Reduction of Emissions in IDI Diesel Engine by Air Injection

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Abstract

Combustion process in diesel engine is influenced by the mixing process, turbulence of the medium, and temperature of combustion. By injecting a gas into the burning mixture it is possible to alter the combustion characteristics and hence the products of combustion. In this study, an experiment was performed to determine the influence of air injection into the pre-chamber of an indirect injection diesel engine. Results showed that at an optimum air injection timing it is possible to have an improved combustion process which results in suppression of both particulate matter and CO at reasonably low NO_x. Two other gases, namely N_2, and argon were also tested and showed the same effect, suggesting that the interaction of the gases makes it possible to reduce the pollutants emissions from an indirect injection (IDI) diesel engine. Argon gas with low heat capacity, reduced remarkably particulate matter at late injection timing and much lower NO_x emission throughout the test range.

1. Introduction

Recently, awareness of environmental hazards caused by emitted combustion products to the atmosphere has made the operation of diesel engine very unfavorable. Stricter legislatures are enforced now and then, limiting the proportions to be emitted by combustion systems to the atmosphere. Although diesel engines' preference is owed to their high fuel economy, they are the main generator of unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NO_x) and particulate matter (PM) whose constituents include soluble organic fractions (SOF) and dry soot. The carcinogenicity of these emissions are well studies [1], and other effects on human beings determined.

It is known that NO in diesel engine which is the main constituent of NO_x, is formed basically from the Zeldovich mechanism which is a temperature controlled process and prompt mechanism [2]. The result of quenched flame in combustible layers close to a cold wall like the cylinder wall, cylinder-head or piston crown is HC formation.

Several methods for emission control in diesel engines have being studied and some are in application. To mention a few, exhaust gas recirculation (EGR), catalytic control, regulation of air/fuel ratio, retarded injection timing and particulate traps are the common ones. All these methods have the disadvantage that they are unable to reach the limits set by authorities, while at the same time, they almost function at the expense of fuel economy.

In this work, the influence of compressed air injection into a modified pre-chamber of a diesel engine is studied, at various equivalence ratios and engine loads. Obtained results indicate that it is possible to reduce simultaneously particulate matter and oxides of nitrogen while maintaining a reasonable fuel economy. To understand the phenomenon better, N_2 and Ar were also tested. Following the same procedure, above gases were

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injected to the pre-chamber and emissions concentrations determined. It has been observed that all gases cause a reduction in SOF, HC, dry soot and NO_x at certain injection timing. This phenomenon can be attributed to the temperature quenching which is a function of heat transfer taking place after the injection of air and mixing enhancement of the flow of still burning mixture in the chamber. Inertial interaction of the gas molecules is also a factor in the emission reduction phenomenon through entrainment on the final combustion stages.

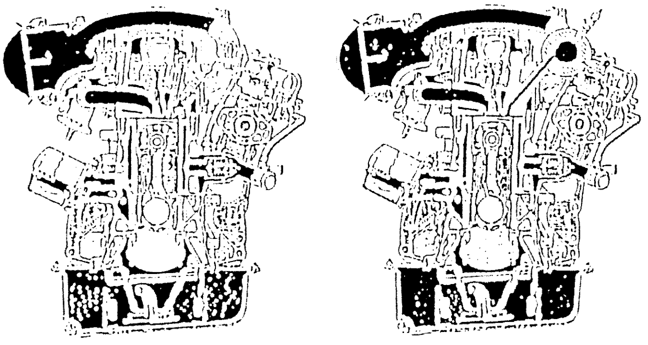
2. Experimental engine and procedures

Figure 1 shows the experimental engine in its original construction (a) and a modified pre-chamber engine (b). The configuration and dimensions of the pre-chamber are shown in Fig. 2. The main aim was to provide an optical access to the interior of the pre-chamber. Table 1. lists the most important specifications of the experimental engine.

Table 1 Experimental engine specifications

Engine type	4 stroke IDI diesel
Bore X stroke	83 X 83 mm
Displacement	1.8 liters
No. of cylinder	4
Maxim. power	65 PS/4500 rpm
Injector type	Throttle
Injection timing	10 deg. BTDC

A modified pre-chamber of 25 mm diameter and 17 mm depth was made, having approximately the same volume as the original. In order to provide optical access, the connecting passage between the main and pre-chamber was elongated by 10 times the original. An assumption that the longer passage will affect mainly heat and flow losses but maintaining the combustion behaviors was made as presented in the previous works [5]. Loading of the engine was made by means of a dynamometer model EWS-100-LT with a maximum power and speed of 100 PS and 13000 rpm, respectively. Gas sampling was made by means of an electronically controlled solenoid valve opening, actuated by a signal from the photo-detector sensing the crank angle of the engine, and gas sampled conveyed from sampling probe in the manifold via a quartz filter to a sampling bag. From the sampling bag, gas analysis was carried out to determine the concentrations of HC, NO and NO_x. Difference in mass of quartz filter before and after sampling determines the PM quantity, while the quantity of dry soot was obtained by removal of SOF using dichloromethane solution from the filter and measuring the mass again.



(a)Original (b)Modified

Fig. 1 Experimental engine

Compressed gas at approximately 5 MPa was injected to the pre-chamber at a specific injection timing (crank angle setting) ranging from 0° to 60° ATDC and a duration of 30°. One arrangement in which the gas injection port, fuel injection nozzle and connecting passageway make a Y form was chosen following the previously reported results [5], where a complete combustion process was confirmed by means of high speed photography with a remarkable reduction of PM and NO_x. Variables monitored were PM, SOF,HC, CO, NO, NO_x and dry soot at different air injection timings and equivalence ratios. The quantity of gas injected per cycle was estimated and the dilution effect on the concentration accounted for in the reported results. Compressed nitrogen gas and Argon were assessed at an equivalent ratio of 0.4 to elucidate the effect of gas injection into the pre-chamber.

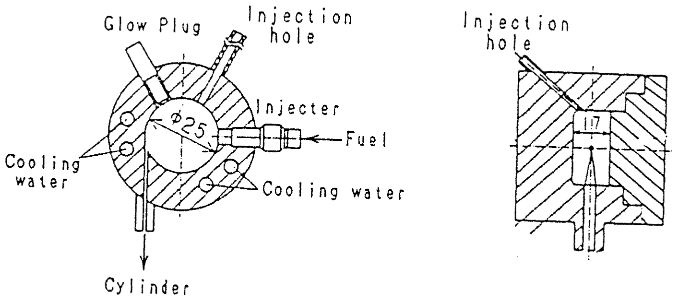


Fig. 2 Pre-chamber configuration

3. Discussion of results

At no load condition, and no air is injected into the pre-chamber, emission levels are as depicted by Fig. 3 where the fuel equivalence ratio is 0.2. PM is in the order of 300 ppm, SOF being about 200 ppm while dry soot accounts for the remaining PM. Load increase depicted by the fuel equivalent ratio λ (Fig. 3) increases PM emission exponentially, while SOF portion decreases slightly. Increased PM in this case is due to the increase in dry soot, showing an agreement with the theory that dry soot increases with fuel richness. In Fig. 3 also NO_x and NO are shown to decrease initially to a minimum at λ=0.4, and increase again to a level higher than at no load operation. Total HC increases to a maximum at λ=0.4 and decreases later on, almost back to the original level.

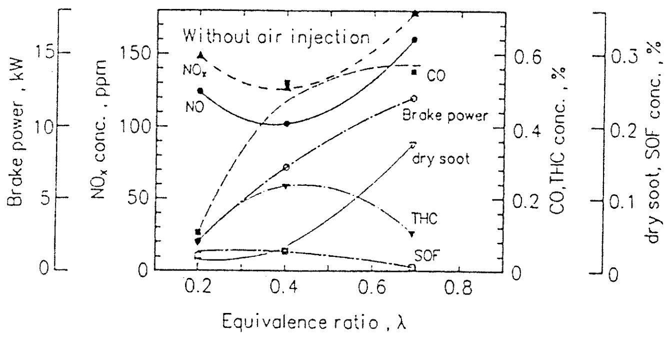


Fig. 3 PM, SOF, soot, NO_x and total HC results for normal operation (without air)

3.1 Air injection results

Results obtained from experiments where injection of compressed air was done at various injection timings and λ=0.2, 0.4 and 0.69 are shown in Fig. 4 through 8 for PM, SOF, dry soot, NO_x and NO.

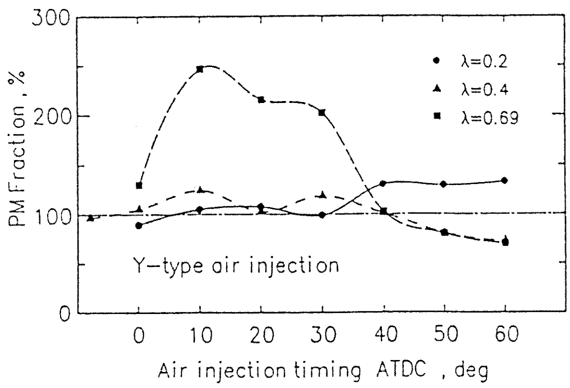


Fig. 4 PM results for air injection λ=0.2, 0.4 and 0.69

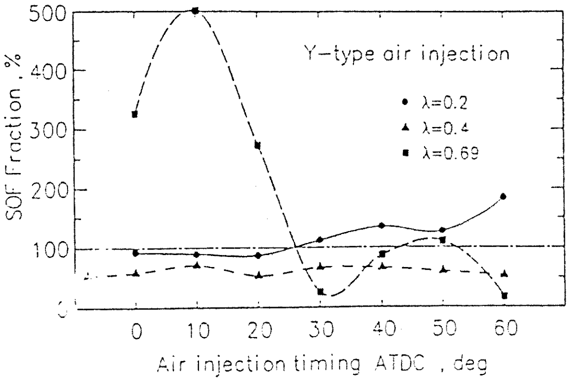


Fig. 5 SOF results for air injection λ=0.2, 0.4 and 0.69

PM fraction

Figure 4 shows that particulate matter increases with air injection timing to around 15° ATDC and remains high to 30° ATDC before decreasing rapidly to 40° ATDC for λ=0.69 (fuel rich). Beyond 40° the decrease rate is low and PM concentration is also below normal chamber emissions. At an equivalent ratio of 0.2, PM level remains almost constant to 30° ATDC and increases slightly beyond. PM trend for λ=0.4 is almost the same as for 0.69. A similar pattern of results are also obtained for dry soot data shown in Fig. 6 where this can hint out the fact that the PM trends are due to variations of dry soot concentration. Figure 5 shows an abrupt increase of SOF fraction from 0° to 10° air injection timings at an equivalence ratio of 0.69, to 500%, thereafter decreases rapidly to a minimum level of about 30% at 30° crank angle. This is a sinusoidal characteristic which is observable for other equivalence ratios, but differing in damping coefficients. The last lap of increase-decrease is within below 100% fraction of the normal, signifying a reduction. At an equivalence ratio of 0.4, SOF fraction remains approximately constant while for 0.2 it is constant until 25° ATDC beyond which it increases.

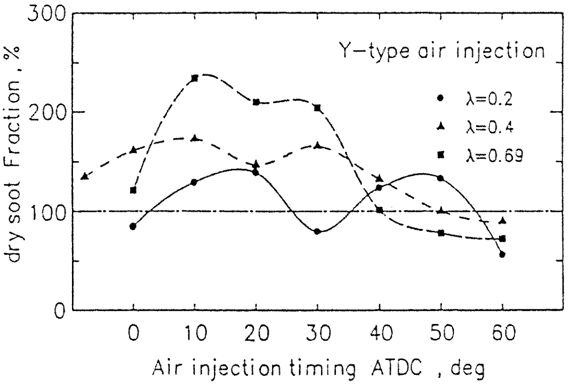


Fig. 6 Dry soot fraction for air injection λ=0.2, 0.4 and 0.69

At an equivalence ratio of 0.69, the mixture is richer than 0.4 and 0.2, offering high concentration of PM and probably HC together with dry soot. High temperature occurring here accelerates dry soot formation, which is suppressed on air injection. Along the injection timing range, the chamber pressure increases a short interval after fuel injection, where the pressure increase becomes substantial to restrict air injection at this time. This is the range from 0° to 20° ATDC, although a time lag between the time of detection and the actual pressure buildup in the pre-chamber may occur. Initially local combustion improvement occurs (premixed combustion flame structure) which increases the temperature at local fuel rich regions, causing increased soot formation by ionic/radical reactions [10]. Decreasing PM beyond 40° may be attributed to entrainment of oxygen which assists soot re-burning in the main chamber.

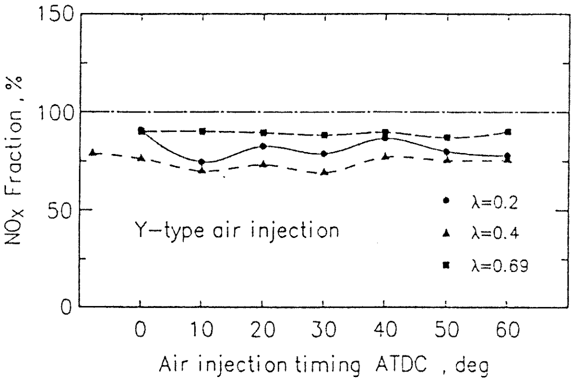


Fig. 7 NO_x fraction for air injection λ=0.2, 0.4 and 0.69

NO_x emission

Figure 7 shows results for NO_x concentration at various air injection timings. For all load conditions, emission of NO_x is suppressed by an amount ranging between 20% and 25%. Alteration of the injection timing is shown to have almost no effect on the NO_x emission at all equivalence ratios. As shown in Fig. 8, NO fraction behaves on the same trend as the NO_x, where it can also be seen to be equal to NO_x proportion in Fig.7.

Phenomenon of NO_x decrease is attributable to either quenching of the combustion process or quenched mixture temperature which suppress the formation of thermal NO. In the latter case, HC is increased which can lead to regions of locally higher concentration of HC fragment (radicals). These accelerates ionic formation of prompt NO formation. Similarity of trends for NO_x and NO can be explained by means of the reported findings of Hillard, et al [7], which showed that in diesel engines, the emissions of NO_2 are very low compared to NO especially at low load operations. Another explanation for this behavior is by the role of kinetic energy of the injected air on the mixing and combustion process. It can be summarily said that air injected increases turbulent kinetic energy, therefore enhancing mixing of fuel-air. This improves combustion but at a later step temperature drops due to heat transfer and hence low thermal NO emission. On the other hand, if injection is done at a later time during combustion, it will add an excess amount of oxygen which can readily burn the already formed dry soot. The last school of thought can be attached to the injection timing beyond 40° ATDC.

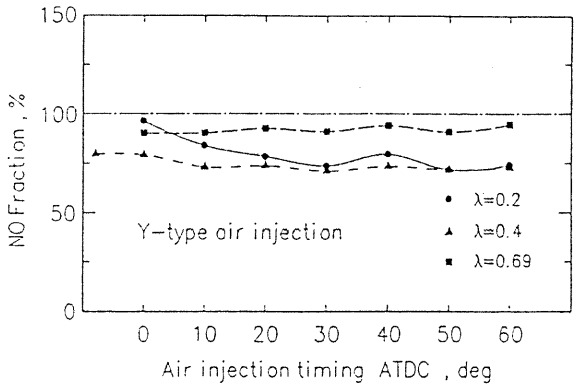


Fig. 8 NO results for air injection operation λ=0.2, 0.4 and 0.69

3.2 Effect of injecting N_2 and Ar gases

Nitrogen gas with some similarities in physical properties as air and Ar with low heat capacity were selected for the comparative experiment. Results for PM fraction, SOF, dry soot, NO_x and NO are shown in Figs. 9 through 12.

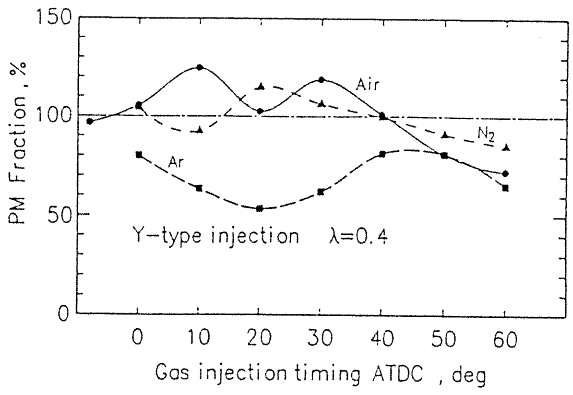


Fig. 9 Comparison of air, N_2 and Ar injection effect on PM λ=0.4

Nitrogen gas injection results show a sinusoidal characteristics of PM concentration, which is also noticeable for soot concentration in Figs. 9 and 10. In both figures, Ar shows lower PM and SOF fractions. Dry soot fraction is lower than for air injection for both gases, but amplified a little in the case of N_2 injection (Fig. 11). Again argon injection causes a reduction in dry soot, in the same trend as for PM and SOF. Between 0° and 30° ATDC, Ar causes a decrease in PM, soot and SOF, but increases afterwards. At this range, the concentration detected with N_2 injection is at a higher level in sinusoidal variations with injection timing.

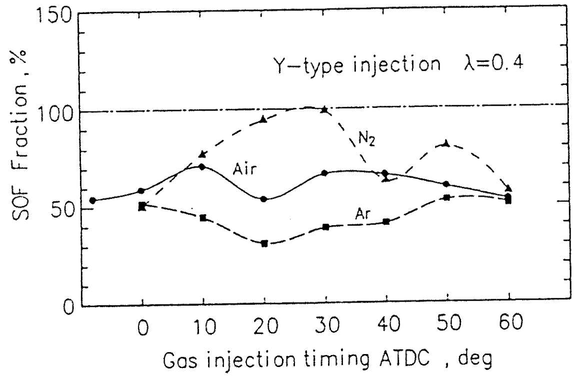


Fig. 10 Comparison of effects of air, N_2 and Ar injection on SOF $\lambda=0.4$

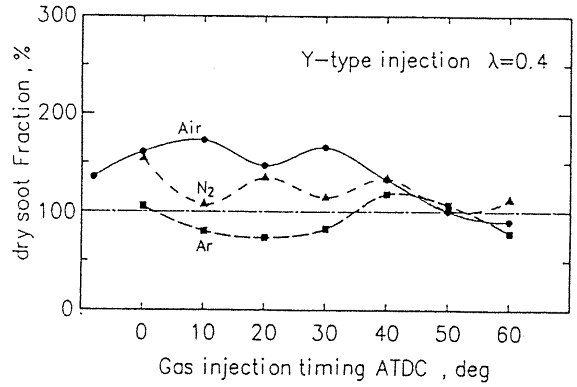
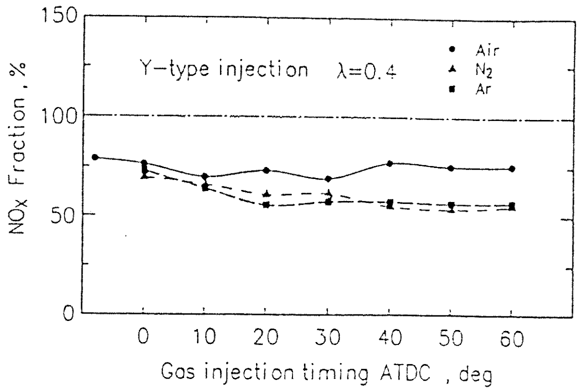
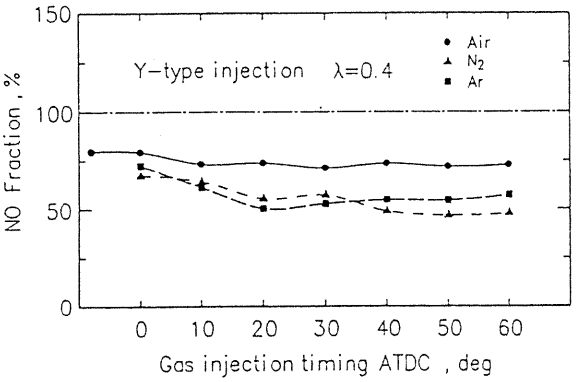


Fig. 11 Comparison of effects of injecting air, N_2 and Ar on dry soot $\lambda=0.4$

Figure 12(a) shows the NO_x fraction while 12(b) the NO fraction at varied gas injection timing. As mentioned earlier, compared to normal combustion, air injection reduces the emission of NO_x which can be seen as a reduction in NO. Injection of argon reduces the concentration of NO below the magnitude reduced by air injection, and the same trend is depicted for nitrogen injection.



(a) NO_x fraction for air, N_x and Ar injection $\lambda=0.4$



(b) NO fraction for air, N_2 and Ar injection $\lambda=0.4$

Fig. 12 Comparison of results for NO_x and NO

Injection of gases other than air does not show a substantial decrease in PM and dry soot at late injection timings. This is due to the oxygen addition at the later time which assists in re-burning of carbon particles as proposed by Yamaura, K., et al [6]. In this case turbulence plays a major role, suggesting that together with oxygen addition, air induces an amplification of turbulence on the burning gaseous mixtures.

3.3 General discussion

Results reported above show that late air injection is effective in reducing particulate matter at a high load condition. This is by the carbon re-burning mechanism mentioned above. Nitrogen oxides on the other hand maintain a constantly low level (20%), for all injection timings. The lowering of temperature may be due to temperature quenching, which although it reduces thermal NO, an increase due to prompt is possible. This phenomenon can also account for low HC concentration, in the expense of SOF reduction. It can be noted that whereas PM formation in IDI diesel engines occurs in both main and pre-chambers almost equally, large part of NO is formed in the later where combustion is more inhomogeneous [8]. The induction of turbulence and temperature quenching may be the reason for the emissions reduction, but there is also a possibility of affected heat transfer to the chamber walls during combustion.

Injection of an inert gas does not effect the burning process of soot, but improves the combustion by means of induced kinetic energy, together with temperature quenching. Nitrogen shows the similar influence as argon, but since the kinetic energy magnitude is lower, the reduction is comparatively lower. There is also a possibility of chemical interactions due to the third body collision due to induced nitrogen gas. In this case, at low temperature there is a possibility of prompt NO mechanism of reverse reaction to reducing NO emission.

4. Conclusion

Emission gas concentrations were observed experimentally, and the results show that;

(a) Air injection can suppress NO_x formation and hence its emission. On the other hand, although at an early air injection timing PM increases, a reduction is attained later.

(b) Argon injection is more effective in suppression of both PM and NO_x compared to N_2 and air injection. This is due to kinetic energy interaction and the low heat capacity of Ar compared to the other gases.

(c) While N_2 injection show a power reduction of 5% and a 10°C exhaust temperature drop, air injection reduced the brake power by 2% and cause a temperature drop of 5°C. Ar injection do not affect power and temperature, assuring higher thermal efficiency. This suggest that argon is the most suitable gas for reduction of emissions at high load operations.

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