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(71) Applicant: **Magneti Marelli S.p.A.**
Corbetta (MI) (IT)

(72) Inventor: **The designation of the inventor has not yet been filed**

(74) Representative: **Maccagnan, Matteo et al**
Studio Torta S.p.A.
Via Viotti, 9
10121 Torino (IT)

(54) Method for estimating the exhaust gas flow rate for an internal combustion engine

(57) A method for estimating the exhaust gas flow rate (m) for an internal combustion engine (1); the internal combustion engine (1) is provided with an exhaust system for emitting the gases produced by the combustion into the atmosphere, which comprises, in turn, a manifold (5) for collecting the exhaust gases, an exhaust duct (10) connected to the exhaust manifold (5), and at least one sensor (24) housed along the exhaust duct (10) so as to be hit when by the exhaust gases in use; the estimation method comprises the steps of calculating the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature; and estimating the exhaust gas flow rate (m) as a function of the electric power (P) to supply to the sensor (24) in order to keep the sensor (24) itself at a constant temperature.

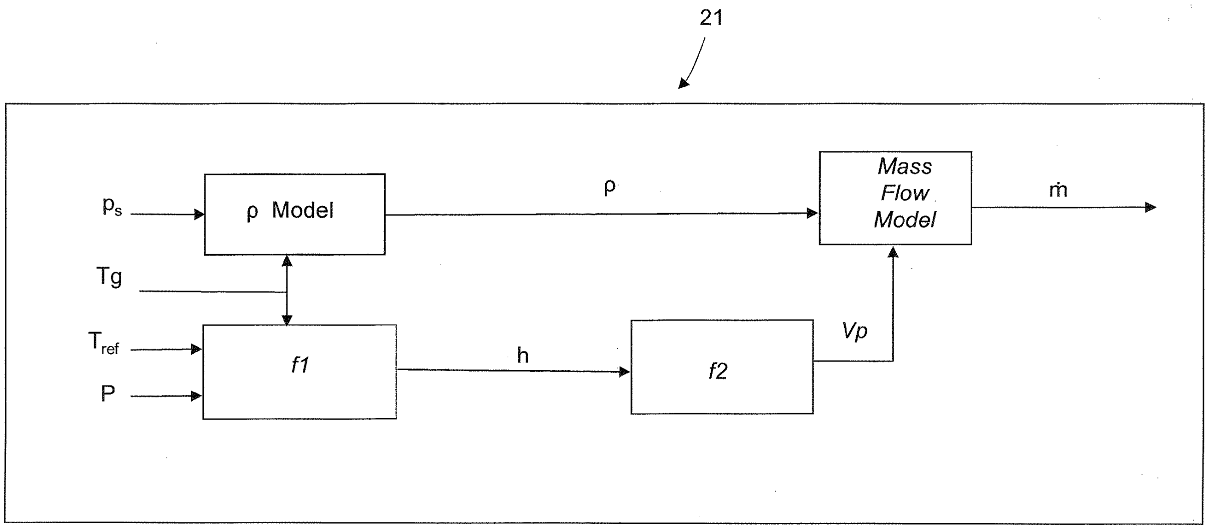

Fig. 2

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Description

TECHNICAL FIELD

[0001] The present invention relates to a method for estimating the exhaust gas flow rate for an internal combustion engine.

PRIOR ART

[0002] Internal combustion engines are typically provided with a number of injectors that inject the fuel for the combustion into respective cylinders, each of which is connected to an intake manifold by means of at least one respective intake valve and to an exhaust manifold by means of at least one respective exhaust valve. Said exhaust manifold is connected to an exhaust pipe, which feeds the exhaust gases produced by the combustion to an exhaust system, which emits the gases produced by the combustion into the atmosphere and normally comprises at least one catalyzer (possibly provided with particulate trap) and at least one muffler arranged downstream of the catalyzer. Furthermore, most internal combustion engines are provided with an air flow meter which is suited to measure the air flow rate aspirated by the internal combustion engine.

[0003] Knowing the exhaust gas flow rate is needed in order to optimize the management of a plurality of exhaust components.

[0004] Typically, such an exhaust gas flow rate is calculated by an electronic control unit of the internal combustion engine by adding the air flow rate aspirated by the internal combustion engine provided by the air flow meter to the fuel flow rate used during the injection into the four cylinders; or alternatively by means of a speed density law. In both cases, however, determining the exhaust gas flow rate is critical because it is neither sufficiently accurate nor reliable.

DESCRIPTION OF THE INVENTION

[0005] It is the object of the present invention to provide a method for estimating the exhaust gas flow rate for an internal combustion engine, which method is free from the drawbacks of the prior art, reliable and easy and cost-effective to implement.

[0006] According to the present invention, a method for estimating the exhaust gas flow rate for an internal combustion engine is provided as disclosed in the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] The present invention will now be described with reference to the accompanying drawings which illustrate a non-limitative example of embodiment thereof, in which:

- figure 1 diagrammatically shows a supercharged internal combustion engine provided with an electronic control unit which implements a method for estimating the exhaust gas flow rate according to the present invention;
- figure 2 shows the method for estimating the exhaust gas flow rate implemented by the electronic control unit of the internal combustion engine in figure 1 by means of a block chart.

PREFERRED EMBODIMENTS OF THE INVENTION

[0008] In figure 1, numeral 1 indicates as a whole an internal combustion engine supercharged by means of a turbocharger supercharging system.

[0009] The internal combustion engine 1 comprises four injectors 2, which inject the fuel directly into four cylinders 3, each of which is connected to an intake manifold 4 by means of at least one respective intake valve (not shown) and to an exhaust manifold 5 by means of at least one respective exhaust valve (not shown). The intake manifold 4 receives fresh air (i.e. air coming from the external environment) through an intake duct 6, which is provided with an air cleaner 7 and is adjusted by a throttle 8. An air flow meter 7*, which is suited to measure the air flow rate $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1, is arranged along the intake duct 6 downstream of the air cleaner 7.

[0010] An intercooler 9 for cooling the intake air is arranged along the intake duct 6. An exhaust duct 10, which feeds the exhaust gases produced by the combustion to an exhaust system, is connected to the exhaust manifold 5, emits the gases produced by the combustion into the atmosphere, and normally comprises at least one catalyzer 11 (possibly provided with particulate trap) and at least one silencer (not shown) arranged downstream of the catalyzer 11.

[0011] The supercharging system 2 of the internal combustion engine 1 comprises a turbocharger 12 provided with a turbine 13, which is arranged along the exhaust pipe 10 to turn at high speed under the bias of the exhaust gases expelled from the cylinders 3, and a compressor 14, which is arranged along the intake pipe 6 and is mechanically connected to the turbine 13 in order to be rotatably fed by the turbine 13 itself and increase the pressure of the air fed into the intake pipe 6.

[0012] A bypass pipe 15 is provided along the exhaust pipe 10 and is connected in parallel to the turbine 13 so as to have the ends thereof connected upstream and downstream of the turbine 13 itself; a wastegate valve 16 is arranged along the bypass pipe 15 and is adapted to adjust the exhaust gas flow rate flowing through the bypass pipe 15 and is driven by a solenoid valve 17. A bypass pipe 18 is provided along the intake pipe 6 and is connected in parallel to the compressor 14 so as to have the ends thereof connected upstream and downstream of the compressor 14 itself; a Poff valve 19 is arranged along the bypass pipe 18, is adapted to adjust the exhaust gases which flow through the bypass pipe 18 and is driven by an EGR solenoid valve 20.

[0013] The internal combustion engine 1 is controlled by an electronic control unit 21, which governs the operation of all the components of the internal combustion engine 1. The electronic control unit 21 is connected to a sensor 22 which measures the temperature T_{aircol} and the pressure P_{aircol} of the air present in the intake manifold 4, to a sensor 23 which measures the revolution speed ω_{mot} of the internal combustion engine 1, and to a sensor 24 (typically a linear oxygen sensor of the UHEGO or UEGO type - known and not described in detail) which measures the air/fuel ratio λ upstream of the catalyzer 11.

[0014] The method implemented by the electronic control unit 21 for estimating the exhaust gas flow rate is described below.

[0015] Firstly, it is worth noting that in order to guarantee the reliability and correct operation of the sensor 24 (i.e. of the linear oxygen sensor of the UEGO type, for instance) which measures the air/fuel ratio λ in the exhaust gases, the sensor 24 must keep an internal temperature as stable as possible.

[0016] In order to respond to this need, the internal combustion engine 1 is thus equipped with a controller CS, which is provided to control the sensor 24, is connected to the electronic control unit 21 and to the sensor 24, and is arranged, according to a first variant, close to the sensor 24 or, according to an alternative variant, directly inside the electronic control unit 21.

[0017] The controller CS is made to guarantee that the internal temperature of the sensor 24 is kept constant as the surrounding conditions vary, which conditions are typically the exhaust gas flow rate crossing the sensor 24 and the temperature of the exhaust gas flow crossing the sensor 24.

[0018] The controller CS is provided with a heater, which is made to supply electric power P, which by Joule effect is transformed into thermal power in order to keep the temperature inside the sensor 24 constant.

[0019] In particular, the estimation method includes determining a reference temperature value T_{ref} for the sensor 24 during a preliminary step of setting up and adjusting.

[0020] According to a first variant, such a reference temperature value T_{ref} is constant and preferably comprised between 760 °C and 850 °C.

[0021] Furthermore, according to a preferred embodiment, the reference temperature value T_{ref} is determined so that it is higher than the temperature Tg of the exhaust gases; such a condition occurs particularly in compression ignited internal combustion engines 1, in which the average temperature T_{g_avg} of the exhaust gases is lower than that of spark ignited internal combustion engines 1.

[0022] The controller CS is thus provided to compare the reference temperature value T_{ref} with a temperature inside the sensor 24. The temperature inside the sensor 24 is determined by the controller CS as a function of the resistance $R(T_{ref})$ of the heater inside the sensor 24 itself. Obviously, the controller CS is provided to control the heater and vary the supplied electric power P, which is turned by Joule effect into thermal power in order to keep the temperature inside the sensor 24 constant as a function of the result of the comparison between the reference temperature value T_{ref} and of the temperature inside the sensor 24.

[0023] The temperature inside the sensor 24 is variable as a function of a plurality of parameters, such as the exhaust gas flow rate $\dot{m}$ hitting the sensor 24 and the temperature T_g of the exhaust gases hitting the sensor 24.

[0024] In other words, the electronic control unit 21 is configured to determine the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature and to estimate the exhaust gas flow rate $\dot{m}$ as a function of the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature.

[0025] Consequently, the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature is also variable as a function of the pressure of the exhaust gases hitting the sensor 24, of the exhaust gas flow rate $\dot{m}$ hitting the sensor 24 and of the temperature T_g of the exhaust gases hitting the sensor 24; and therefore the exhaust gas flow rate $\dot{m}$ hitting the sensor 24 can be established by knowing the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature, since the pressure value ps of the exhaust gases close to the sensor 24 is estimated by the electronic control unit 21 and varies limitedly during the normal operation of the internal combustion engine 1, while the temperature T_g of the exhaust gases hitting the sensor 24 may be determined by using a sensor or estimated by the electronic control unit 21 (e.g. by means of the method described in patent application EP-A-2110535).

[0026] The controller CS is thus made to work in a closed loop by determining the temperature inside the sensor 24 and modulating the electric heating power P which is supplied to the sensor 24 itself.

[0027] Furthermore, the electronic control unit 21 is configured to estimate the exhaust gas flow rate $\dot{m}$ as a function of the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature.

[0028] The heating electric power P supplied to the sensor 24 must balance the thermal power that the sensor 24 yields to the exhaust gases when in use. The thermal power that the sensor 24 yields to the exhaust gases is as a function of the exhaust gas flow rate $\dot{m}$ of the temperature Tg of the exhaust gases hitting the sensor 24. Such a balancing between the heating electric power P supplied to the sensor 24 and the thermal power that the sensor 24 yields to the exhaust gases may be expressed by means of the following equation:

$$\varepsilon_d * P_s - q_{tot} = \Delta\dot{E} \qquad [1]$$

[0029] Wherein:

ε_d thermal power coefficient supplied to the sensor 24;
P_s electric heating power P supplied to the sensor 24 and known by the electronic control unit 21;
q_{tot} total thermal power/heat transferred by the sensor 24 to the exhaust gases; and
$\Delta\dot{E}$ energy increase supplied to the sensor 24 in the unit of time.

[0030] Wherein:

$$q_{tot} = q_{conv} + q_{irr} \qquad [2]$$

with:

q_{conv} heat transferred by convection by the sensor 24 to the exhaust gases; and
q_{irr} heat transferred by radiation by the sensor 24 to the exhaust gases.

[0031] By replacing equation [2] in equation [1] it results that:

$$\varepsilon_d * P_s - q_{conv} - q_{irr} = \Delta\dot{E} \qquad [3]$$

[0032] It thus results that:

$$\varepsilon_d \frac{V_{eff}^2}{R(T_{ref})} - h \cdot A_s \cdot (T_{ref} - T_g) - A_s \cdot q''_{irr} = \Delta\dot{E} \qquad [4]$$

[0033] Wherein:

V_{eff} effective voltage supplied to the sensor 24 by the controller CS of the temperature and known by the electronic control unit 21;
$R(T_{ref})$ resistance of the heater of the sensor 24, as a function of the temperature reference value T_{ref} for the sensor 24;
h heat transfer coefficient;
A_s heat transfer area between the sensor 24 and the exhaust gases;
T_{ref} reference temperature value for the sensor 24; and
Tg temperature of the exhaust gases hitting the sensor 24.

[0034] In stationary conditions, the equation [4] may be simplified assuming that:

- the energy increase $\Delta\dot{E}$ supplied to the sensor 24 in the unit of time is negligible (i.e. considering that in stationary conditions the ratio of the electric heating power P supplied to the sensor 24 and the thermal power that the sensor 24 yields to the exhaust gases is constant); and that
- the heat transferred by radiation per unit of time by the sensor 24 to the exhaust gas is either negligible or comparable to the heat transferred by convection per unit of time by the sensor 24 to the exhaust gases.

[0035] By simplifying the equation [4], it is thus possible to obtain the heat exchange coefficient h as follows:

$$h = \frac{1}{A_s \cdot (T_{ref} - T_g)} \cdot \varepsilon_d \cdot P_S$$
$$P_s = \frac{V_{eff}^2}{R(T_{ref})} \qquad [5]$$

[0036] As shown in greater detail in figure 2, the electronic control unit 21 is thus configured to control the exhaust gas flow rate $\dot{m}$ as follows:

- the Model p calculation block is suited to receive in input the temperature T_g of the exhaust gases and the pressure value p_s of the exhaust gases close to the sensor 24 and outputs the density value p of the exhaust gases close to the sensor 24 by means of the perfect gas equations;
- as described above, the *f1* calculation block is suited to receive in input the temperature Tg of the exhaust gases, the reference temperature value T_{ref} for the sensor 24 and the heating electric power value P supplied to the sensor 24 and to output the heat exchange coefficient h by means of the equation system described above;
- the *f2* calculation block is suited to receive in input the heat exchange coefficient h, calculate the gas speed close to the sensor 24 and output the average speed Vp of the exhaust gases in the exhaust pipe 10 by means of King's law, for instance; and
- the *Mass Flow Model* calculation block is adapted to receive in input the average speed Vp of the exhaust gases close to the sensor 24 and the density ρ of the exhaust gases close to the sensor 24 and to output the exhaust gas flow rate $\dot{m}$ by means of the flow equation assuming a one-dimensional flow.

[0037] It has been empirically determined that the average percentage error in the exhaust gas flow rate $\dot{m}$ estimated with the estimation method described above is less than 5%.

[0038] Furthermore, it is worth noting that the following occurs in stationary conditions:

$$\dot{m}_{AFM} + \dot{m}_{EGR} = \dot{m}_{Cyl} \qquad [6]$$

wherein:

$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine 1 and measured by the air flow meter 7*;
$\dot{m}_{EGR}$ air flow coming from the burnt gas recirculation; and
$\dot{m}_{cyl}$ air flow entering the cylinders 3.

[0039] Typically, the air flow $\dot{m}_{cyl}$ entering the cylinders 3 is estimated using the speed density model and is adequately robust and accurate.

[0040] In given conditions, in particular with the EGR valve closed and thus with no air flow $\dot{m}_{EGR}$ coming from gas recirculation, the air flow rate $\dot{m}_{AFM}$ aspired by the internal combustion engine 1 and measured by the air flow meter 7* coincides with the air flow rate $\dot{m}_{cyl}$ entering the cylinders, i.e.:

$$\dot{m}_{AFM} = \dot{m}_{Cyl} \qquad [7]$$

[0041] Furthermore, the following occurs again in stationary conditions:

$$\dot{m}_{AFM} + \dot{m}_{FUEL} = \dot{m} \qquad [8]$$

wherein:

$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine 1 and measured by the air flow meter 7*;
$\dot{m}_{FUEL}$ fuel flow rate entering the cylinders 3 (the value is known and supplied by the electronic control unit 21); and
$\dot{m}$ exhaust gas flow rate.

[0042] By replacing equation [7] in equation [8] it immediately results that:

$$\dot{m}_{Cyl} + \dot{m}_{FUEL} = \dot{m} \qquad \text{and}$$

$$\dot{m}_{Cyl} = \dot{m} - \dot{m}_{FUEL} \qquad [9]$$

[0043] As mentioned above, the air flow rate $\dot{m}_{cyl}$ entering the cylinders 3 is estimated by means of the speed density model with the following formula:

$$\dot{m}_{SD} = \eta_V * V_{Cyl} * \rho * n/2 \qquad [10]$$

where:

$\dot{m}_{SD}$ entering air flow rate calculated using the speed density model;
η_v volumetric filling coefficient;
V_{cyl} volume in cylinders 3 / displacement of the internal combustion engine 1 [m^3];
ρ density of the gases entering the internal combustion engine 1; and
n engine rpm per unit of time.

[0044] In these conditions, the estimated exhaust gas flow rate $\dot{m}$ can be corrected, in particular by correcting the calculation of the heat exchange coefficient h.

[0045] Indeed, the following apply in these conditions:

$$\eta_V * V_{Cyl} * \rho * n/2 = \dot{m} - \dot{m}_{FUEL} \qquad \text{and}$$

$$\dot{m} = \eta_V * V_{Cyl} * \rho * n/2 + \dot{m}_{FUEL} \qquad [11]$$

[0046] Formula [11] thus allows to calculate the exhaust gas flow rate $\dot{m}$ by means of the speed density model minus the fuel flow rate $\dot{m}_{FUEL}$ entering the cylinders 3. Clearly, the exhaust gas flow rate value $\dot{m}$ calculated by means of the speed density model may be compared with the exhaust gas flow rate value $\dot{m}$ calculated by means of the estimation method illustrated in the figure 2, and the exhaust gas flow rate value $\dot{m}$ calculated by means of the speed density model may be used to update the calculation block *f1* which outputs the heat exchange coefficient h so as to consolidate the estimation method described above.

[0047] The estimated exhaust gas flow rate $\dot{m}$ may be used by the electronic control unit 21 for various purposes, some of which will be described below (regardless of the sensor 24 used to implement the mentioned exhaust gas flow rate $\dot{m}$ estimation method).

[0048] According to a first embodiment, the flow rate balance may be expressed as shown by the equation [8], so that the following derives:

$$\dot{m}_{AFM} = \dot{m} - \dot{m}_{FUEL} \qquad [12]$$

wherein:

$\dot{m}_{FUEL}$ fuel flow rate entering the cylinders 3 (the value is known and supplied by the electronic control unit 21);
$\dot{m}$ exhaust gas flow rate estimated by means of the estimation method described above; and
$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine 1.

[0049] The air flow rate $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 may thus be alternatively measured by the air flow meter 7* or calculated by means of the difference of the equation [12].
[0050] It is thus apparent that implementing the method described above for estimating the exhaust gas flow rate $\dot{m}$ may allow to eliminate the air flow meter 7* because the air flow $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 is calculated by means of the difference of the equation [12].
[0051] Alternatively, implementing the method for estimating the exhaust gas flow rate m may allow to check the coherence with the aspirated air flow rate values $\dot{m}_{AFM}$ measured by the air flow meter 7* (regardless of the sensor 24 used for implementing the mentioned estimation of the exhaust gas flow rate $\dot{m}$).
[0052] Furthermore, the aspirated air flow rate value $\dot{m}_{AFM}$ measured by the air flow meter 7* becomes less reliable over time because the performance of the air flow meter 7* decays considerably (by way of example, passing from an initial measurement dispersion of 4% to a measurement dispersion of 15% may be considered) and the implementation of the estimation method described above allows to obtain a very accurate estimation of the exhaust gas flow rate m which can be used to correct the air flow rate $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 measured by the flow meter 7*. In other words, the electronic control unit 21 is configured to measure the air flow rate $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 by means of the air flow meter 7*; comparing the air flow rate $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 measured by the air flow meter 7* with the air flow rate value $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 determined as a function of the fuel flow rate $\dot{m}_{FUEL}$ entering into the cylinders 3 and of the exhaust gas flow rate $\dot{m}$ produced by the combustion of the internal combustion engine 1 estimated using the method described above; and updating the air flow meter 7* as a function of the comparison between the air flow rate value $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 and measured by the air flow meter 7* and the air flow rate value $\dot{m}_{AFM}$ aspirated by the internal combustion engine 1 determined as a function of the fuel flow rate $\dot{m}_{FUEL}$ entering the cylinders 3 and the exhaust gas flow rate $\dot{m}$ produced by the combustion of the internal combustion engine 1 estimated using the method described above.
[0053] According to a further embodiment (not shown in detail), the internal combustion engine 1 comprises an EGR gas recirculation circuit divided into a low-pressure branch and a high-pressure branch, in addition to an air flow meter 7* and a sensor 24 placed immediately downstream of the turbine 13 of the turbocharger 12 and upstream of the catalyzer 11.
[0054] In other words, the electronic control unit 21 is configured to estimate the exhaust gas flow rate $\dot{m}$ produced by the combustion of the internal combustion engine 1 to be emitted into the atmosphere according to the method described above (regardless of the sensor 24 used); to determine both the exhaust gas flow rate $\dot{m}_{EGR\_LP}$ recirculated through the low-pressure branch LP of the EGR circuit of the internal combustion engine 1 and the exhaust gas flow rate $\dot{m}_{EGR\_HP}$ recirculated through the high-pressure branch HP of the EGR circuit of the internal combustion engine 1 as a function of the exhaust gas flow rate $\dot{m}$ produced by the internal combustion engine 1; and to control the internal combustion engine 1 as a function of the exhaust gas flow rate $\dot{m}_{EGR\_LP}$ recirculated through the low-pressure branch LP of the EGR circuit of the internal combustion engine 1 and by the exhaust gas flow rate $\dot{m}_{EGR\_HP}$ recirculated through the HP branch of the EGR circuit of the internal combustion engine 1.
[0055] In this case, the balancing of the flow rates may be expressed by means of the following system of two equations with two unknown factors:

$$\begin{aligned} \dot{m}_{AFM} + \dot{m}_{EGR\_LP} + \dot{m}_{EGR\_HP} &= \dot{m}_{SD} \\ \dot{m}_{AFM} + \dot{m}_{FUEL} &= \dot{m}_{S} - \dot{m}_{EGR\_LP} \qquad [13] \end{aligned}$$

wherein:

$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine 1 and measured by the air flow meter 7*;
$\dot{m}_{FUEL}$ fuel flow rate entering the cylinders 3 (the value is known and supplied by the electronic control unit 21);
$\dot{m}_{EGR\_LP}$ exhaust gas flow rate recirculated through the low-pressure branch of the EGR circuit of the internal combustion engine;
$\dot{m}_{EGR\_HP}$ exhaust gas flow rate recirculated through the high-pressure branch of the EGR circuit of the internal combustion engine;
$\dot{m}_{SD}$ air flow rate entering the cylinders 3 calculated using the speed density model; and
$\dot{m}_{S}$ exhaust gas flow rate through the sensor 24 and obtained by means of the estimation method described above.

[0056] In the system of two equations [13], the unknown factors are the exhaust gas flow rate $\dot{m}_{EGR\_LP}$ recirculated through the low-pressure branch of the EGR circuit of the internal combustion engine 1 and the exhaust gas flow rate $\dot{m}_{EGR\_HP}$ recirculated through the high-pressure branch of the EGR circuit of the internal combustion engine 1. The system of two equations [13] is thus easily solved and allows to establish how the flow rate is split into an EGR gas recirculation circuit divided into a low-pressure branch and a high-pressure branch.

[0057] According to a further embodiment (not shown in detail), the internal combustion engine 1 comprises an EGR gas recirculation circuit divided into a low-pressure branch and a high-pressure branch, in addition to an air flow meter 7* and a sensor 24 placed immediately downstream of the catalyzer 11.

[0058] In this case, the flow rate balancing may be expressed by means of the equation that follows:

$$\dot{m}_{AFM} + \dot{m}_{FUEL} = \dot{m}'_{S} \qquad [14]$$

wherein:

$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine 1 and measured by the air flow meter 7*;
$\dot{m}_{FUEL}$ fuel flow rate entering the cylinders 3 (the value is known and supplied by the electronic control unit 21); and
$\dot{m}'_{s}$ exhaust gas flow rate through the sensor 24' placed immediately downstream of the catalyzer 11 and obtained by means of the estimation method described above.

[0059] Knowing the exhaust gas flow rate $\dot{m}'_{s}$ through the sensor 24' placed immediately downstream of the catalyzer 11 allows to optimize the management of the downstream devices (e.g. of the SCR - *selective catalytic reduction* - system).

[0060] According to a further embodiment (not shown in detail), the internal combustion engine 1 comprises a number of sensors NOx placed typically downstream of the catalyzer 11 and/or downstream of the SCR - *selective catalytic reduction* - system (if present) and, consequently, downstream of the sensor 24. Estimating the exhaust gas flow rate $\dot{m}$ by means of the method described above allows to know with considerable accuracy also the exhaust gas flow rate hitting the other sensors NOx with evident advantages both in terms of accuracy and response dynamics.

[0061] Finally, the estimation of the exhaust gas flow rate $\dot{m}$ may be used to estimate a further magnitude of the exhaust system, i.e. the exhaust pressure P3 (independently from the sensor 24 used).

[0062] Indeed, the turbine manufacturers 13 typically provide the characteristic curves of the turbines 13 themselves which are represented by a plurality of curves (in the case of a variable geometry turbine 13, also known as VGT) or by a single curve (in the case of a fixed geometry turbine 13) on the exhaust gas flow rate $\dot{m}$ / P3/P4 ratio map.

[0063] Thus, the ratio of the exhaust pressure P3 and of the exhaust gas flow rate $\dot{m}$ may be expressed as follows:

$$P3/P4 = f\ (\dot{m},\ pos_{vgt})$$

[0064] Wherein:

P4 pressure downstream of the turbine 13; the value of the pressure P4 downstream of the turbine 13 may be estimated by means of the updating method described in patent application BO2011A000213; and
P3 exhaust pressure upstream of the turbine 13;
$\dot{m}$ exhaust gas flow rate through the sensor 24 and obtained by means of the method described above; and
pos_{vgt} control position of the turbine 13 in the case of variable geometry turbine 13 - also known as VGT.

[0065] Obtaining the ratio of the exhaust pressure P3 upstream of the turbine 13 and the pressure P4 downstream of the turbine 13 is immediate knowing the exhaust gas flow rate $\dot{m}$ through the sensor 24, which is estimated with the method described above, the control position of the turbine 13 in the case of the variable geometry turbine 13 and having the characteristic curve of the turbine 13 available. Knowing such a ratio and having obtained the pressure P4 downstream of the turbine 13 (e.g. by means of the updating method described in patent application BO2011A000213), the exhaust pressure P3 upstream of the turbine 13 is also obtained.

[0066] The exhaust pressure P3 described above may be also estimated in transient conditions, in which case it is much more reliable than the traditional estimates which are characterized by a high degree of uncertainty, above all in transient conditions.

[0067] Reference was made in the description above to the use of a linear oxygen sensor 24 of the UEGO (Universal Exhaust Gas Oxygen) or UHEGO (Universal Heated Exhaust Gas Oxygen) type, which measures the air/fuel ratio λ of the exhaust gases to implement the exhaust gas estimation method; it is apparent that such an exhaust gas estimation method can be advantageously applied also by using other similar heated sensors, such as for example a non-linear sensor (also known as ON/OFF type oxygen sensor which measures the air/fuel ratio in the exhaust gases, a sensor adapted to measure the concentration of NH3 or of NOx etc).

[0068] It is worth noting that the method described above does not include the use of a dedicated sensor to be accommodated also the exhaust duct 10 so as to be hit, when in use, by the exhaust gases to estimate the exhaust gas flow rate $\dot{m}$; instead, the implementation of such a method is possible by means of the sensors 24 already provided in the internal combustion engine 1 for other functions, such as, for example, measuring the air/fuel ratio λ in the exhaust gases (in the case of the linear oxygen sensor 24 of the UEGO or UHEGO type), measuring the air/fuel ratio of the exhaust gases (in the case of the non-linear oxygen sensor of the ON/OFF type) or of measuring the concentration of NH3 or of NOx etc.

[0069] According to a preferred variant, since the internal combustion engine 1 is often provided with a plurality of heated sensors 24 arranged along the exhaust duct 10, the electronic control unit 21 is provided to estimate the exhaust gas flow rate m both by means of a sensor 24 (e.g. the linear oxygen sensor 24 of the UEGO or UHEGO type which measures the air/fuel ratio λ of the exhaust gases) and by means of a further sensor 24' (e.g. the sensor 24' to measure the concentration of NH3 or NOx). In essence, the exhaust gas flow rate m in as a function of the electric power P to be supplied to the sensor 24 in order to keep the sensor 24 itself at a constant temperature; and is estimated the exhaust gas flow rate $\dot{m}$ as a function of the electric power P to be supplied to the second sensor 24' in order to keep the second sensor 24' itself at a constant temperature.

[0070] The electronic control unit 21 is thus provided to compare the estimated exhaust gas flow rate $\dot{m}$ by means of the sensor 24 with the estimated exhaust gas flow rate $\dot{m}$ made by means of the sensor 24' and to generate an error signal if the absolute value difference between the estimated exhaust gas flow rate $\dot{m}$ obtained by means of the sensor 24 and the estimated exhaust gas flow rate $\dot{m}$ obtained by means of the sensor 24' is higher than a safety value (which can be calibrated and is usually determined in a preliminary step of setting up and adjusting). In this manner, it is also possible to diagnose possible malfunctions of the sensors 24, 24' which are provided to measure the air/fuel ratio λ of the exhaust gases or to measure the concentration of NH3 or of NOx.

[0071] The estimation method described above has many advantages.

[0072] Firstly, it is possible to obtain an accurate, reliable estimate of the exhaust gas flow rate $\dot{m}$ simply by using the information that regard the sensor 24 and that are already known by the electronic control unit 21. Furthermore, the insertion of additional components is not needed (the sensor 24 is already provided to measure the air/fuel ratio λ of the exhaust gases). Finally, the estimation method described above is easy to implement and does not imply an excessive computing burden for the electronic control unit 21.

Claims

1. A method for estimating the exhaust gas flow rate ($\dot{m}$) for an internal combustion engine (1); the internal combustion engine (1) is provided with an exhaust system for emitting the exhaust gases produced by the combustion into the atmosphere, which comprises, in turn, a manifold (5) for collecting the exhaust gases, an exhaust duct (10) connected to the exhaust manifold (5), and at least one sensor (24) housed along the exhaust duct (10) so as to be hit, when in use, by the exhaust gases chosen from the following sensors (24): linear oxygen sensor (24) of the UEGO (Universal Exhaust Gas Oxygen) or UHEGO (Universal Heated Exhaust Gas Oxygen) type suited to measure the air/fuel ratio of the exhaust gases, non-linear oxygen sensor (24) (or ON/OFF type oxygen sensor) suited to measure the air/fuel ratio of the exhaust gases, sensor (24) suited to measure the concentration of NH3 or NOx;
the estimation method comprises the steps of:

   - determining the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at

a constant temperature; and
- estimating the exhaust gas flow rate ($\dot{m}$) as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature.

2. An estimation method according to claim 1, wherein the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature can vary as a function of the exhaust gas flow rate ($\dot{m}$) hitting the sensor (24), and of the temperature (T_{eff}) of the exhaust gases hitting the sensor (24).

3. A method according to claim 1 or 2, wherein the internal combustion engine (1) comprises a first sensor (24) and a second sensor (24') housed along the exhaust duct (10) so as to be hit, when in use, by the exhaust gases, both chosen from the following sensors (24, 24'): linear oxygen sensor (24, 24') of the UEGO (Universal Exhaust Gas Oxygen) or UHEGO (Universal Heated Exhaust Gas Oxygen) type suited to measure the air/fuel ratio of the exhaust gases, non-linear oxygen sensor (24, 24') (or oxygen sensor of the ON/OFF type) suited to measure the air/fuel ratio in the exhaust gases, sensor (24, 24') suited to measure the concentration of NH3 or of NOx; the method comprising the further steps of:

estimating the exhaust gas flow rate ($\dot{m}$) as a function of the electric power (P) to be supplied to the first sensor (24) in order to keep the first sensor (24) itself at a constant temperature;
estimating the exhaust gas flow rate ($\dot{m}$) as a function of the electric power (P) to be supplied to the second sensor (24') in order to keep the second sensor (24') itself at a constant temperature;
comparing the estimated exhaust gas flow rate ($\dot{m}$) obtained by means of the first sensor (24) and the estimated exhaust gas flow rate ($\dot{m}$) obtained by means of the second sensor (24'); and
generating an error signal if the absolute value difference between the estimated exhaust gas flow rate ($\dot{m}$) obtained by means of the first sensor (24) and the estimated exhaust gas flow rate ($\dot{m}$) obtained by means of the second sensor (24') is greater than a safety value.

4. A method according to one of the preceding claims and comprising the further steps of:

- determining a reference temperature value (T_{ref}) in a preliminary step of setting up and adjusting;
- determining the internal temperature of the sensor (24);
- comparing the internal temperature of the sensor (24) with the reference temperature value (T_{ref}); and
- determining the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature as a function of the comparison between the internal temperature of the sensor (24) and the temperature reference value (T_{ref}).

5. An estimation method according to any one of the preceding claims, wherein the step of estimating the exhaust gas flow rate ($\dot{m}$) as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature comprises the sub-steps of:

calculating the density (p) of the exhaust gases close to the sensor (24);
calculating the average speed (Vp) of the exhaust gases as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature; and
estimating the exhaust gas flow rate ($\dot{m}$) as a function of the density (p) of the exhaust gases close to the sensor (24) and as a function of the average speed (Vp) of the exhaust gases.

6. A control method according to claim 5, wherein the step of calculating the average speed (Vp) of the exhaust gases as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature comprises the sub-steps of:

calculating a heat transfer coefficient (h) as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature; and
calculating the average speed (Vp) of the exhaust gases as a function of the heat transfer coefficient (h).

7. A control method according to claim 6, wherein the step of calculating a heat transfer coefficient (h) as a function of the electric power (P) to be supplied to the sensor (24) in order to keep the sensor (24) itself at a constant temperature is performed by means of the equations:

$$h = \frac{1}{A_s \cdot (T_{ref} - T_g)} \cdot \varepsilon_d \cdot P_S$$

$$P_s = \frac{V_{eff}^2}{R(T_{ref})}$$

wherein

V_{eff} effective voltage supplied to the sensor (24);
$R(T_{ref})$ resistance of the sensor (24) as a function of the reference temperature value (T_{ref}) for the sensor (24);
h heat transfer coefficient;
A_s area of the heat transfer between the sensor (24) and the exhaust gases;
T_{ref} reference temperature value; and
Tg temperature of the exhaust gases.

8. An estimation method according to claim 6, wherein the internal combustion engine (1) is provided with a number of cylinders (3); the method comprises the further steps of:

determining, by means of a speed density type law, the air flow rate ($\dot{m}_{Cyl}$) entering the cylinders (3) ;
checking whether some given working conditions of the internal combustion engine (1) are fulfilled; and
updating the calculation of the heat transfer coefficient (h) as a function of the air flow rate ($\dot{m}_{Cyl}$) entering the cylinders (3) determined by means of a speed density type law.

9. An estimation method according to one of the preceding claims, wherein the internal combustion engine (1) is provided with a number of cylinders (3); the method including the further steps of:

determining the fuel flow rate ($\dot{m}_{FUEL}$) entering the cylinders (3);
determining the air flow rate ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) as a function of the fuel flow rate ($\dot{m}_{FUEL}$) entering the cylinders (3) and the exhaust gas flow rate ($\dot{m}$) produced by the combustion of the internal combustion engine (1) to be emitted into the atmosphere; and
controlling the internal combustion engine (1) as a function of the air flow rate ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) itself.

10. An estimation method according to claim 9, wherein the internal combustion engine (1) is provided with a further sensor (7*) configured to measure the air flow rate ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) and housed along the intake duct (6) of the internal combustion engine (1) itself; the method including the further steps of:

measuring the air flow rate ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) by means of the further sensor (7*);
comparing the air flow rate ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) measured by the further sensor (7*) with the air flow rate value ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) determined as a function of the fuel flow rate ($\dot{m}_{FUEL}$) entering the cylinders (3) and of the exhaust gas flow rate ($\dot{m}$) produced by the combustion of the internal combustion engine (1); and
updating the further sensor (7*) as a function of the comparison between the air flow rate value ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) measured by the further sensor (7*) and the air flow rate value ($\dot{m}_{AFM}$) aspirated by the internal combustion engine (1) determined as a function of the flow rate ($\dot{m}_{FUEL}$) of the fuel entering the cylinders (3) and of the exhaust gas flow rate ($\dot{m}$) produced by the combustion of the internal combustion engine (1).

11. An estimation method according to one of the preceding claims, wherein the internal combustion engine (1) is supercharged by means of a turbocharger (12) provided with a turbine (13) and with a compressor (14); the control method comprises the steps of:

determining the exhaust pressure (P3) upstream of the turbine (13) as a function of the exhaust gas flow rate ($\dot{m}$) produced by the combustion of the internal combustion engine (1) by means of a characteristic mass flow rate/compression ratio map of the operation of the turbine (13); and controlling the supercharged internal combustion engine (1) as a function of the exhaust pressure (P3) upstream of the turbine (13).

12. An estimation method according to claim 11, wherein the turbine (13) is a variable geometry turbine (13); the method includes the further steps of:

determining the exhaust pressure (P3) upstream of the turbine (13) as a function of the control position (pos_{vgt}) of the turbine (13) on a characteristic mass flow rate/compression ratio map of the operation of the turbine (13); and
controlling the supercharged internal combustion engine (1) as a function of the exhaust pressure (P3) upstream of the turbine (13).

13. An estimation method according to claim 11 or 12 and comprising the further steps of:

determining the pressure (P4) downstream of the turbine (13);
determining the exhaust pressure (P3) upstream of the turbine (13) as a function of the pressure (P4) downstream of the turbine (13) on a characteristic mass flow rate/compression ratio map of the operation of the turbine (13); and
controlling the supercharged internal combustion engine (1) as a function of the exhaust pressure (P3) upstream of the turbine (13).

14. An estimation method according to any one of the preceding claims, wherein the internal combustion engine (1) comprises an EGR gas recirculation circuit split into a low-pressure branch (LP) and a high-pressure branch (HP); the estimation method includes the further steps of:

determining both the exhaust gas flow rate (m_{EGR_LP}) circulated through the low-pressure branch (LP) of the internal combustion engine (1) and the exhaust gas flow rate ($\dot{m}_{EGR\_HP}$) recirculated through the high-pressure branch (HP) of the EGR circuit of the internal combustion engine (1) as a function of the exhaust gas flow rate ($\dot{m}$) of the produced by the combustion of the internal combustion engine (1); and
controlling the internal combustion engine (1) as a function of the exhaust gas flow rate ($\dot{m}_{EGR\_LP}$) recirculated through the low-pressure branch (LP) of the EGR circuit of the internal combustion engine (1) and the exhaust gas flow rate ($\dot{m}_{EGR_H}$p) recirculated through the high-pressure branch (HP) of the EGR circuit of the internal combustion engine (1).

15. An estimation method according to claim 14, wherein the step of determining both the exhaust gas flow rate ($\dot{m}_{EGR\_LP}$) circulated through the low-pressure branch (LP) of the internal combustion engine (1) and the exhaust gas flow rate ($\dot{m}_{EGR\_HP}$) of the recirculated through the high-pressure branch (HP) of the EGR circuit of the internal combustion engine (1) as a function of the exhaust gas flow rate ($\dot{m}$) produced by the combustion of the internal combustion engine (1) is performed by means of the following system of equations:

$$\dot{m}_{AFM} + \dot{m}_{EGR\_LP} + \dot{m}_{EGR\_HP} = \dot{m}_{SD}$$

$$\dot{m}_{AFM} + \dot{m}_{FUEL} = \dot{m}_{S} - \dot{m}_{EGR\_LP}$$

wherein:

$\dot{m}_{AFM}$ air flow rate aspirated by the internal combustion engine (1);
$\dot{m}_{FUEL}$ fuel flow rate entering the cylinders (3) of the internal combustion engine (1);
$\dot{m}_{EGR\_LP}$ exhaust gas flow rate recirculated through the low-pressure branch (LP) of the EGR circuit of the internal combustion engine (1);
$\dot{m}_{EGR\_HP}$ exhaust gas flow rate recirculated through the high-pressure branch (HP) of the EGR circuit of the internal combustion engine (1);
$\dot{m}_{SD}$ air flow rate entering the cylinders (3) of the internal combustion engine (1) calculated using the speed density model; and

$\dot{m}_S$ exhaust gas flow rate through the sensor (24).

16. An electronic control unit (21) for the automotive industry, which is configured to implement, when in use, the method for estimating the exhaust gas flow rate ($\dot{m}$) for an internal combustion engine (1) according to any of the claims from 1 to 15.

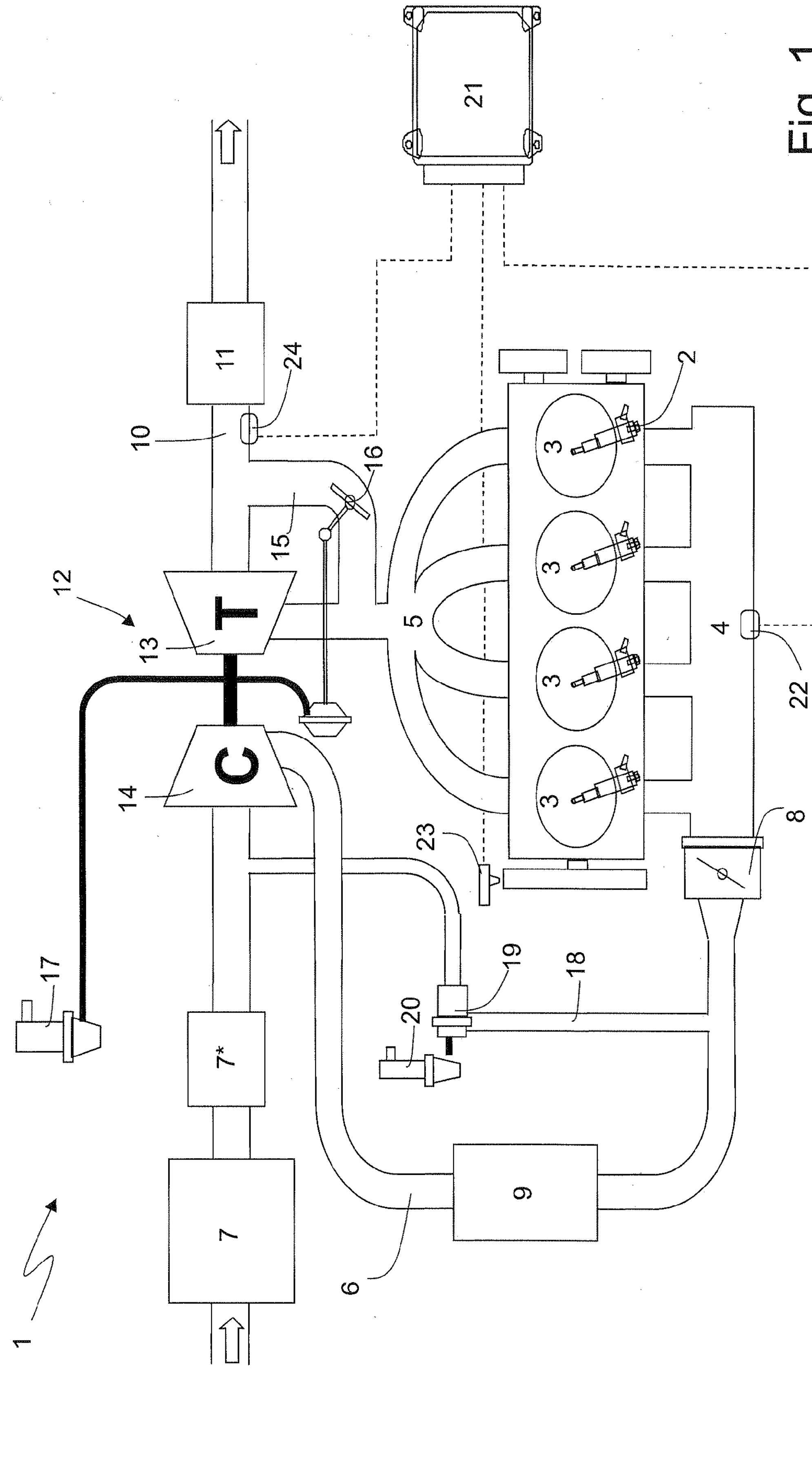

Fig. 1

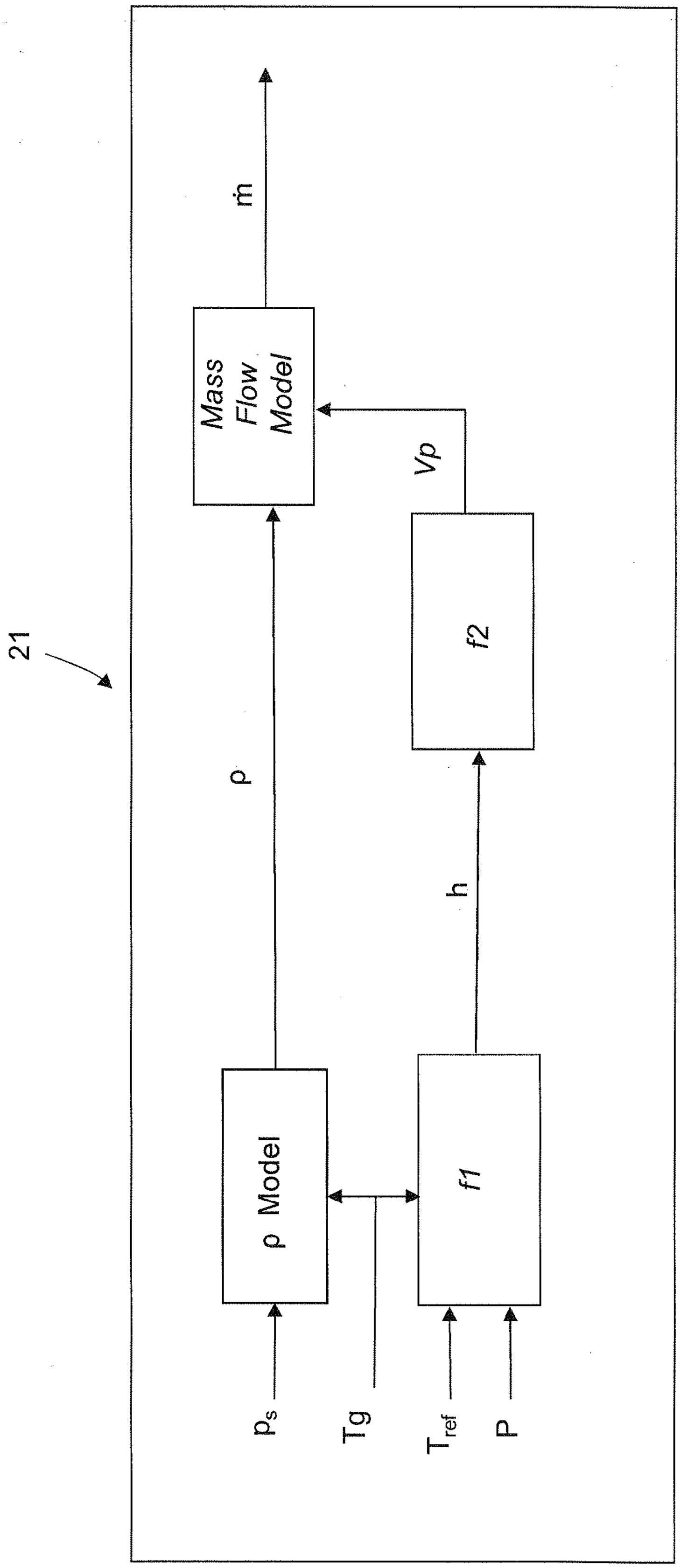

Fig. 2

EUROPEAN SEARCH REPORT

Application Number
EP 13 18 4641

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Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 1 529 952 A2 (HITACHI LTD [JP]) 11 May 2005 (2005-05-11) * paragraphs [0008] - [0067] * * paragraphs [0209] - [0222] * * paragraph [0251] * -----	1-16	INV. F02D41/14 F02D41/18
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TECHNICAL FIELDS SEARCHED (IPC)
F02D
G01M

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	13 January 2014	Calabrese, Nunziante

CATEGORY OF CITED DOCUMENTS

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