CPU 61 proceeds to step 370.

[0084] When the CPU 61 makes a "No" determination in step 350, the CPU 61 proceeds to step 360 so as to determine whether the NO_x discharge quantity deviation ΔNOx is negative. When the CPU 61 makes a "Yes" determination in step 360, the CPU 61 proceeds to step 365 so as to increase the opening of the EGR control valve 52 from the current degree by a predetermined amount. Subsequently, the CPU 61 proceeds to step 370. When the CPU 61 makes a "No" determination in step 360 (i.e., when the NO_x discharge quantity deviation ΔNOx is zero), the CPU 61 proceeds to step 370 without changing the opening of the EGR control valve 52.

[0085] In this manner, the opening of the EGR control valve 52 is changed according to the NO_x discharge quantity deviation ΔNOx. In step 370, the CPU 61 stores, as the fuel injection quantity qfinc in the present operation cycle, the fuel injection quantity qfin actually injected. In the subsequent step 375, the CPU 61 stores, as the fuel injection pressure Pcrc in the present operation cycle, the base fuel injection pressure Pcrbase at which fuel was actually injected. Subsequently, the CPU 61 proceeds to step 395 so as to end the current execution of the present routine. Through the above-described processing, control of fuel injection quantity, fuel injection timing, fuel injection pressure, and opening of the EGR control valve 52 is achieved.

<Calculation of NO_x Discharge Quantity>

[0086] Meanwhile, the CPU 61 repeatedly executes, at predetermined intervals, a routine shown by the flowcharts of FIG. 9 and adapted to calculate actual NO_x discharge quantity NOxact. Therefore, when a predetermined timing has been reached, the CPU 61 starts the processing from step 900, and then proceeds to step 905 so as to determine whether the crank angle CA at the present point in time coincides with ATDC-180°.

[0087] Description will be continued under the assumption that the crank angle CA at the present point in time has not yet reached ATDC-180°. In this case, the CPU 61 makes a "No" determination in step 905, and then proceeds directly to step 935 so as to determine whether the fuel injection start timing (i.e., the final fuel injection timing finjfin) for the fuel injection cylinder has come. Since the crank angle CA at the present point in time has not yet reached ATDC-180°, the CPU 61 makes a "No" determination in step 935, and then proceeds directly to step 995 so as to end the current execution of the present routine.

[0088] After that, the CPU 61 repeatedly performs the processing of steps 900, 905, 935, and 995 until the crank angle CA reaches ATDC-180°. When the crank angle CA has reached ATDC-180°, the CPU 61 makes a "Yes" determination when it proceeds to step 905, and then proceeds to step 910. In step 910, the CPU 61 stores, as bottom-dead-center cylinder interior gas temperature Ta0, bottom-dead-center cylinder interior gas pressure Pa0, bottom-dead-center intake new air flow rate Ga0, and bottom-dead-center engine speed NE0, respectively, the intake gas temperature Tb, the intake pipe pressure Pb, the intake new air flow rate Ga, and the engine speed NE, which are detected by means of the intake gas temperature sensor 72, the intake pipe pressure sensor 73, the airflow meter 71, and the crank position sensor 74, respectively, at the present point in time (ATDC-180°).

[0089] Subsequently, the CPU 61 proceeds to step 915 so as to store, as bottom-dead-center intake-gas oxygen concentration RO2c, the intake-gas oxygen concentration RO2_in detected by means of the intake-gas oxygen concentration sensor 76 at the present point in time (ATDC-180°). In the subsequent step 920, the CPU 61 computes the cylinder interior total gas quantity Gcyl in accordance with the above-described Eq. (3). Here, the values stored at step 910 are employed as the bottom-dead-center cylinder interior gas pressure Pa0 and the bottom-dead-center cylinder interior gas temperature Ta0.

[0090] Subsequently, the CPU 61 proceeds to step 925 so as to compute an intake new air quantity Gm from the bottom-dead-center intake new air flow rate Ga0 and the bottom-dead-center engine speed NE0 in accordance with the above-defined function f. In the subsequent step 930, the CPU 61 computes an EGR gas quantity Gegr on the basis of the cylinder interior total gas quantity Gcyl computed in step 920 and the intake new air quantity Gm, and in accordance with the above-described Eq. (7). Subsequently, the CPU 61 proceeds to step 935 so as to make a "No" determination, and then proceeds to step 995 so as to end the current execution of the present routine.

[0091] After that, the CPU 61 repeatedly performs the processing of steps 900, 905, 935, and 995 until the fuel injection timing (i.e., the final fuel injection timing finjfin) comes. When the final fuel injection timing finjfin comes, the CPU 61 makes a "Yes" determination in step 935 and then proceeds to step 940 so as to calculate the intake gas NO_x concentration RNOx_in in accordance with the above-described Eq. (6). Here, the values computed in steps 930 and

920 are employed as the EGR gas quantity Gegr and the cylinder interior total gas quantity Gcyl, respectively. The value which has been computed in step 965 (to be described later) at the fuel injection start timing in the previous operation cycle is employed as the exhaust gas NO_x concentration RNOx_ex.

[0092] Subsequently, the CPU 61 proceeds to step 945 so as to compute an A-region circulated NO_x quantity NOxA in accordance with the equation shown in step 945 of FIG. 9; the equation corresponding to the above-described Eqs. (4) and (5). Here, the latest value stored in step 370 of FIG. 3 is employed as the fuel injection quantity qfinc in the present operation cycle. After that, the CPU 61 proceeds via step 950 to step 1000 of FIG. 10 so as to start processing for computing a combustion-generated NO_x ratio RNOx_burn.

[0093] When the CPU 61 proceeds from step 1000 to 1005, the CPU 61 estimates and determines the highest flame temperature Tflame from the engine speed NE at the present point in time, the fuel injection quantity qfinc in the present operation cycle, and a table (shown in the step 1005 of FIG. 10) which is used for obtaining the highest flame temperature Tflame.

[0094] Subsequently, the CPU 61 proceeds to step 1010 so as to obtain the above-mentioned table search value dataMap1 (= K1·log(RO2c)) from the latest value of the bottom-dead-center intake-gas oxygen concentration RO2c, which has been obtained in step 915 of FIG. 9, and the above-described table Maplog1.

[0095] Similarly, the CPU 61 proceeds to step 1015 so as to obtain the above-mentioned table search value dataMap2 (= K2·log(qfinc)) from the fuel injection quantity qfinc in the present operation cycle, which has been stored in step 370 of FIG. 3, and the above-described table Maplog2. In the subsequent step 1020, the CPU 61 obtains the above-mentioned table search value dataMap3 (= K3·log(Pcrc)) from the fuel injection pressure Pcrc in the present operation cycle, which has been stored in step 375 of FIG. 3, and the above-described table Maplog3. In the subsequent step 1025, the CPU 61 obtains the above-mentioned table search value dataMap4 (= K4/Tflame)) from the latest highest flame temperature Tflame, which has been determined in step 1005, and the above-described table Mapinvpro.

[0096] Subsequently, the CPU 61 proceeds to step 1030 so as to obtain "log(RNOx_burn)" in accordance with the above-described Eq. (11). In the subsequent step 1035, the CPU 61 determines a combustion-generated NO_x ratio RNOx_burn from the log(RNOx_burn) and the above-described table Mapinvlog, and then proceeds via step 1095 to step 955 of FIG. 9.

[0097] When the CPU 61 proceeds to step 955, the CPU 61 determines a B-region combustion-generated NO_x quantity NOxB in accordance with the above-described Eq. (1). Subsequently, the CPU 61 proceeds to step 960 so as to determine an exhaust gas NO_x concentration RNOx_ex in accordance with the above-described Eq. (8). In the subsequent step 965, the CPU 61 determines an actual NO_x discharge quantity NOxact in accordance with the above-described Eq. (9), and then proceeds to step 995 so as to end the current execution of the present routine. After that, the CPU 61 repeatedly performs the processing of steps 900, 905, 935, and 995 until ATDC-180° for the fuel injection cylinder comes again.

[0098] As described in the above processing, a new latest actual NO_x discharge quantity NOxact is obtained each time the fuel injection start timing comes. The obtained new actual NO_x discharge quantity NOxact is used in step 325 of FIG. 3 as described above. As a result, the final fuel injection timing finjfin and the opening of the EGR control valve 52 to be applied to the fuel injection cylinder in the next operation cycle are feedback-controlled on the basis of the new actual NO_x discharge quantity NOxact.

[0099] As described above, the NO_x generation quantity estimation method for an internal combustion engine according to the embodiment of the present invention estimates B-region combustion-generated NO_x quantity NOxB; i.e., the quantity of NO_x generated in a combustion region (region B) as a result of combustion, on the basis of the following four peripheral condition quantities which largely affect the B-region combustion-generated NO_x quantity NoxB: the concentration of a gas in intake gas serving as a raw material for generating NO_x (intake gas oxygen concentration RO2c), a load index value representing the degree of load of the engine (fuel injection quantity qfinc), an atomization index value representing the degree of atomization of fuel in combustion chamber (fuel injection pressure Pcrc), and the highest flame temperature Tflame. Therefore, the B-region combustion-generated NO_x quantity NOxB can be accurately estimated to accurately follow the actual relation between the above four peripheral condition quantities and the B-region combustion-generated NO_x quantity NOxB.

[0100] The present invention is not limited to the above-described embodiment, and may be modified in various manners within the scope of the present invention. For example, the following modifications may be employed. In the above-described embodiment, fuel injection quantity qfinc is employed as the load index value representing the degree of load of the engine, but output torque of the engine may be employed as the load index value. In addition, the inside wall temperature of the combustion chamber may be employed as the load index value.

[0101] In the above-described embodiment, fuel injection pressure Pcrc is employed as the atomization index value representing the degree of fuel atomization in the combustion chamber, but swirl ratio may be employed as the atomization index value. In addition, excess air ratio in the combustion region (region B) may be employed as the atomization index value.

[0102] In the above-described embodiment, the highest flame temperature Tflame is estimated on the basis of engine speed NE and fuel injection quantity qfinc, but the highest flame temperature Tflame may be estimated on the basis of engine speed NE and output torque of the engine.

Claims

1. An NO_x generation quantity estimation method for an internal combustion engine, **characterized in that** a quantity of NO_x generated in a combustion chamber of the internal combustion engine as a result of combustion of gas mixture containing fuel and air is estimated, as a combustion-generated NO_x quantity, on the basis of a peripheral condition quantity in relation to the gas mixture which affects the combustion-generated NO_x quantity.

2. An NO_x generation quantity estimation method for an internal combustion engine according to claim 1, wherein the combustion-generated NO_x quantity is estimated on the basis of at least a load index value which represents the degree of load of the engine and serves as the peripheral condition quantity.

3. An NO_x generation quantity estimation method for an internal combustion engine according to claim 2, wherein the load index value is a value based on at least one of fuel injection quantity, drive torque of the engine and temperature of the inner wall surface of the combustion chamber.

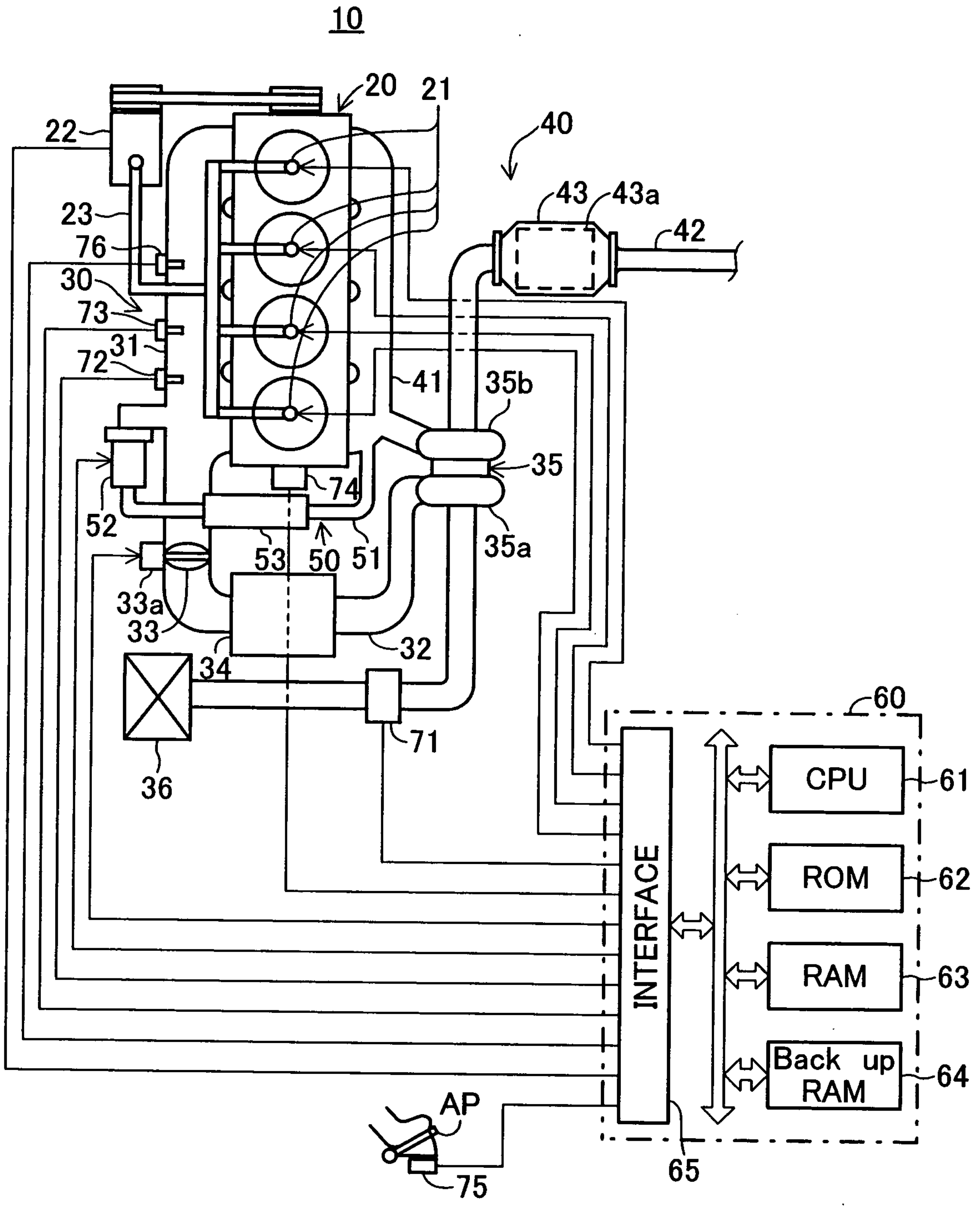
4. An NO_x generation quantity estimation method for an internal combustion engine according to claim 1 or 2, wherein the combustion-generated NO_x quantity is estimated on the basis of at least an atomization index value which represents the degree of atomization of fuel chamber and serves as the peripheral condition quantity.

5. An NO_x generation quantity estimation method for an internal combustion engine according to claim 4, wherein the atomization index value is a value based on at least one of fuel injection pressure, swirl ratio and excess air ratio in a region where combustion occurs.

6. An NO_x discharge quantity estimation method for an internal combustion engine adapted to estimate, as an NO_x discharge quantity, a quantity of NO_x contained in exhaust gas discharged from an exhaust passage of the engine to the outside, **characterized by** comprising the steps of:

   estimating a combustion region, the combustion region being a portion of a combustion chamber in which combustion of gas mixture containing fuel and air occurs;
   estimating, by use of the NO_x generation quantity estimation method according to any one of claims 1 to 5, a quantity of NO_x generated in the combustion region as a result of the combustion of the gas mixture as a combustion-generated NO_x quantity;
   estimating a quantity of NO_x in a non-combustion region, the non-combustion region being the remaining portion of the combustion chamber; and
   estimating the NO_x discharge quantity on the basis of the combustion-generated NO_x quantity and the quantity of NO_x in the non-combustion region.

FIG.1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43a
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41
35b
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35a
74
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50
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33a
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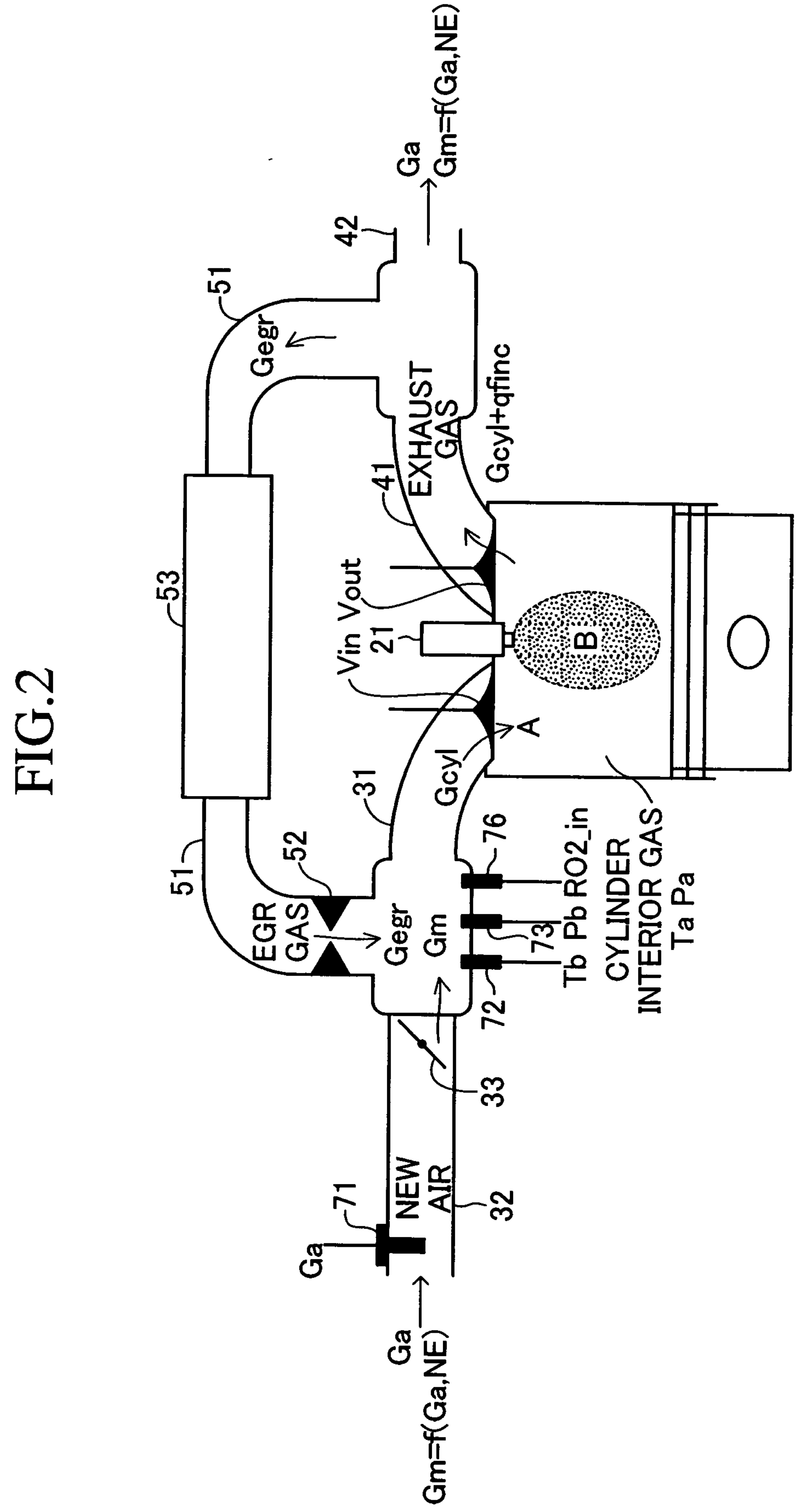
34
32
36
71
60
CPU
61
ROM
62
RAM
63
Back up RAM
64
INTERFACE
65
AP
75

FIG.2


Ga
Gm=f(Ga,NE)
Ga
71
NEW AIR
32
33
72
73
76
Tb Pb RO2_in
CYLINDER INTERIOR GAS
Ta Pa
EGR GAS
52
51
Gegr
Gm
31
Gcyl
A
Vin Vout
21
B
41
EXHAUST GAS
Gcyl+qfinc
53
51
Gegr
42
Ga
Gm=f(Ga,NE)

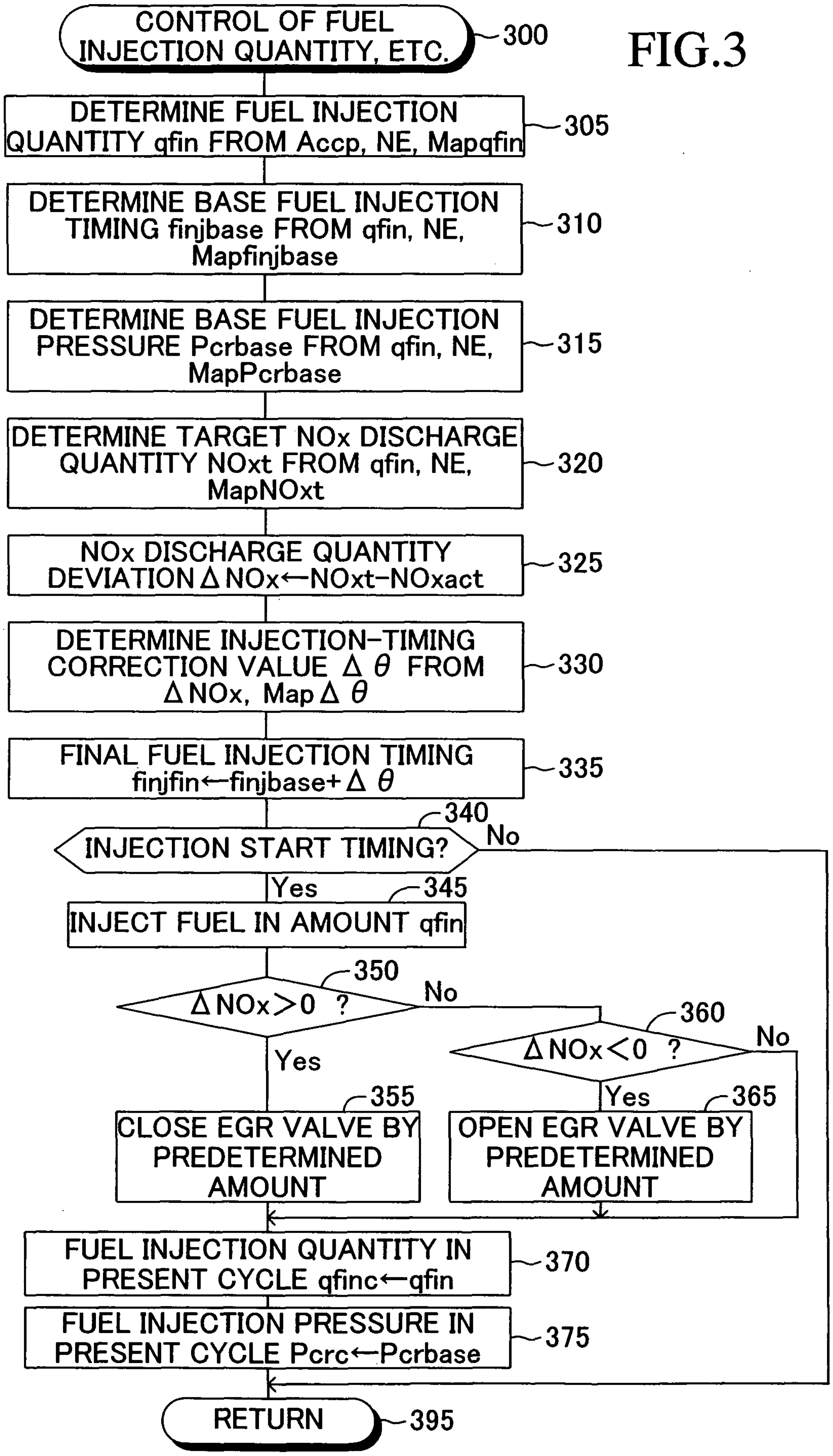

CONTROL OF FUEL INJECTION QUANTITY, ETC.
300
DETERMINE FUEL INJECTION QUANTITY qfin FROM Accp, NE, Mapqfin
305
DETERMINE BASE FUEL INJECTION TIMING finjbase FROM qfin, NE, Mapfinjbase
310
DETERMINE BASE FUEL INJECTION PRESSURE Pcrbase FROM qfin, NE, MapPcrbase
315
DETERMINE TARGET NOx DISCHARGE QUANTITY NOxt FROM qfin, NE, MapNOxt
320
NOx DISCHARGE QUANTITY DEVIATION ΔNOx←NOxt−NOxact
325
DETERMINE INJECTION−TIMING CORRECTION VALUE Δθ FROM ΔNOx, MapΔθ
330
FINAL FUEL INJECTION TIMING finjfin←finjbase+Δθ
335
340
INJECTION START TIMING?
No
Yes
345
INJECT FUEL IN AMOUNT qfin
350
ΔNOx>0 ?
No
360
ΔNOx<0 ?
No
Yes
Yes
355
CLOSE EGR VALVE BY PREDETERMINED AMOUNT
365
OPEN EGR VALVE BY PREDETERMINED AMOUNT
FUEL INJECTION QUANTITY IN PRESENT CYCLE qfinc←qfin
370
FUEL INJECTION PRESSURE IN PRESENT CYCLE Pcrc←Pcrbase
375
RETURN
395

FIG.3

FIG.4

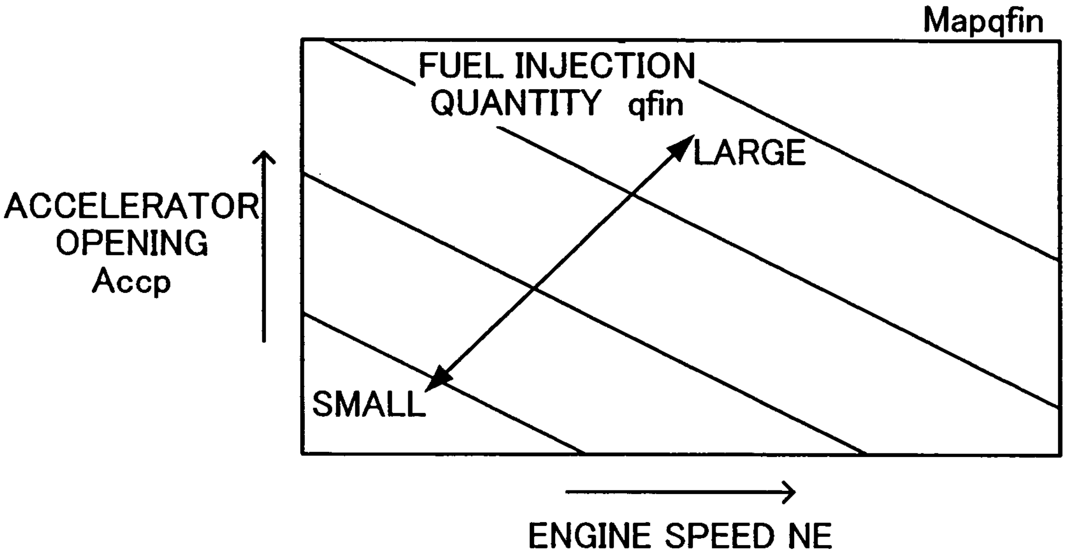

Mapqfin
FUEL INJECTION
QUANTITY qfin
LARGE
SMALL
ACCELERATOR
OPENING
Accp
ENGINE SPEED NE

FIG.5

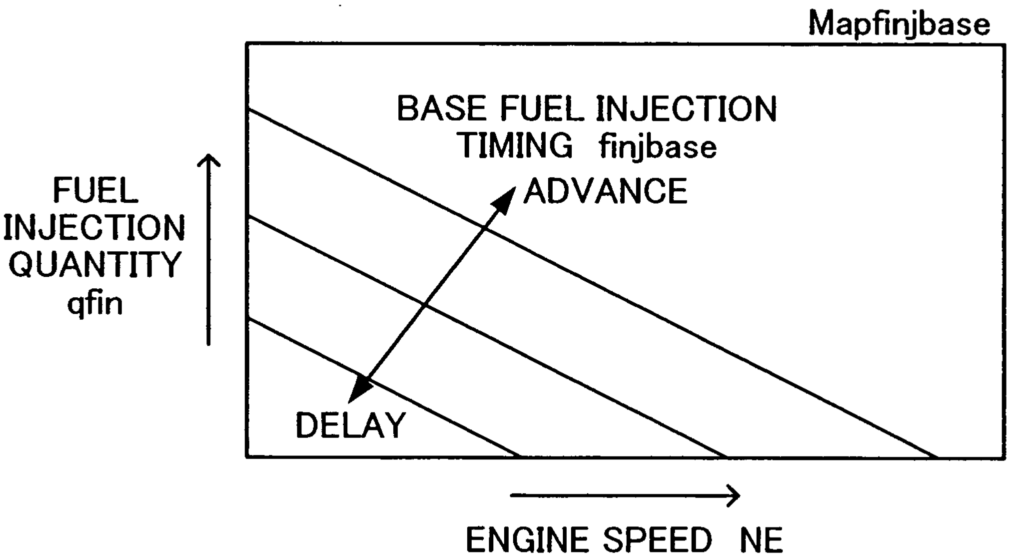

Mapfinjbase
BASE FUEL INJECTION
TIMING finjbase
ADVANCE
DELAY
FUEL
INJECTION
QUANTITY
qfin
ENGINE SPEED NE

FIG.6

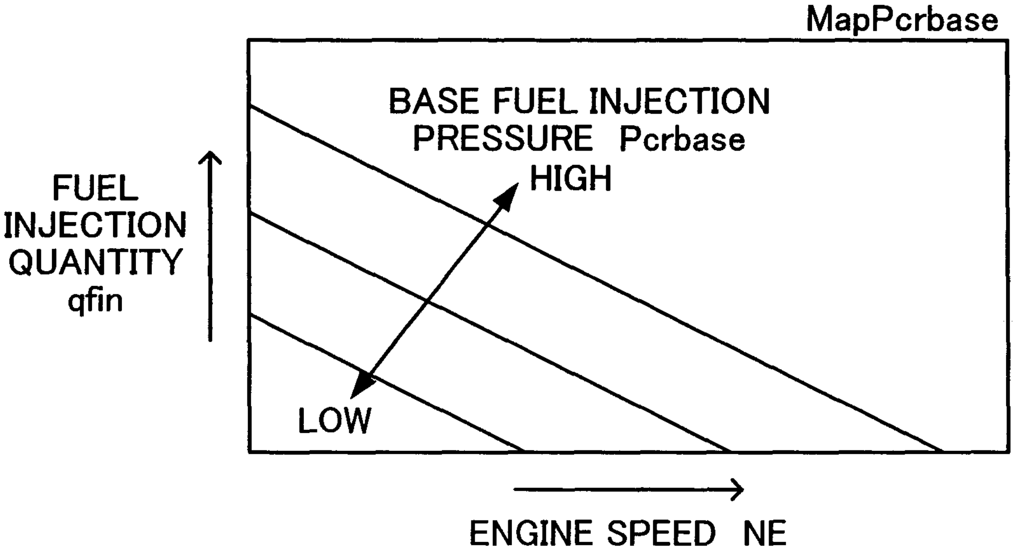

MapPcrbase
BASE FUEL INJECTION PRESSURE Pcrbase
HIGH
LOW
FUEL INJECTION QUANTITY qfin
ENGINE SPEED NE

FIG.7

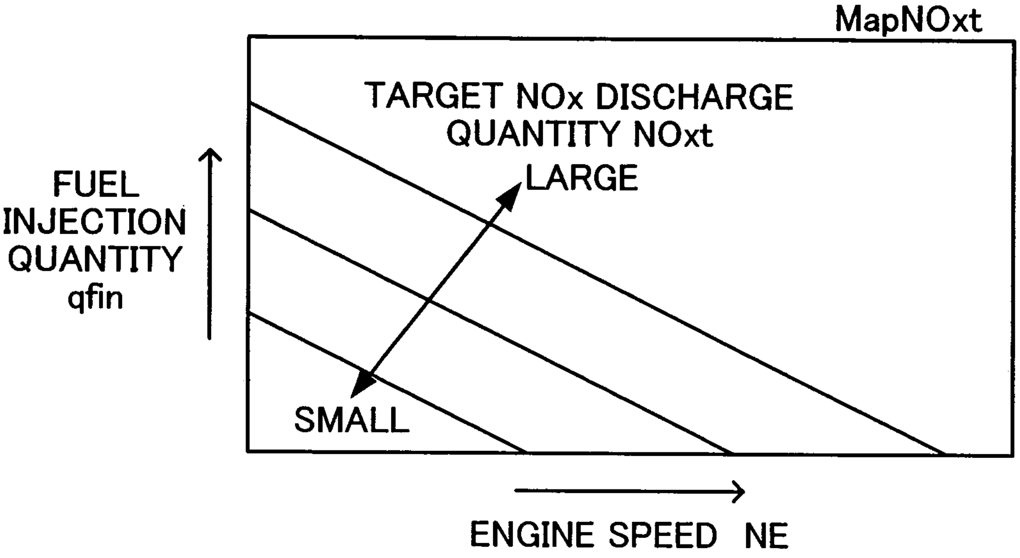

MapNOxt
TARGET NOx DISCHARGE QUANTITY NOxt
LARGE
SMALL
FUEL INJECTION QUANTITY qfin
ENGINE SPEED NE

FIG.8

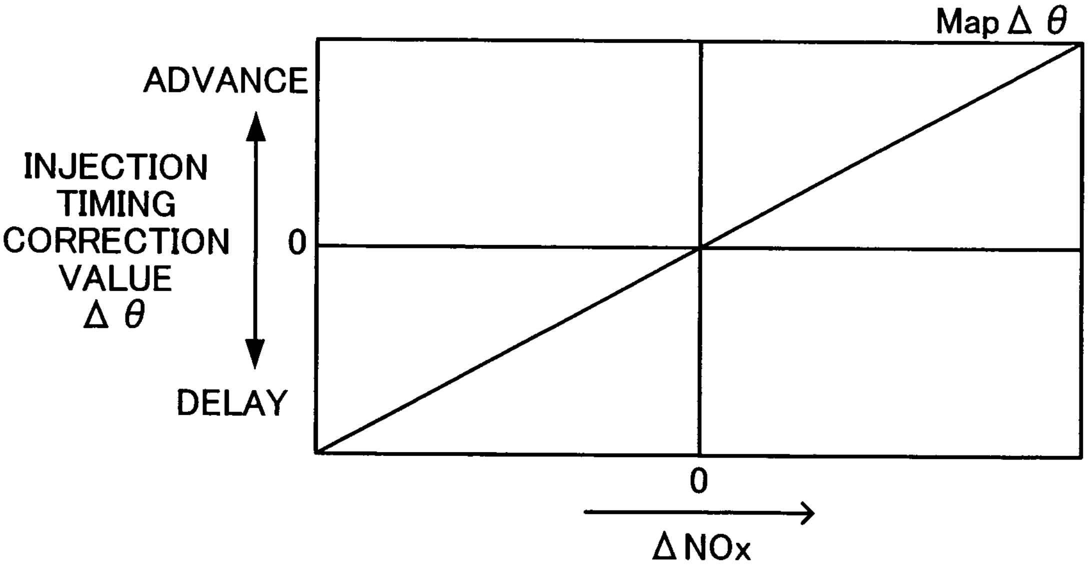

Map Δ θ
ADVANCE
INJECTION TIMING CORRECTION VALUE Δ θ
0
DELAY
0
Δ NOx

FIG.9

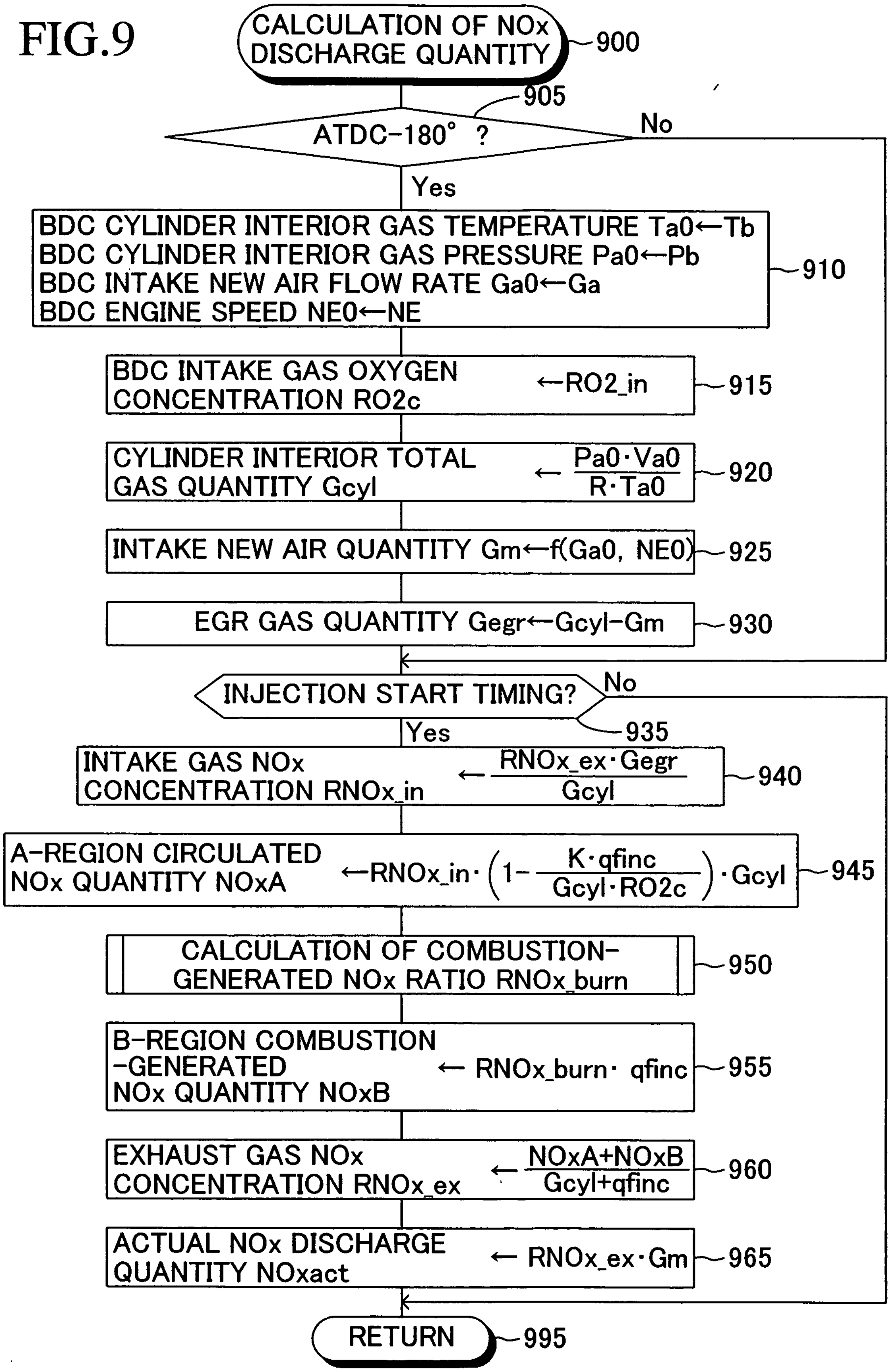
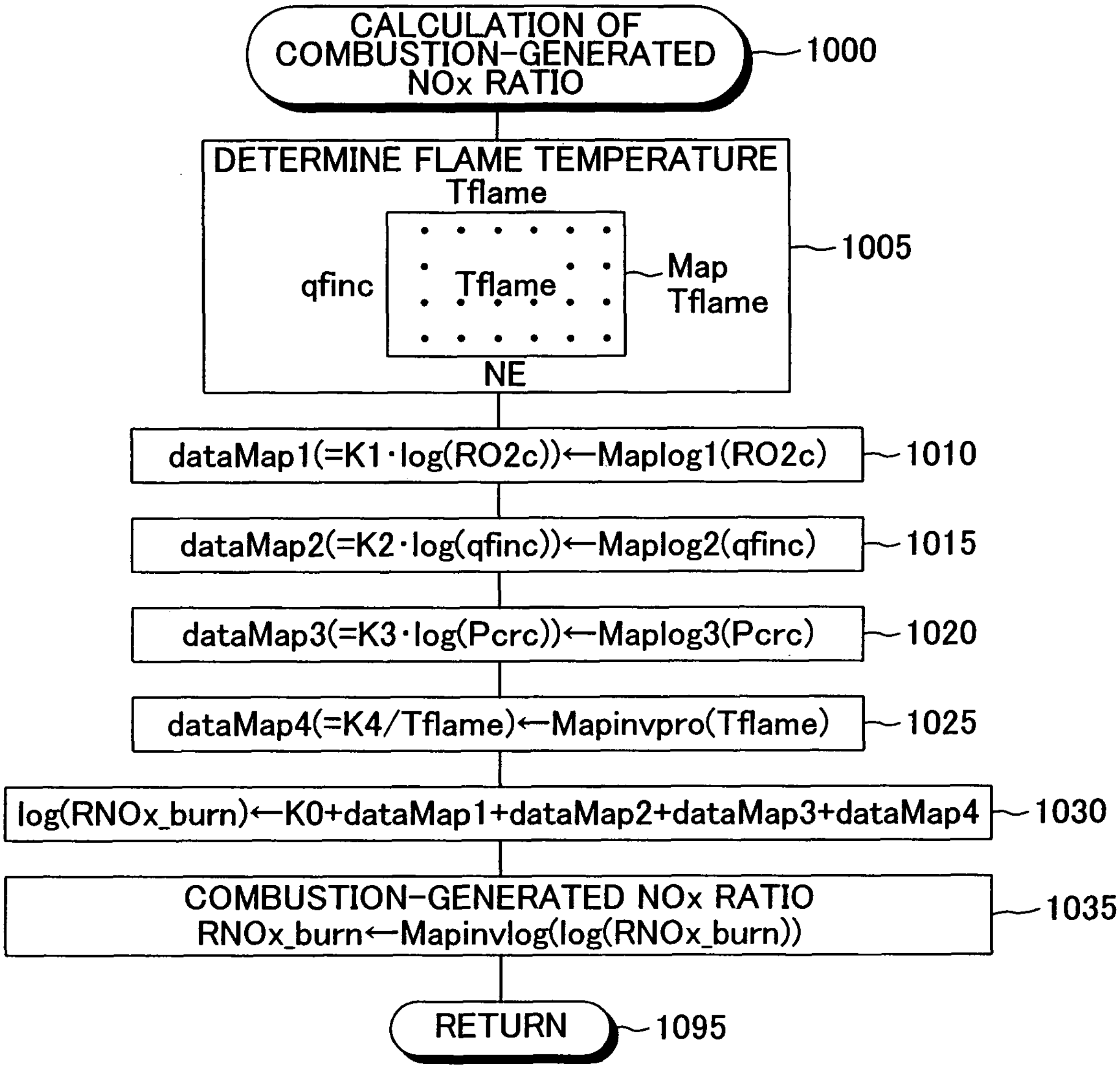

CALCULATION OF NOx DISCHARGE QUANTITY
900
905
ATDC−180° ?
No
Yes
BDC CYLINDER INTERIOR GAS TEMPERATURE Ta0←Tb
BDC CYLINDER INTERIOR GAS PRESSURE Pa0←Pb
BDC INTAKE NEW AIR FLOW RATE Ga0←Ga
BDC ENGINE SPEED NE0←NE
910
BDC INTAKE GAS OXYGEN CONCENTRATION RO2c ←RO2_in
915
CYLINDER INTERIOR TOTAL GAS QUANTITY Gcyl ← Pa0·Va0 / R·Ta0
920
INTAKE NEW AIR QUANTITY Gm←f(Ga0, NE0)
925
EGR GAS QUANTITY Gegr←Gcyl−Gm
930
INJECTION START TIMING?
No
Yes
935
INTAKE GAS NOx CONCENTRATION RNOx_in ← RNOx_ex·Gegr / Gcyl
940
A−REGION CIRCULATED NOx QUANTITY NOxA ←RNOx_in·(1− K·qfinc / Gcyl·RO2c)·Gcyl
945
CALCULATION OF COMBUSTION−GENERATED NOx RATIO RNOx_burn
950
B−REGION COMBUSTION −GENERATED NOx QUANTITY NOxB ← RNOx_burn· qfinc
955
EXHAUST GAS NOx CONCENTRATION RNOx_ex ← NOxA+NOxB / Gcyl+qfinc
960
ACTUAL NOx DISCHARGE QUANTITY NOxact ← RNOx_ex·Gm
965
RETURN
995

FIG.10


CALCULATION OF COMBUSTION-GENERATED NOx RATIO
1000
DETERMINE FLAME TEMPERATURE Tflame
qfinc
Tflame
Map Tflame
NE
1005
dataMap1(=K1·log(RO2c))←Maplog1(RO2c)
1010
dataMap2(=K2·log(qfinc))←Maplog2(qfinc)
1015
dataMap3(=K3·log(Pcrc))←Maplog3(Pcrc)
1020
dataMap4(=K4/Tflame)←Mapinvpro(Tflame)
1025
log(RNOx_burn)←K0+dataMap1+dataMap2+dataMap3+dataMap4
1030
COMBUSTION-GENERATED NOx RATIO RNOx_burn←Mapinvlog(log(RNOx_burn))
1035
RETURN
1095