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Effect of Exhaust Gas Recirculation (EGR) on Exhaust Performance in an IDI Diesel Engine

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Abstract
Exhaust gas process in an internal combustion engine for the purpose of removing combustion products from the cylinder has always been considered. At the same time for reducing NOx as poisonous pollutant especially in diesel engines, use of EGR is widely employed as an effective way. In this investigation the influence of application of EGR in an IDI diesel engine on residual gas mass fraction as an indicator of exhaust performance was evaluated via an analytical procedure based on experimental data. It was observed that use of EGR contributes decreasing backflow mass and increasing trapped mass which both the former and latter are consisting parts of overall cylinder residual mass. The out coming result was that the cylinder residual gas mass fraction totally reduces as the EGR ratio goes further.
Keywords: Diesel engine, Exhaust stroke, Residual gas, EGR

Introduction

Since diesel engines have a higher thermal efficiency comparing with SI engines, diesel inefficiencies are considered as a great significance. In this way, pollution reduction policies like Euro 3 to 5 are applied to vehicle industries [1]. Experiments show that introducing a fraction of exhaust gas to cylinder can decrease nitrogen radical complexes dramatically. This can be done by lessening oxygen concentration which leads to higher combustion delay and avoids maximum temperature which is the main factor of NOx formation [2]. Using exhaust gas recirculation in diesel engines as a way of NOx suppression has been evaluated in literature in order to remove drawbacks like smoke increase or power loss. Beside the importance of emission control of diesel engines, the controlling over engine combustion and performances always attracts the attention of designers where the exhaustion of combustion products is very important. One of the aims of exhaust stroke is to lower the residual gas mass fraction so the estimation of cylinder residual mass is needed to evaluate the performance of exhaust stroke. Also the calculation of cylinder residuals contributes better understanding of volume inefficiency and flame instability.

In addition to this, knowing the residual gas mass fraction helps us to estimate cylinder condition at the start of compression stroke which is a basic problem in engine simulations[3].

In this investigation, through an analytical pro based on ideal diesel engine cycle and by experimental data from a diesel engine test be influence of EGR application, load and speed on c residual gas were evaluated and two main reasc residual formation which are trapped mass and e backflow were analyzed separately.

Test Bed Setup

This experiment is done in author's lab on an IDI engine in three different engine speeds of 1500, 20 3000 rpm and different engine loads corresponding 50 and 75 percent of maximum achievable load i speed. In each case three EGR mass ratio of 0%, 1(20% were employed in order to investigate the eff EGR application from lean to rich combustion con In each test the EGR mass flow was being calcula codes in MATLAB software based on constant volume which is drawn into the cylinder.

It should be noted that employed EGR modificatic high pressure loop type with air-cooled intercool engine test bed is shown in Fig.1.

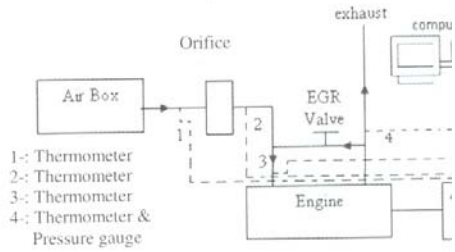

Fig.1

Model Description

The model which was firstly proposed in [4] and a was adapted to diesel engines in [3] divides cylinder residual gas to two main parts which ar back flow of the burned gas from exhaust port valve overlapping and this is because of highe pressure of the exhaust port from intake port an trapped mass in cylinder just before IVO which i dependent to fuel-air equivalence ratio. The m

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Abstract
Exhaust gas process in an internal combustion engine for the purpose of removing combustion products from the cylinder has always been considered. At the same time for reducing NOx as poisonous pollutant especially in diesel engines, use of EGR is widely employed as an effective way. In this investigation the influence of application of EGR in an IDI diesel engine on residual gas mass fraction as an indicator of exhaust performance which affects the engine combustion through its influence on charge mass temperature and dilution was evaluated via an analytical procedure based on experimental data. It was observed that use of EGR contributes decreasing backflow mass and increasing trapped mass which both the former and latter are consisting parts of overall cylinder residual mass. The out coming result was that the cylinder residual gas mass fraction totally reduces as the EGR ratio goes further.
Keywords: Diesel engine, Exhaust stroke, Residual gas, EGR

Introduction

Since diesel engines have a higher thermal efficiency comparing with SI engines, diesel inefficiencies are considered as a great significance. In this way, pollution reduction policies like Euro 3 to 5 are applied to vehicle industries [1]. Residual gas is already burned gas from previous engine cycles that is left in the cylinder. The amount of residual gas is often measured as a fraction of the total mass and the definition of residual gas fraction is the ratio between the mass of residual gas and the total mass. There are two ways to increase the amount of residual gas in the cylinder. Either through Exhaust Gas Recycling, EGR, which is to lead back the exhaust gases to the cylinder, or to close the exhaust valve before all exhaust gas has left the cylinder. The second alternative, when residual the residual gas stays in the cylinder, is sometimes called internal EGR. Residual gas in compression-ignition engines has a profound effect on performance, combustion stability, volumetric efficiency and emissions which experiments show that introducing a fraction of exhaust gas to cylinder can decrease nitrogen radical complexes dramatically. Residual gas affects the combustion process in compression-ignition engines through its influence on charge mass, dilution, temperature and flame speed.

Residual gas influences combustion mainly by acting as a diluent which decreases the flame speed and temperature of the resulting charge which this can be done by lessening oxygen concentration which leads to higher combustion delay and avoids maximum temperature which is the main factor of NOx formation [2]. Using exhaust gas recirculation in diesel engines as a way of NOx suppression has been evaluated in literature in order to remove drawbacks like smoke increase or power loss.

Beside the importance of emission control of diesel engines, the controlling over engine combustion and performances always attracts the attention of designers where the exhaustion of combustion products is very important. One of the aims of exhaust stroke is to lower the residual gas mass fraction so the estimation of cylinder residual mass is needed to evaluate the performance of exhaust stroke. Also the calculation of cylinder residuals contributes better understanding of volume inefficiency and flame instability.

In addition to this, knowing the residual gas mass fraction helps us to estimate cylinder condition at the start of compression stroke which is a basic problem engine simulation [3].

In this investigation, through an analytical procedure based on ideal diesel engine cycle and by using experimental data from a diesel engine test bed, the influence of EGR application, load and speed on cylinder residual gas were evaluated and two main reasons for residual formation which are trapped mass and exhaust backflow were analyzed separately.

The importance of internal residual to engine combustion quality has long been recognized. Historically, the motivation for developing residual estimation methods comes from the fact that it is needed as an input to a heat release rate analysis.

The physical process of residual generation is complex. During the gas exchange process pressure and velocity pulsations are generated in the intake and exhaust manifolds due to fluid inertia and wave action. These pulsations strongly affect the gas flows through the engine valves that determine the residual content of the trapped charge.

Because of the complexity of the process, various experimental techniques have been applied to measure residuals in engines. These can be broadly classified into a) optical, and b) gas-sampling methods.

Optical methods include CARS (coherent ant-Stokes Raman spectroscopy), LIF (laser induced fluorescence), Raman scattering and infrared absorption [4,5]. These require much tedious calibration and analysis to be numerically accurate, and also generally require optical access to the combustion chamber. Some recent work has focused on small, spark plug sized, infrared absorption sensors, but accuracy in a firing engine has not been demonstrated.

Gas sampling methods include several approaches. One approach is nitrous oxide or hydrocarbon sampling, either directly from the cylinder or from the exhaust port, in combination with skip firing [6-7]. Another approach, the oldest and most widely used, is direct cylinder sampling with CO_2 measurement [8-9]. Recent developments have enabled sample extraction through a capillary tube for relatively easy access to the cylinder. All of the gas sampling techniques require elaborate and expensive instrumentation, and may not be feasible for routine engine calibration work, especially if measurements from all cylinders of a multi-cylinder engine are needed in order to obtain an engine average residual value.

The experimental approach has the advantage that we deal with the actual physical system, and the desired quantity is determined by measurement, within the limits of experimental error. However, this approach is expensive, time-consuming, and often impractical.

In view of the difficulty of residual measurement, there has been significant effort toward modeling the residual generation process which are reliable and accurate. The intent of this paper is to use such a model to evaluate the influence of EGR application, load and speed on cylinder residual gas as an exhaust performance factor.

Test Bed Setup

This experiment is done in author's lab on an IDI diesel engine in three different engine speeds of 1500, 2000 and 3000 rpm and different engine loads corresponding to 25, 50 and 75 percent of maximum achievable load in each speed. In the tests three EGR mass ratio of 0%, 10% and 20% were employed in order to investigate the effects of EGR application from lean to rich combustion conditions. In each test the EGR mass flow was being calculated via codes in MATLAB software based on constant intake volume which is drawn into the cylinder.

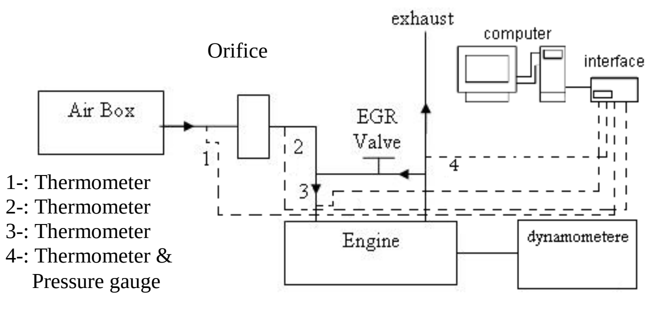


Fig.1

It should be noted that employed EGR modification is of high pressure loop type with air-cooled intercooler. The engine test bed is shown in Fig.1.

Model Description

The model is based on the physical processes that determines the residual gas mass which was firstly proposed in [11] and after that was adapted to diesel engines in [3] divides the in-cylinder residual gas to two main parts which are (1) the back flow of the burned gas from exhaust port during valve overlapping caused by higher static pressure of the exhaust port from intake port and (2) the trapped mass in cylinder just before IVO which is tightly dependent to fuel-air equivalence ratio. So as mentioned before, The residual gas mass is attributed to: (1) the back-flow of the burned gas from the exhaust port to the cylinder during the valve overlap period, and (2) the trapped gas in the cylinder at top dead center:

$$m_r = \int_{IVO}^{EVC} \dot{m}_e d\theta + m_{TDC} \qquad (1)$$

Where IVO is the crank angle at intake valve opening, *EVC* is the crank angle at exhaust valve closure, and m_{TDC} is the mass trapped in the cylinder at top dead center. Furthermore, $\dot{m}_e$ represents: (1) the mass flow rate of the combustion products from the exhaust port back into the cylinder, which occurs when the pressure in the exhaust port is above the pressure in the intake port, and (2) the mass flow rate of the trapped burned gas from the cylinder to the exhaust port when the intake pressure is higher than the exhaust pressure during the valve overlap period. The residual gas mass fraction Xr is then given by:

$$X_r = \frac{m_r}{m_c} \qquad (2)$$

where m_c is the total charge mass per cycle. To estimate the contribution of the overlap period, i.e., the first term of Eq.(1), to Xr , the back-flow process is modeled using the smaller of the intake and exhaust valve curtain areas [4]. As a result, the residual gas fraction contribution due to the overlap back-flow can be described as

$$\frac{\int_{\theta IVO}^{\theta EVC} \dot{m}_e d\theta}{m_c} \propto \frac{\rho_5 \sqrt{\frac{(P_e - P_i)}{\rho_5}}.V_d \frac{OF}{\Delta\theta}\frac{\Delta\theta}{N}}{m_c} \qquad (3)$$

In Eq.(3), $\Delta\theta$ is the valve overlap period, ρ_5 is the burned gas density, V_d is the displacement volume of the engine, and N is the engine speed. The subscripts 'e' and 'i' refer to exhaust and intake, respectively. Furthermore, OF is the overlap factor , given by [4]

$$OF = \frac{D_i A_i + D_e A_e}{V_d} \qquad (4)$$

where Di and De are the inner seat diameters of the intake and exhaust valves and

$$A_i = \int_{IVO}^{i=e} L_i d\theta \quad \text{and} \quad A_e = \int_{i=e}^{EVC} L_e d\theta \qquad (5)$$

In the above expressions, *Li* and *Le* are the intake and exhaust valve lifts, and $\theta_{i=e}$ is the crank angle When the intake lift is equal to the exhaust lift.

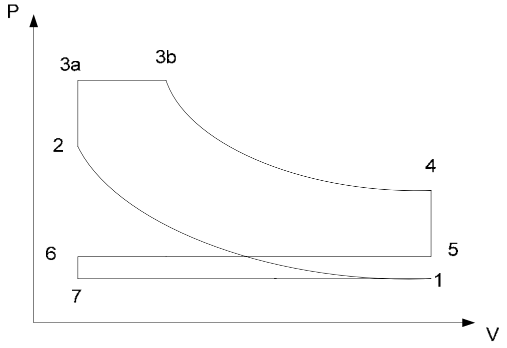


Fig. 2 Schematic of an ideal engine cycle

From a general ideal cycle analysis (see Fig. 2), the exhaust pressure P_e, corresponds to P_5 , and the intake pressure P_i corresponds to P_1. As a result, the right hand side of Eq. (3) is proportional to:

$$\frac{\rho_5\sqrt{\frac{(P_e-P_i)}{\rho_5}}.V_d\,\frac{OF}{\Delta\theta}\frac{\Delta\theta}{N}}{m_c}\propto(\frac{RT_1}{P_5})^{1/2}.(\frac{P_5}{P_1})^{\frac{\gamma+1}{2\gamma}}.\frac{r_c-1}{r_c}$$

$$.\frac{(1+\beta)^{\frac{\gamma-1}{2\gamma}}}{(1+\beta+\omega)^{1/2}}.\sqrt{|P_5-P_1|}.\frac{OF}{N} \qquad (6)$$

where R is the gas constant, r_c is the compression ratio, Q_{hv} is the reaction heat of fuel, and α is the constant volume combustion fraction defined as

$$\alpha=\frac{m_{f,2-3a}}{m_f} \qquad (7)$$

Where $m_{f,2-3a}$ represents the mass of fuel burned during the constant volume process of the cycle, i.e., process 2-3a in Fig.2. In Eq. (6), β and ω are defined as:

$$\beta=\frac{\alpha.m_f.Q_{hv}}{mC_v r_c^{\gamma-1}T_1} \qquad (8)$$

and

$$\omega=\frac{(1-\alpha)m_f Q_{hv}}{mC_p r_c^{\gamma-1}T_1} \qquad (9)$$

Where m is the in-cylinder air mass.
The contribution to Xr by the second term in Eq. (1) can be represented as

$$\frac{m_{TDC}}{m_c}=\frac{m_6}{m_c}\propto\frac{\rho_5}{\rho_2}=\frac{1}{r_c}(\frac{P_5}{P_1})^{\frac{1}{\gamma}}\frac{(1+\beta)^{\frac{\gamma-1}{\gamma}}}{1+\beta+\omega} \qquad (10)$$

In the literature it has been found that the redsidual gas attributed to the trapped gas depends on the equivalence ratio ϕ [12]. Then, the above equation is empirically modified to give [12]:

$$\frac{m_{TDC}}{m_c}\propto\frac{1}{r_c}(\frac{P_5}{P_1})^{\frac{1}{\gamma}}\frac{(1+\beta)^{\frac{\gamma-1}{\gamma}}}{1+\beta+\omega}. \qquad (11)$$
$$(\phi^2-0.5295\phi+0.5295)$$

and the residual gas fraction Xr; is given as

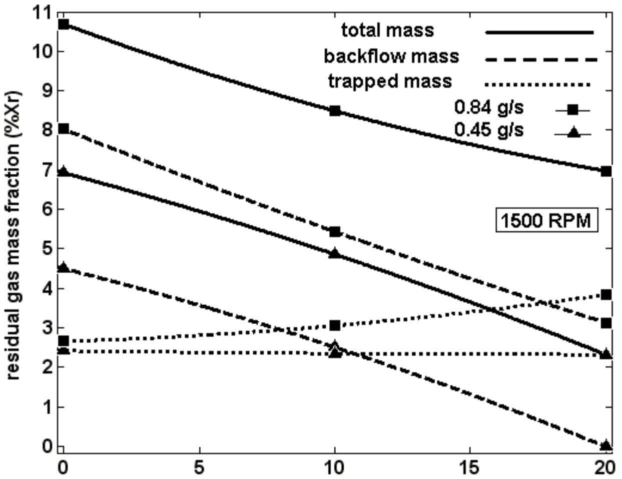
$$x_r=C_1.(\frac{RT_1}{P_5})^{1/2}.(\frac{P_5}{P_1})^{\frac{\gamma+1}{2\gamma}}.\frac{r_c-1}{r_c}. \qquad (12)$$
$$\frac{(1+\beta)^{\frac{\gamma-1}{2\gamma}}}{(1+\beta+\omega)^{1/2}}.\sqrt{(P_5-P_1)}.OF+C_2.\frac{1}{r_c}.(\frac{P_5}{P_1})^{1/\gamma}\frac{(1+\beta)^{\frac{\gamma+1}{\gamma}}}{1+\beta+\omega}.$$
$$(\phi^2-0.5295\phi+0.5295)$$

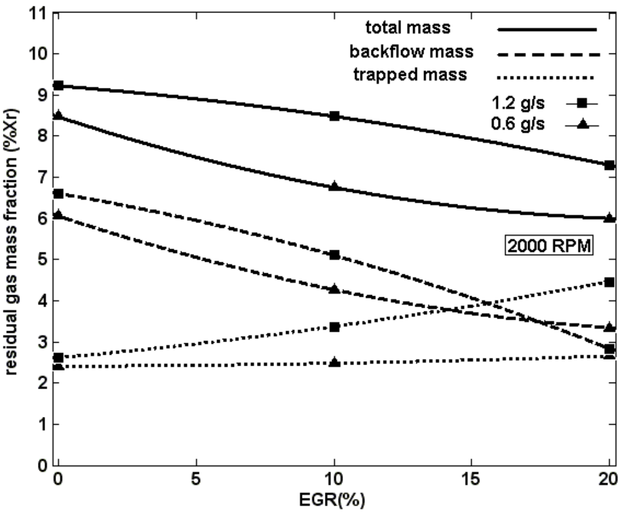
Where C1 and C2 are model constants to be determined. at this point, the only assumption that has been made is the ideal cycle assumption, and thus the model should be valid for both SI and CI engines.
For this case, the compression ratio r_c is 1/22, the exhaust pressure is 1 bar, the intake temperature is 300K, Q_{hv} is 44.0 MJ/kg, m_f/m is 1/15.6, α is 1 and γ is 1.35. Comparing with Eq. (11) in [11], the model constants C1 and C2 are calculated to be 3.3089 and 2.2662, respectively. Therefore, Eq. (12) Becomes:

$$x_r=3.3089.(\frac{RT_1}{P_5})^{1/2}.(\frac{P_5}{P_1})^{\frac{\gamma+1}{2\gamma}}.\frac{r_c-1}{r_c}. \qquad (13)$$
$$\frac{(1+\beta)^{\frac{\gamma-1}{2\gamma}}}{(1+\beta+\omega)^{1/2}}.\sqrt{(P_5-P_1)}.OF+2.2662.\frac{1}{r_c}.(\frac{P_5}{P_1})^{1/\gamma}\frac{(1+\beta)^{\frac{\gamma+}{\gamma}}}{1+\beta+\alpha}$$
$$(\phi^2-0.5295\phi+0.5295)$$

In the above equation, P*1* and P5 are absolute pressures in bars, the engine speed *N* is in *rev/s*, the overlap factor OF is in $^\circ/m$,C*v* is in *J/kg.K* and *Qhv* is in *J/kg.*
The pressure difference term (P5 – P1) in Eq.(3) has been replaced by the absolute value of the pressure differ in Eq. (13) so that the correlation may also be applied when the intake pressure is greater than the exhaust pressure. In this case, the numerical value for C1 is replaced by - C1.

Results and discussion





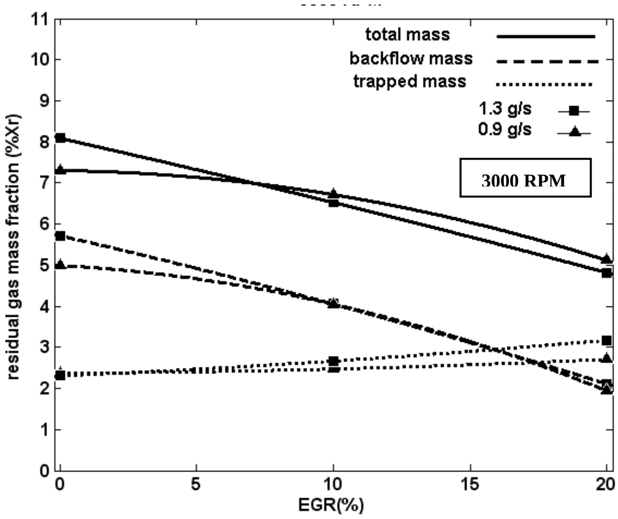


Fig.3,Development of residual gas mass fraction for different EGR ratio in an IDI diesel engine at 1500, 2000 rpm and 3000 rpm under two fuel injection rates.(OF=0.93)

There are some points concluded from above figures which are presented in brief:

1. It is clear from the Fig.1 that the total residual mass fraction decreases while increasing EGR mass ratio. This is mostly because of the decrease in induced backflow mass which is caused by the following reasons:
a) As the EGR valve opens, the static pressure of exhaust line reduces because a fraction of exhaust gas is subtracted from the exhaust line and as it is known, the ratio of Pe/Pi plays a main role in sending the exhaust gas back to the cylinder during valve overlapping.
b) The temperature of the intake mixture goes up as the EGR ratio increases. This can contribute to the scavenging process while valve overlapping and as a result of this, less exhaust gas is allowed to get in the cylinder.
2. The trapped mass at IVO cumulates with increasing EGR ratio. This change is due to decrease of intake air mass caused by volume efficiency deterioration as a result of using EGR which can increase fuel-air equivalence ratio and affect the second term in equation(1).
3.The residual gas mass fraction gets more as the equivalence fuel-air ratio goes further. This is due to an increase in exhaust port static pressure which contributes increasing Pe/Pi ratio and as a result, back flow induced mass increases.
4.It is observed from the figures that by engine speed increase, the amount of residuals reduces. It can be interpreted as the decrease of valve overlap time causing less chance for exhaust gas to get back to the cylinder.

Conclusion

Residual gas is already burned gas from previous engine cycles that is left in the cylinder. The amount of residual gas is often measured as a fraction of the total mass and the definition of residual gas fraction is the ratio between the mass of residual gas and the total mass.

In this investigation the influence of application of EGR in an IDI diesel engine on residual gas mass fraction as an indicator of exhaust performance which affects the engine combustion through its influence on charge mass temperature and dilution was evaluated via an analytical procedure based on experimental data. The use of EGR improves the exhaust performance by totally reducing the in cylinder residual gas mass fraction. This reduction is mainly because of reduction in backflow mass in valve over lapping. This trend is more prevalent at lower engine speeds.

Nomenclature

	subscripts	η	Efficiency
v	Volumetric	r	Compression ratio
r	Residual	x	Mass fraction
e	Exhaust	ϕ	Equivalence ratio
i	Intake	P	Pressure
1	Start of compression	T	Temperature
5	Start of exhaust	N	Speed
c	Compression	R	Gas constant
		m	Mass
		γ	Specific heat ratio

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