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Experimental Investigation of the Effects of Air Injection and Injection Timingin a Natural Aspirated DI Diesel Engine

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ABSTRACT

In this experimental study, the effect of creating an air jet inside the combustion chamber by establishing an air-cell inside of the piston body at different injection timings in a DI diesel engine has been studied at 2000 rpm and full load operation. The performed tests include studying the Soot and NOx emissions, combustion and performance parameters. The obtained experimental results show that using an air-cell inside the piston causes in simultaneous reduction of Soot and NOx emissions. In additon, advanced injection timing results in increasing of brake power and reduction of brake specific fuel consumption(bsfc) with increasing of maximum pressure in the combustion chamber and maximum value of heat release rate. Furthermore, the results showed that the best time injection for air cell engine is 13BTDC, in which the NOx and soot emissions decrease by 15% and 50%, respectively, while BSFC and power remains relatively unchanged.

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1. INTRODUCTION

Today, DI diesel engines are used more than other engines due to their higher efficiency. Although, the NOx and Soot emissions produced in these engines are more than those of IDI diesel engine, but there are suitable technologies to reduce these emissions.

Due to contrast behavior of producing Soot and NOx emissions, it is essential that an appropriate method be used to simultaneous reduction of these emissions [1]. Some of the useful technologies to reduce the Soot and NOx, which have been used so far, include fuel injection with high pressure, multiple injections, advancing and retarding the fuel injection time and using swirl with higher intensity [2-4]. Flaig et al [5] have studied the effect of increasing injection pressure using common rail system over DI diesel engines. Fuel injection with high pressure into the combustion chamber results in atomization and improvement of air and fuel mixing and reduces the Soot emission. However, this method results in increasing of NOx emission due to providing better conditions to pre mixed combustion. Han et al. [6] using exhaust gas recirculation (EGR) and retired the fuel injection time could reduce the NOx emission significantly. However, this method has resulted in increasing of Soot emission. Mingfa et al [7] have studied the simultaneous using of multiple injection and EGR. Millo et al [8] have improved the engine performance and reduced the emissions produced in diesel engine using common rail system and EGR. It is essential that production of Soot and NOx emissions have converse relation in all the methods. Naguno et al [9] have reduced the amount of Soot and NOx significantly using air-accumulation generator. Foster and Choi [10] have studied the effect of mixing improvement on Soot and NOx emissions in an experimental work by jet injection of dioxide carbon and gas nitrogen with high Pressure into combustion chamber. Mather and Reitz [11] have presented a design in which a secondary chamber created inside the piston body and connects to the primary combustion chamber through throats. The obtained results from this method show the simultaneous reduction of Soot and NOx emissions significantly. Jafarmadar and Hosseinzadeh [12] have numerical studied the creating of air-cell inside the piston and insulate the piston in order to

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improve the performance parameters. The study of the relevant literature shows that no attempt has been done up to now in order to experimentally study the effects of air injection and injection timing on the combustion, performance and emission characteristics in DI naturally aspirated diesel engine. In the present experimental work, the effect of creating an air jet by embedding an air-cell within piston and the effect of different times of fuel injection in 10˚ btdc, 13° btdc, 20° btdc and 25° btdc on Soot and NOx emissions, combustion parameters and performance parameters in DI diesel engine has been studied. Results show that creating an air-cell inside the piston body and advancing injection timing amount of 3° crank angle, cause a decrease soot and nox emissions about 50% and15%, respectively and keep the bsfc and brake power in a suitable range.

2. THE PROCESS OF CREATING AN AIR-CELL INSIDE THE PISTON BODY:

To embed an air-cell inside the piston, at first the bottom of piston has been punchedby a drill as shown in Figure 1 and then the drill has been replaced by a turning pen which has been provided to this purpose previously, by which the air- cell is created inside the piston, as shown in Figure 2. In the next step, by another drill from the bowl part of piston, four throats has been created in order to connect the secondary chamber to the primary combustion chamber, as shown in Figure 3 and at last, fill the initially created hole through a cap using welding of argon gas (Figure 4). The prepared piston is shown from top view in Figure 5 and schematic view of modify piston shown in Figure 6.

3. EXPERIMENTAL SETUP AND PROCEDURE:

In this work, the produced emissions, combustion and performance parameters of four cylinders, four stroke, water-cooled and natural aspirated direct injection diesel engine has been studied. Table 1 shows the important characteristics of the tested engine.

Figure 1. Boring bottom of piston

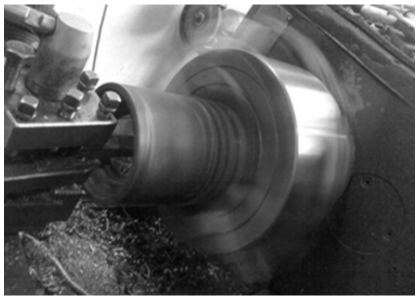

Figure 2. Creating an air-cell at the piston body

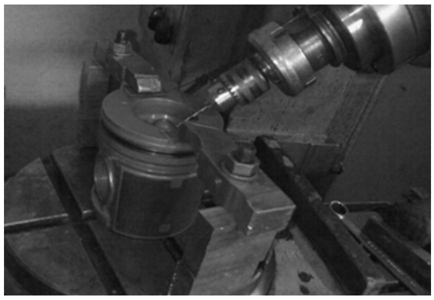

Figure 3. Creating throats at the piston bowl

Figure 4. Capping the hole by Argon gas welding

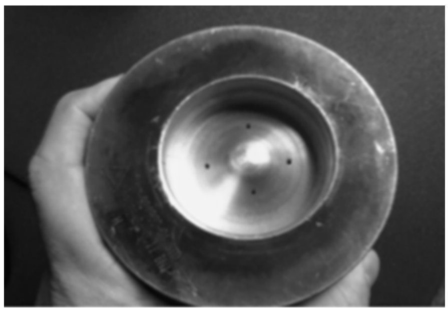

Figure 5. The modified piston from top view

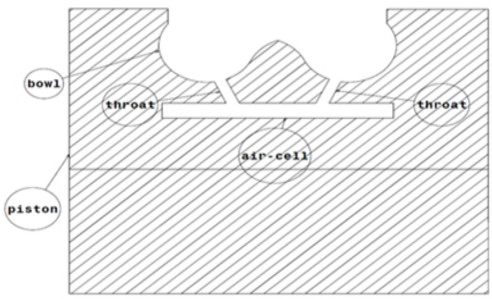

Figure 6. Schematic view of modify piston

The experiment includes a nature aspiration engine with fixed speed of 2000 rpm. A shaft to measure the performance parameters has connected this engine to a hydraulic dynamotor (made by England Ford factory). In addition, the emission detector (AVL DICOM4000) is used to measure the emissions of NOx (ppm), CO (%by volume) and HC (PPM) in gases exhausting from engine. The particulates are determined by measuring the weight of a filter placed in the path of exhausting gases before and after sampling. A probe used to sample the exhausting particulates in the output manifold. A pressure transducer of piezoelectric type (Indi Module 621) installed at the same level of combustion chamber over engine so that it reports the pressure of each moment by sampling the internal pressure of combustion chamber. In this engine, this transducer tuned in a way that the pressure of combustion chamber reported at each 0.1 point of crank angle. In order to increase the accuracy of experiment and decrease the possible error in reading the results, all the analyzing devices of output products calibrated before and after performing each test. Measuring of emissions repeated five times at each experiment and finally their average used in the analysis of results. The injection timing (advancing or retarding) have been adjusted by screw the camshaft of injection pump. The given tests have been performed over the base engine at first and in the next step the pistons containing air-cell have been replaced with primary pistons. The other tests have been done accompanied with new pistons in different times of fuel injection in 10˚btdc, 13˚btdc, 20˚btdc and 25˚ btdc.

4. RESULTS AND DISCUSSION

4. 1. Emission Analysis

4. 1. 1. Oxide of Nitrogen (NOx) Figure 8 shows the variation of NOx emission in five test steps. Using an air-cell within piston leads to entering some of the air from primary combustion chamber into air-cell in compression course and stored there. This action, reduce the available air in the pre-mixed combustion step, combustion is incomplete and maximum temperature of combustion chamber is reduce, so the amount of NOx pollution is reduced. The comparison of the measured data between two cases at injection time 10 BTDC shows that the value of NOx emission for air cell engine decreases because of a reduction in peak temperature in cylinder due to the decreased compression ratio (decrease from 17.5 to 16.5). By advanced fuel injection timing, more times is provided to mix the fuel with air. It results in improvement of combustion process and increasing the temperature of combustion chambe; so, NOx formation increases. Hence, the effect of decreased compression ratio can be compensated by advanced injection timing especially in fuel injection times at 20° BTDC and 25. From Figure 7, it is observed that using refined pistons with adjusting injection times in 10°BTDC and 13° BTDC results in reduction of NOx emission by 24% and 10% compared to basic state (fuel injection starting in 10° btdc with initial pistons). In fuel injection times at 20° BTDC and 25° BTDC it increased by 8 and 12% compared to basic condition.

Figure 7. The photo of experimental setup

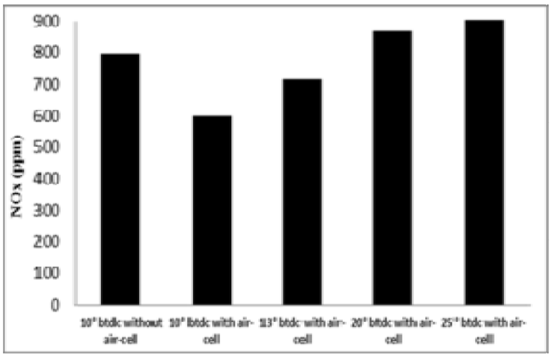

Figure 8. Experimental results for NOx emissions in 10°btdc without air-cell,10°btdcwith air-cell,13°btdc with air-cell, 20°btdc with air-cell and 25°btdc with air-cell

TABLE 1. Engine specifications

Engine	MT4.244
Number of cylinders	4-in line, Vertical
Cubic Capacity	3.99 liters
Compression ratio	17.5:1
Combustion system	Direct injection
Cooling	Water cooled with oil cooler
Duration of injection (deg)	20
Injection system	Pump-line-nozzle
Number of nozzle orifice × diameter (mm)	5 × 0.276
Displacement (lit)	3.99
Rate of fuel injected (kg/hr)	15.22
Fuel injection pump	DPA
Number of valves/cylinder	2/4

4. 1. 2. Smoke (Soot) Figure 9 depicts the variation of Soot emission in five performed test steps. Due to pressure difference between air-cell and primary chamber in expansion course, the stored air inside the air-cell has returned into primary combustion chamber This makes better turbulence and increasing of available oxygen during the diffusion combustion step. This action provides more oxidation of Soot emission and the amount of this pollution decreased. Advanced injection timing reduces the Soot emission due to better mixing and improvement of combustion. As Figure 8 shows, the amount of Soot has been reduced using an air-cell in different times of fuel injection in 10˚ BTDC, 13˚ BTDC, 20˚ BTDC and 25˚ BTD Ccompared to base state by 41, 50, 57 and 63%, respectively.

4. 2. Combustion Analysis

4. 2. 1. Cylinder Pressure Figure 10 shows the pressure variation of combustion chamber with crank angle in five given experimental steps. Air-cell has resulted in reduction of combustion intensity by reducing the available air during the pre-mixed combustion step and compression ratio. Thus, the value of P_{max}, which is in the pre-mixed combustion step, reduced. At injection timing of 10° BTDC, the value of peak pressure in cylinder at air cell engine decreases in comparison to base state because of the retardation of combustion at this engine. Advanced injection timing by providing more time to mix the fuel with air, the ignition delay time increases. More amount of fuel is evaporated in this step and pre-mixed combustion is done with higher intensity, so it increases the peak of cylinder pressure. P_{max} variations are equal to -4.2, -2, 8 and 12.2% by applying new pistons and in different times of fuel injection at 10°BTDC, 13°BTDC, 20°BTDC and 25°BTDC compared to base condition operating, respectively. The comparison of the results show that the effect of reducing compression ratio in air cell engine compensated by advanced injection timing.

4. 2. 2. Heat Release Rate Figure 11 represents the heat release rate variation with crank angle in five performed test steps. This research calculated the apparent rate of heat release $\left(\frac{dQ}{d\theta}\right)$ from the measured pressure diagram using the following equation.

$$\frac{dQ}{d\theta} = \left(\frac{\gamma-1}{\gamma}\right) P \frac{dV}{d\theta} + \left(\frac{1}{\gamma-1}\right) V \frac{dP}{d\theta} \quad (1)$$

$\theta$is the crank angle, V is the cylinder volume as a function of the crank angle , p is the pressure of the combustion chamber and γ is specific heat ratio.

By reduction of pre-mixed combustion intensity, the value of $((dQ/d\theta)_{max})$ decreases due to air reduction in the initial steps of combustion. However, better diffusion combustion by air injection from air- cell into the primary combustion chamber in the expansion course was observed. Advancing the injection timing by making the longer ignition delay period, leads to increase theburning rate. It also provides the context of increasing the pressure and temperature of combustion chamber suddenly, so it increases the $((dQ/d\theta)_{max})$. The variations of peak curve of heat release rate are equal to -9, -2, 27 and 32% by applying new pistons in different injection times at 10°BTDC, 13°BTDC, 20°BTDC and 25°BTDC compared to base state.

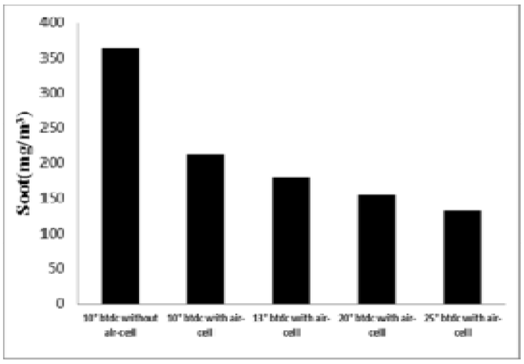

Figure 9. Experimental results for soot emissions in 10°btdc without air-cell,10°btdcwith air-cell,13°btdc with air-cell, 20°btdc with air-cell and 25°btdc with air-cell

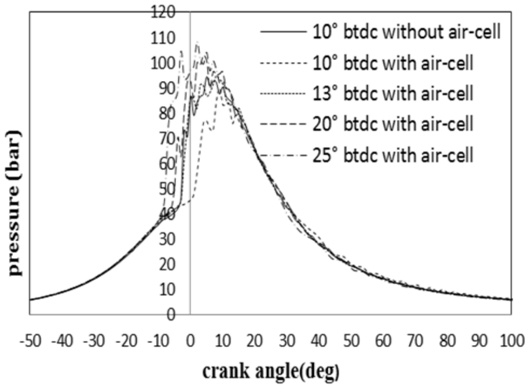

Figure 10. Cylinder pressure against crank angle

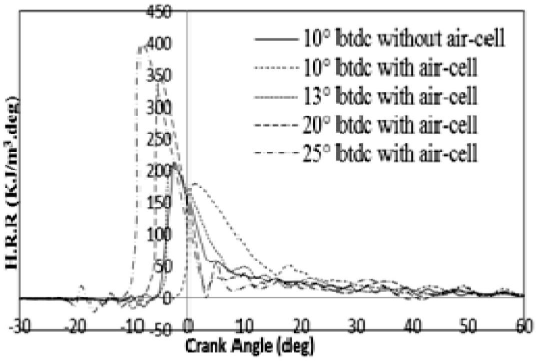

Figure 11. Cylinder heat release rate against crank angle

4. 3. Performance Analysis

4. 3. 1. Brake Specific Fuel Consumption (bsfc)

The brake specific fuel consumption is a concept to evaluate the capability of engine to convert the existing energy in fuel to useful work. Figure 12 shows the bsfc variation. Applying air-cell inside the piston results in loss of combustion intensity and pressure of combustion chamber in the initial steps of combustion and increases the bsfc. By advancing the fuel injection time, the amount of bsfc decreased due to increasing the pressure of combustion chamber and pre-mixed combustion intensity. The variation of brake specific fuel consumption equal to 10, 2 -6 and -11% by applying modify pistons in different times of fuel injection in 10° BTDC, 13° BTDC, 20° BTDC and 25° BTDC compared to base condition, respectively.

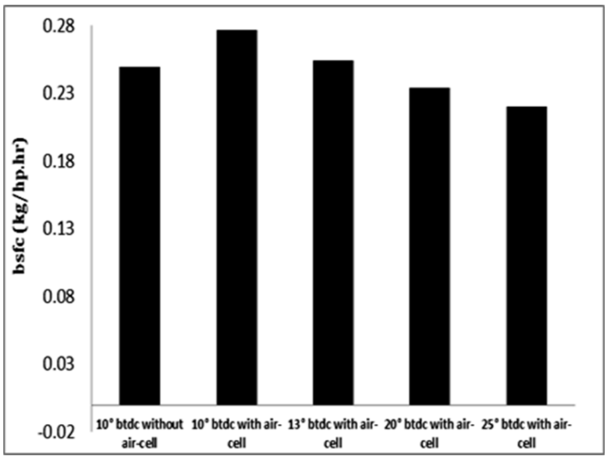

Figure 12. Experimental results for bsfc in 10°btdc without air-cell,10°btdcwith air-cell,13°btdc with air-cell,20°btdc with air-cell and 25°btdc with air-cell

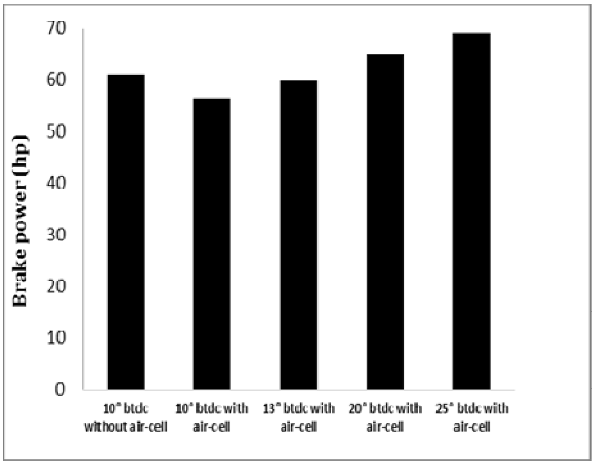

Figure 13. Experimental results for brake power in 10°btdc without air-cell,10°btdcwith air-cell,13°btdc with air-cell,20°btdc with air-cell and 25°btdc with air-cell

4. 3. 2. Brake Power

Figure 13 shows the brake power variation. The engine power has converse relation with bsfc parameter [13]. The brake power variation equal to -8.3, -1.9, 6.1 and 11% by applying new pistons in different times of fuel injection in 10° BTDC, 13° BTDC, 20° BTDC and 25° BTDC compared to base state, respectively.

5. CONCLUSION

The obtained results of present experimental work are as follows:

- ❖ Applying an air-cell can be an effective method to reduce the Soot emission from a direct injection diesel engine through increasing the mixing and availability of enough air in the diffusion combustion course by air jet injection into combustion chamber. In addition, using air-cell leads to simultaneous reduction of NOx exhausting from engine due to reduction of internal temperature of cylinder and lack of air in the first step of combustion.
- ❖ Advancing the injection timing by increasing the mixing time leads to reduction of Soot production, but in turn, it increases the NOx by improving the combustion conditions. This action improves the performance parameters of engine (brake power and brake specific fuel consumption).
- ❖ By applying a combinational method including usage of air-cell in the piston and starting the fuel injection at 13°btdc, we can reduce the Soot and NOx emissions compared to base engine (15 and 50% respectively). In addition, the performance parameters can be maintained in an acceptable range. (Increasing bsfc about 2% and decreasing the brake power about 1.9%)

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چکیده

در تحقیق تجربی حاضر اثر تزریق جت هوا به داخل محفظه احتراق به وسیله ایجاد سلول هوا در داخل بدنه پیستون در زمان های مختلف شروع پاشش سوخت در دور موتور ۲۰۰۰rpm و حالت بار کامل موتور مورد بررسی قرار گرفته است. تست های انجام شده بر روی موتور دیزل مورد نظر شامل بررسی رفتار آلاینده های دوده و اکسید های نیتروژن،پارامتر های احتراقی و پارامترهای عملکردی می‌باشد. نتایج بدست آمده نشان می دهند که به کار گیری سلول هوا موجب کاهش همزمان آلاینده های دوده و اکسید های نیتروژن خروجی از موتور دیزل شده است. به جلوتر انداختن شروع پاشش سوخت با افزایش فشار متوسط محفظه احتراق، نرخ آزاد سازی حرارت و توان ترمزی موتور موجب کاهش مصرف سوخت ویژه ترمزی موتور می‌شود.هم‌چنین نتایج نشان می‌دهند که شروع پاشش سوخت در ۱۳ درجه قبل از نقطه مرگ بالا همراه با به کارگیری سلول هوا در داخل پیستون مناسبترین حالت برای عملکرد موتور محسوب می‌شود که در این حالت مقدار آلاینده دوده ۵۰٪ و مقدار آلاینده اکسید ازت ۱۵٪ کاهش یافته در حالی که پارامترهای احتراقی و عملکردی موتور در محدوده مناسبی حفظ شده‌اند.

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