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The Effect of Cylinder Deactivation on the Performance Parameters of a Bi-fuel Engine

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ABSTRACT

To meet consumer and legislation requirements, various technologies have been used worldwide to achieve optimal fuel consumption and to reduce greenhouse gas emissions. One of the proposed technologies is cylinder deactivation using various methods, including, injectors cutting off, closing the intake and exhaust valves and crankshaft decoupling. In this paper, a GT-Power model is created to investigate the engine performance of a 1.7L bi-fuel natural-gas engine. The model is also evaluated to predict performance differences between cylinder deactivation and nominal four-cylinder operation, including torque, power, brake specific fuel consumption and exhaust gas temperature. The results showed that cylinder deactivation (CDA) capable of increasing exhaust gas temperature until 40°C, also brake specific fuel consumption (BSFC) reduced by 21%. Comparisons are made between periods of 1500 to 5500 rpm.

1) Introduction

Cylinder deactivation can offer a means of reducing fuel consumption of multi-cylinder engines when operating under part loads. It is most effective on spark-ignition engines that use throttle valves at part load to restrict intake flow, reducing intake manifold pressure. Less efficient engines that are converted to offer deactivated-cylinder-operation showed fuel consumption reduction of as much as 20%. Pumping losses are significantly reduced when an engine is operating in a deactivated-cylinder mode. The use of selective deactivation of cylinders as a tool for regulating the engine output torque is started in the nineteenth century, which has been used in single-cylinder portable engines widely used in agriculture and industry [1].

In such a system, there is a control unit that receives information from sensors. The control unit compares the parameter values with the operating conditions of the engine to determine the possibility of the cylinder deactivation [2].

The advantages of the cylinder deactivation are increasing the efficiency of the engine in part loads, improving the fuel economy by decreasing pumping losses, reducing the friction power in deactivated valves, emission reductions, and better volumetric efficiency and increasing the exhaust gas temperature [3].

There are several ways to deactivate the cylinder, including injector cut off, closing the inlet valves or exhaust valves and crankshaft decoupling [4]. The limitations of this technology are the engine balance, the cost of manufacturing, engine weight, and the complexity of the maintenance system. Also, due to the increased brake mean effective pressure in the active cylinders the probability of knock phenomenon is increased and due to higher temperatures in active cylinders and lower temperatures in inactive cylinders, a large temperature gradient occurs in the engine, which produces high stresses [5, 6].

In 1982, Mitsubishi introduced an engine with a varying number of cylinders called Orion - MD. In this system, an oil pump controls oil pressure for fast and accurate operation of valve deactivation. Mitsubishi demonstrated an 11 percent reduction in fuel consumption in the urban cycle [7].

Ihlemann et al researches have been shown that temporarily deactivating one of the cylinders in a three-cylinder engine reduces fuel consumption. The active cylinders should produce higher average pressure and change in the engine load increases the engine throttle angle valve [8].

Foloki et al introduce deactivation by the hydraulic actuation using the oil pressure to control exhaust and intake valves. General Motors has also introduced a similar system for the 5.5-liter OHV V8 [9].

In GM V6 OHV 3.9 L engine, deactivation is controlled by a set of solenoid valves [10].

Paul et al deactivate the cylinders through the piston they could reduce fuel consumption and power losses [11].

Another method of the cylinder deactivation has been proposed by Burty et al based on the use of the clutch in the crankshaft which allows the separation of parts of the shaft so that the separated cylinders with the shaft don’t rotate. The advantage of this method is that the power is saved, but a high- power battery is required to control the solenoid valves [12].

Choi et al investigate the effects of the cylinder deactivation on the pressure waves in the exhaust system of the six-cylinder engine [13].

Lee et al investigate the deactivation of the cylinders by two fixed and variable methods, resulting in an improvement of fuel consumption 2.2 to 10% in the fixed deactivation method and improved fuel consumption 2.2 to 12.8% for the variable type of cylinder deactivation [14].

An innovative cylinder deactivation approach for 4 - cylinder SI engines propose by multipurpose dual intake.

Also, a new load control strategy that combines cylinder deactivation and variable valve timing is explored by Zhao et al. The results show that pumping losses are reduced and fuel consumption is also improved. This strategy is more effective in the lower speed range and more suited to urban driving [15].

One-dimensional engine modeling of the cylinder deactivation has been performed to investigate the effect of inlet and exhaust valve strategies on engine performance by Said et al. The results show that strategies have a remarkable effect on engine performance. Pumping losses and fuel consumption are reduced and the thermal efficiency of the engine is improved [16].

Barry et al perform the cylinder deactivation by the hydraulic pressure method. This model is unique because it is capable to simulate the effects of the cylinder deactivation on the pressure wave dynamics. The assumption in this analysis is that the effects of torsional balancing on the crankshaft are ignored [17].

The one-dimensional engine model based on experimental data is proposed by Hu et al. The results show that in low rpm, fuel consumption improves about 10 % [18].

Alen et al deactivate the cylinders with trapping the new intake charge and combustion gases. They investigate the effect on torque, fuel consumption and greenhouse gas emissions [19].

In the present research, the effect of cylinder deactivation on engine performance parameters including torque, power, brake specific fuel consumption, and exhaust gas temperature in the bi-fuel CNG engine is investigated by keeping the BMEP constant. Initially, the engine gas exchange system is simulated in the GT-Suite software. Then the model is evaluated using experimental results at two BMEP. It is expected that brake specific fuel consumption decrease and because increasing the exhaust gas temperature, the catalyst performance improves.

2) Governing equations

In the one dimensional simulation in the GT-Suite software, the Woschni GT model for heat transfer is considered:

$$h_c = 3.26 B^{-0.2} p^{0.8} T^{-0.55} \omega^{0.8} \tag{1}$$

where, h_c is the heat transfer coefficient, B is the cylinder diameter, p is the pressure cylinder, T is the mean cylinder temperature and ω is the average velocity of gas inside the cylinder. The engine friction is also calculated using the Chen-Flynn friction model:

$$\begin{aligned} FMEP = FMEP_{const} + AP_{cyl.max} + Bc_{p.m} \\ + Cc_{p.m}^2 \end{aligned} \tag{2}$$

where $FMEP_{const}$ is the constant part of FMEP, A is the maximum cylinder pressure factor, B is the piston average speed factor, C is the mean square piston speed factor, $p_{cyl.max}$ is the maximum cylinder pressure, and $c_{p.m}$is the average piston velocity [18].

Equations 3 to 5 are also used to account for the effects of the angles of ignition, pressure, and residual gas temperature.

$$\frac{dM_e}{dt} = \rho_u A_e (S_T + S_L) \tag{3}$$

$$\frac{dM_b}{dt} = \frac{M_e - M_b}{\tau} \tag{4}$$

$$\tau = \frac{\lambda}{S_L} \tag{5}$$

where M_e is the unburned mass, M_b is the burned mass, ρ_u is the density of the unburned mixture, A_e is the ignited area at the flame front edge, S_T is the turbulent flame velocity, S_L is the laminar flame velocity, and τ is the time constant. The time constant can be calculated from Eq.6.

$$\tau = 5.72 \times 10^6 P \left(\frac{ON}{100}\right)^{3.402} p^{-1.7} \times 10^{\frac{3800}{A \times T_u}} \tag{6}$$

$$T = \int_{IVC}^{t} \frac{1}{\tau} dt \tag{7}$$

$$\begin{aligned} KI = 10000 K_A \times km \left(\frac{V_{TDC}}{V_I}\right) \times 10^{\frac{T_a}{T_u}} \\ \times \max\{0, [1 - (1 - \varphi)^2]\} \\ \times T_{\text{avg}} \end{aligned} \tag{8}$$

where ON is the octane number of fuel, p is instantaneous cylinder pressure, T is the time integral, T_u is the instantaneous unburned gas temperature, KI is knock index, IVC is the intake valve closing time, T_a is activation temperature, km is the percentage of unburned mass, V_{TDC} is the cylinder volume at TDC and T_{avg} is mass averaged induction time integral based on all of the surfaces in contact with unburned gases [15]. The governing equations of the cylinder gas exchange are equations 9 to 12 [20].

$$M_{fresh}(\theta_c) = \eta_v \frac{P_{im} \, V_c(\theta_c)}{R \, T_{im}} \tag{9}$$

$$M_{bg}(\theta_c) = \frac{V_{evc} \, P_{em}}{R \, T_{em}} \tag{10}$$

$$T_c(\theta_c) = Y_{bg}(\theta_c) \times T_{em} + \left[1 - Y_{bg}(\theta_c)\right] T_{im} \tag{11}$$

$$\begin{aligned} P_c(\theta_c) = \big[M_{fresh}(\theta_c) + M_{bg}(\theta_c) \\ + M_{fuel}(\theta_c)\big] \frac{R \, T_c(\theta_c)}{V_c(\theta_c)} \end{aligned} \tag{12}$$

3) Engine simulation

The general specifications of the naturally aspirated bi-fuel engine are given in Table 1. This engine is simulated in the GT-Power software. This software is used to analyze and optimize a wide range of engines and vehicles and their accessories. Numerical calculations in this software are based on the one-dimensional fluid dynamics equations and heat transfer in pipes and other engine components.

Using the drawings and information, a one-dimensional model has been developed. Figure 1 shows the EF7NA engine model in GT-Power software. This model has four cylinders in which the injectors are connected to the runners.

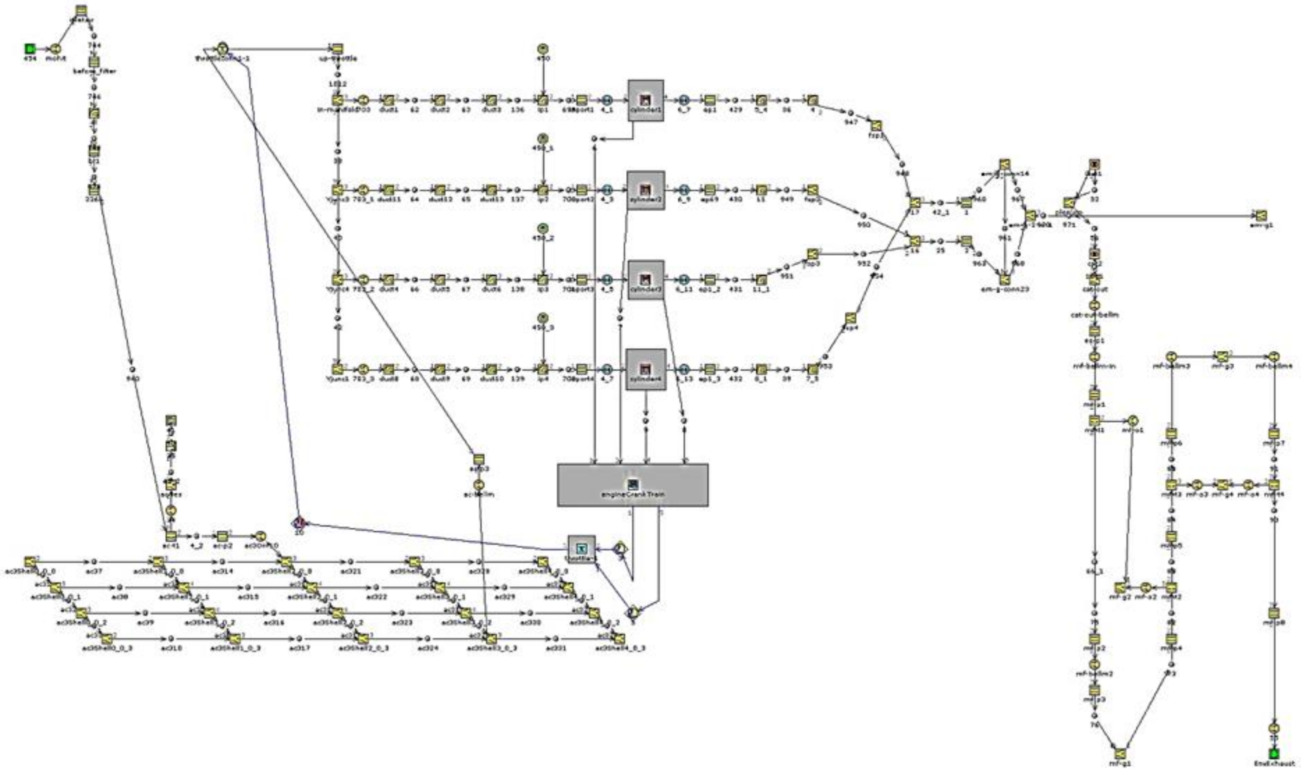

Figure 1: EF7NA Model in GT-Power engine

In this research, the deactivation is done on the cylinders 1 and 4, so no fuel is injected and the cylinder is deactivated. The performance parameters of the engine, including power, torque, brake specific fuel consumption and temperature of the exhaust gases are compared with the experimental data and finally, the effect of deactivation is investigated.

Table 1: General specifications of the EF7NA engine [21]

parameter	value
Bore×Stroke (mm)	78.6×85
Engine Volume (CC)	1649
Engine weight (kg)	140
Rated power (kW)	82@5750 rpm
Maximum torque (N.m)	150@3300 rpm
Connecting rod length (mm)	134.5
Compression ratio	11
Bore pitch (mm)	84

4) Model Validation

After simulation of EF7NA in GT-Power, in-cylinder pressure, torque, power, brake specific fuel consumption and exhaust gas temperature are compared with experimental data at the full load [22, 23].

The numerical simulation results and experimental findings for pressure at full load condition at 5500 rpm are depicted in Fig. 2 which is in good consistency.

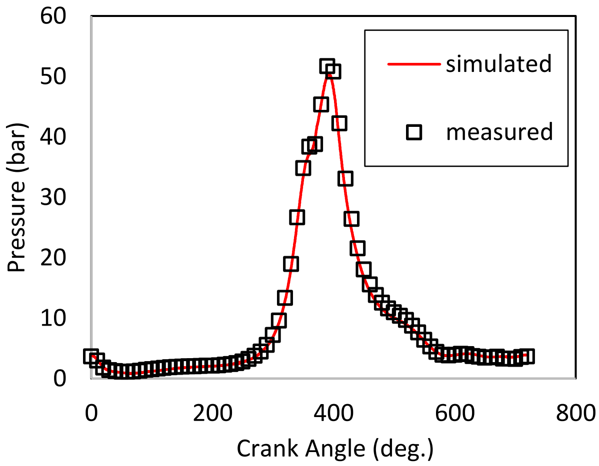

Figure 2: Comparison of simulated and measured in-cylinder pressure at full load

The deviation between the pressures does not exceed 2.5%. Also, the difference in the torque parameter in the 1500 and 3500 rpm is less than 4%, 1% at 2000 and 4500 rpm and less than 3% in 2500, 4000 and 6000 rpm, which is acceptable(Fig. 3).

Figure 4 shows the brake power at different engine speeds. Based on the graph, it is obvious that the difference is in an acceptable range from 1% at 1500 rpm to 3% at 6000 rpm [22-24].

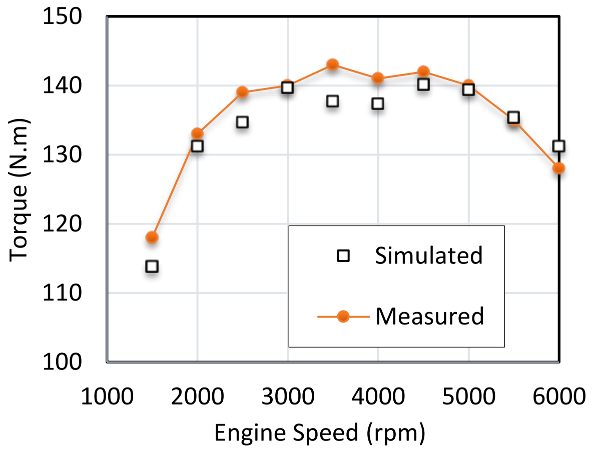

Figure 3: Comparison of simulated and measured torque at full load

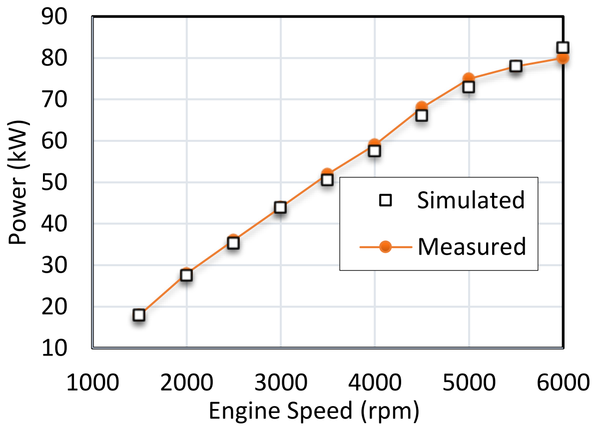

Figure 4: Comparison of simulated and measured power at full load

A comparison of the brake specific fuel consumption at full load is illustrated in Figure 5. The results show that the differences are less than 10% at all rpm [22-24].

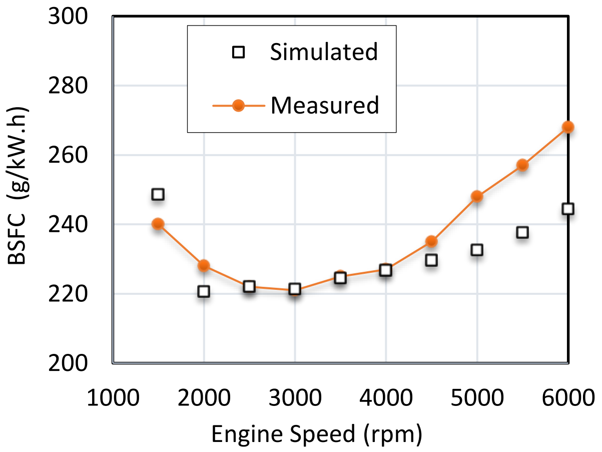

Figure 5: Comparison of simulated and measured brake specific fuel consumption at full load

According to Fig. 6, the errors between the exhaust gas temperature of the simulation model and the actual engine testing are less than 5%, which is acceptable to be used as a correlated model. Based on the data obtained from the simulation and comparing it with the previous experimental ones, it can be concluded that the GT-Power model is reliable [22-24].

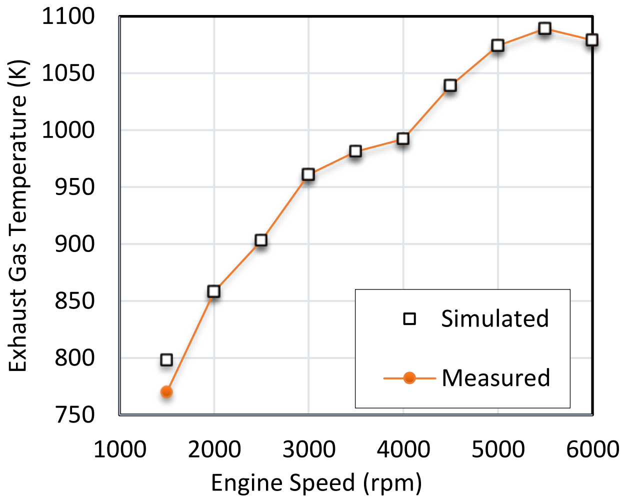

Figure 6: Comparison of simulated and measured exhaust gas temperature at full load

5) Results and discussion

Cylinder deactivation on the EF7NA engine has been accomplished with several methods, including closing the intake valves, closing the exhaust valves, cylinder elimination and injector cut off. The performance parameters (torque, power, brake specific fuel consumption and exhaust gas temperature) obtained in the first three methods were unacceptable because they disrupted the gas exchange process and just fourth method, namely injector cut-off was appropriate and acceptable. Comparison is done at Brake Effective Mean Pressure (BEMP) 2 bar.

When the cylinders are deactivated, the active cylinders aspirate more air to maintain the same BMEP, torque and power (Figs. 7 & 8), thus the throttle angle is increased and pumping losses is reduced.

Based on Fig. 9, the brake specific fuel consumption in the deactivated mode is reduced in comparison with the normal mode, because the throttle is open more and pumping losses is decreased. The reduction is 29% at the 1500 rpm, 24% at the 2500 rpm, 22% at the 3500 rpm, 21% at the 4500 rpm and 22% at the 5500 rpm.

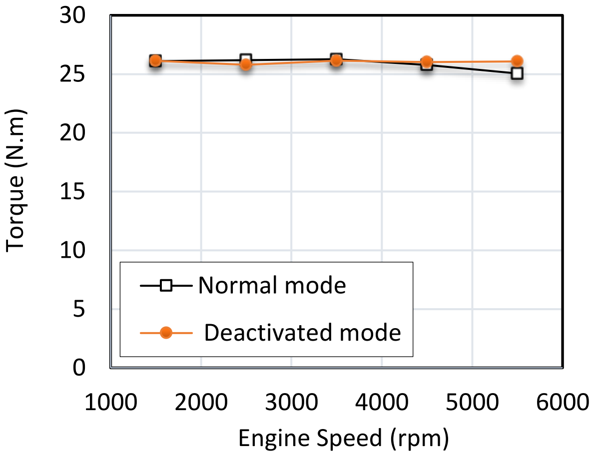

Figure 7: Torque comparison of normal mode and deactivated mode at BEMP 2 bar

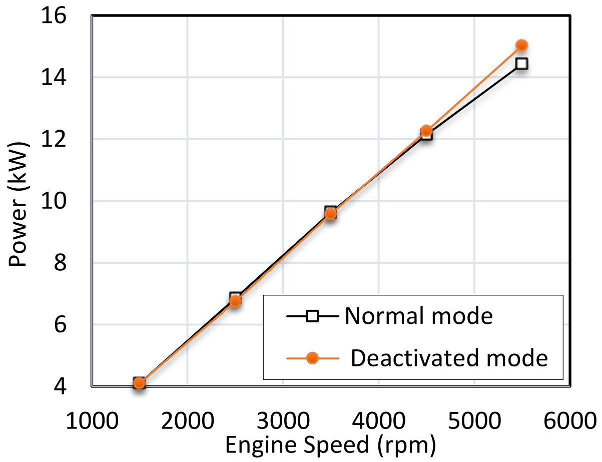

Figure 8: Power comparison between normal mode and deactivated mode at BEMP 2 bar

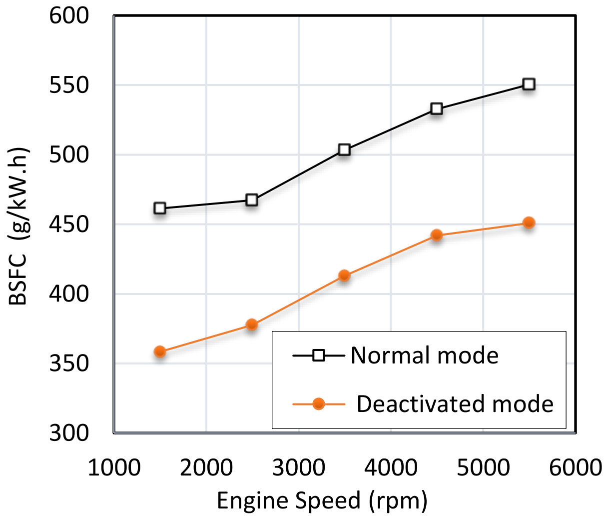

Figure 9: Brake specific fuel consumption comparison between normal mode and deactivated mode at BEMP 2 bar

As shown in Fig. 10, the temperature of the exhaust gases is increased by deactivation of the cylinder, which will result in improving catalyst performance at partial loads. This increase in temperature occurs due to the increased load on the active cylinders and running at the rather optimal operating points. The increased temperate about 50°C at 4500 and 5500 rpm.

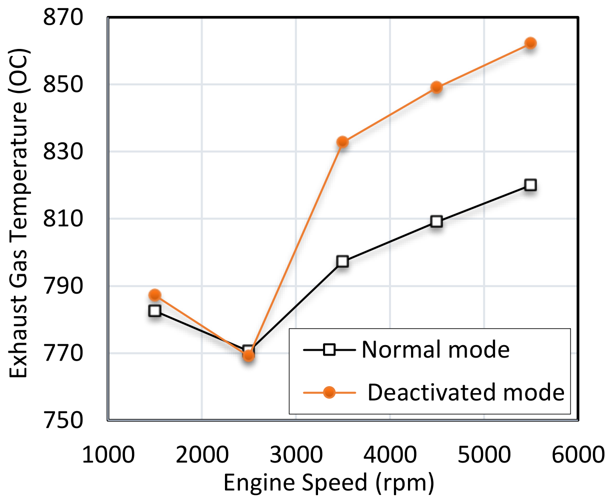

Figure 10: Exhaust gas temperature comparison between normal mode and deactivated mode at BEMP 2 bar

6) Conclusion

In this paper, a valid one-dimensional model of the EF7 bi-fuel engine is achieved. By injector cut-off, the engine performance parameters including torque, power, brake specific fuel consumption, and exhaust gas temperature are compared between normal mode and deactivated mode at BEMP 2 bar which simulated in GT-POWER software.

The results show about a 20% reduction in brake specific fuel consumption at partial loads, which commonly the driving cycles have occurred at this load and the temperature of the exhaust gas also rises to 50°C that causes reducing the catalyst activation time (light off) and better performance.

Acknowledgment

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Nomenclature

Symbol	Description
h_c	Heat transfer coefficient
B	Cylinder diameter
P	Cylinder pressure
T	Average gas temperature
C	Medium Speed Square
$P_{CVL,max}$	Maximum pressure
$C_{p.m}$	Average piston speed
M_b	Burned mass
A_e	Area
S_T	Turbulent Flame speed
S_L	Laminar Flame speed
$\dot{m}$	Mass flow rate
A_S	Heat transfer area
p_{im}	Inlet manifold pressure
p_{em}	Outlet manifold pressure
T_{wall}	Wall temperature
T_{im}	Inlet temperature manifold
C_p	Pressure drop coefficient
T_{em}	The temperature of the exhaust manifold
ω_c	Angular velocity
θ_c	Crank angle Degree
BMEP	Brake Mean Effective Pressure

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اثر غیرفعالسازی استوانه ها بر متغیرهای عملکردی یک موتور دوگانه سوز

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چکیده

روش‌های مختلفی برای بهینه‌سازی مصرف سوخت و کاهش گازهای گلخانه‌ای در دنیا استفاده شده اند. از فناوری‌های مطرح، غیرفعال کردن استوانه با روش‌های مختلفی از جمله، حذف افشانه، بستن دریچه‌های دود و هوا و قطع جرقه است. در این مقاله، غیرفعال کردن استوانه با حذف افشانه روی موتور دوگانه سوز انجام شده است. در ابتدا موتور در نرم‌افزار GT-Suite شبیه‌سازی و با نتایج تجربی، ارزیابی می‌شود. پس از اطمینان از عملکرد مناسب طرح، غیرفعال کردن استوانه شبیه‌سازی می‌شود. شاخص‌های عملکردی موتور شامل گشتاور، توان، مصرف سوخت ویژه و دمای گازهای خروجی، در دو حالت عادی و غیرفعال سازی شدهٔ استوانه‌ها، مقایسه شدند. غیرفعال کردن استوانه در دو فشار مؤثر متوسط ترمزی انجام شد تا موتور به گشتاور و توان خروجی یکسان نسبت به حالت عادی برسد. نتایج نشان داد که دمای گازهای خروجی موتور افزایش و مصرف سوخت ویژه کاهش می‌یابد. مقایسه‌ها در دورهای ۱۵۰۰ تا ۵۵۰۰ دور بر دقیقه انجام شدند.

اطلاعات مقاله

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کلیدواژه‌ها:
GT-Power
افشانه
غیرفعال کردن استوانه
مصرف سوخت ویژهٔ ترمزی
دمای گازهای خروجی