Uhandisi Journal Vol. 21 No. 3, December 1997 pp. 89-102

Influence of Gas Type and Injection System on Simultaneous Reduction of Soot and NO_x in IDI Diesel Engine[1]

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ABSTRACT

Modification has been made to one of the pre-chambers of a 4-cylinder, IDI diesel engine used to study the combustion process for purpose of reducing emissions. With the provisions for optical assessment of the combustion process in the pre-chamber, the effect of high pressure gas injection into THE CHAMBER during combustion has been carried out. Results of this work indicate that high pressure gas injection during combustion can effect simultaneous soot and NO_x reduction with a reasonably low amounts of emission of other diesel engine pollutants. An optimum chamber type is suggested based on the analysis of the effect of air, argon and nitrogen injection

INTRODUCTION

The importance of diesel engines have been so far determined by their high fuel economy and better combustion characteristics. Of recent years, however, the realization of the environmental hazards posed by such emission species like NO_x, particulate matter and hydrocarbons have resulted in the change of the objectives of the present engine research and developers. Year after year the problem of emissions is becoming even more pronounced in the urban centers that in the rural. Intensified use of such engines have lead to stricter regulations and standards meant for controlling the quantities of such pollutants to be emitted into the atmosphere. A trade-off behavior between the emissions of NO_x and particulate matter (PM) exists which has made the efforts of reducing these two pollutants even more difficulty in these engines. In order to reduce NO_x especially the thermal component (Zeldovich NO_x) the flame temperatures have to be lowered. However, lowering the flame temperature signifies flame quenching or distorted combustion, which finaly increases

the formation of PM (smoke).
Although many efforts have been directed towards the reduction of the two pollutants, there is no single method which alone can be applied to this task [1]. Among the common methods include, high pressure fuel injection [2], improvements of the combustion chamber and the fuel injection nozzle designs [3,4]. In effort to attain simultaneous reduction of particulate matter (PM) and NO_x, interaction of the combustion process with intent of improving the combustion process by inducing disturbances in the chamber and at a later time of the cycle to enhance oxidation of the formed PM to consume the formed emissions has been attempted [5]. Preliminary results have indicated that it is possible to reduce PM and NO_x simultaneously without affecting the emissions of other substances [6].Two types of chambers were tested and results were compared , while optimum test conditions were established. In the present paper, experimental results of the validation of the effects of inertial effects and kinematics of the medium of the chamber are discussed in terms of tests with various gas types. Furthermore, various pre-chamber orientations were tested for the purpose of establishing the reasons for the simultaneous reductions realized in the initial experiments.

EXPERIMENTAL SETUP AND PROCEDURES

The engine used is similar to one used in the previous experiments [6], an IDI diesel engine of 1.8 liter displacement, 4 stroke and 4-cylinder, where one of the pre-chambers was modified to suit the gas injection and access to the pre-chamber, especially during combustion. The reason for the selection of the IDI type of engine is the low emissions of such polluting species like PM and NO_x, in the expense of low combustion efficiency due to the flow losses across the passageway (connecting port of the main and the pre-chamber (swirl chamber). Figure 1 (a) shows the configuration of the test pre-chamber while (b) give the three tested orientations of the gas injection nozzle, relative to the fuel nozzle and passageway direction. The pre-chamber diameter is 25 mm, a thickness of 17 mm decided in effort to have minimum influence on the compression ratio and the flow behavior during combustion. The passageway dimensions are 4 mm and 160 mm diameter and length respectively. These dimensions were decided after a series of tests with various parametric factors to establish the optimal dimensions, as compared to the normal cylinder. Comparison of the emissions of such characteristics showed a variation of 10% to the extreme case. This certified the use of the modified pre-chamber for these tests. Two experimental situations were necessary, that is when no visualization was done, the whole chamber and the passageway were made out of metal (high strength steels), while when visualization was done, a quartz glass window provided optical access to the interior of the chamber.

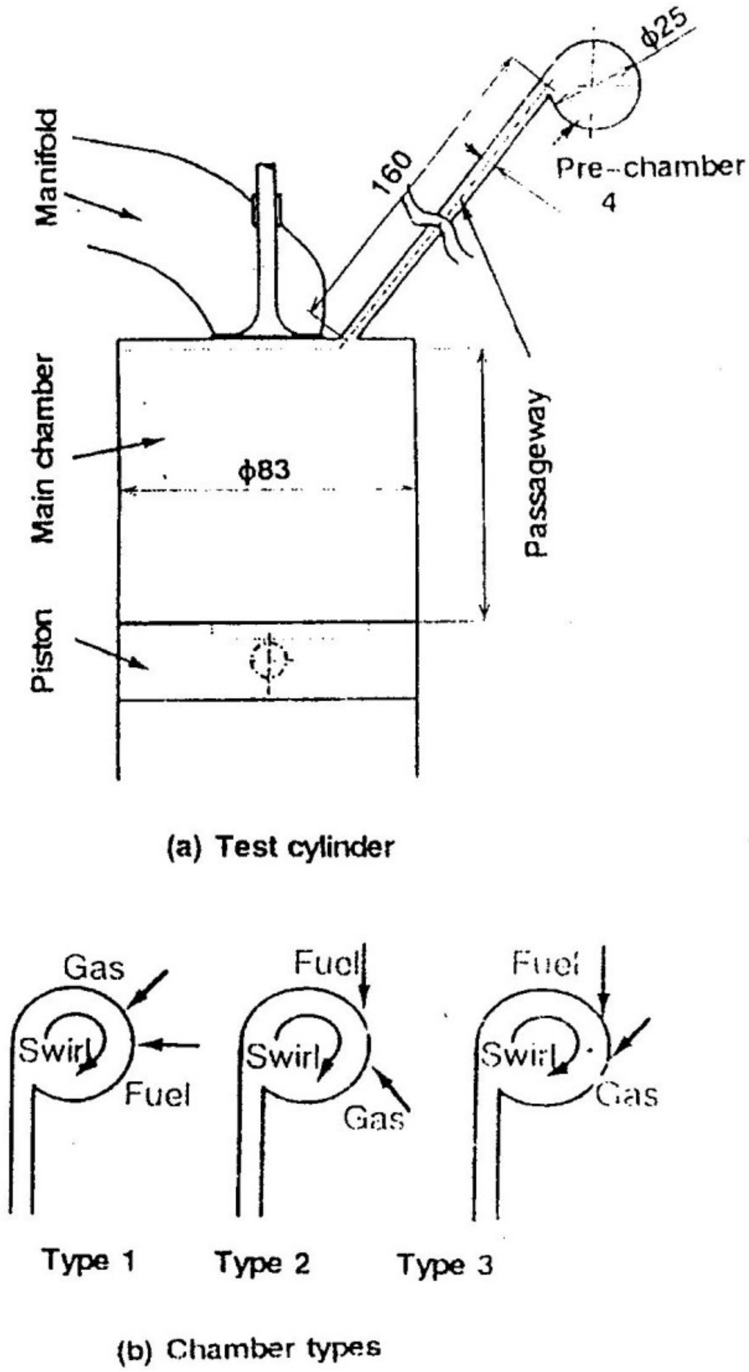


Fig. 1 Experimental cylinder and pre-chamber type

As shown in Fig. 1(b), three types of chambers were tested to make a total of five orientations since results for chamber type I andY were discussed previously, establishing that the suitable type was type Y, which is now conventionally called type 1. Type 1 is the one in which gas and fuel are injected radially towards the center of the pre-chamber while type 2 is made such that fuel and gas are injected tangentially but opposed to each other. Type 3, on the hand is such that both fuel and gas injection directions are in tangential and supporting the swirl motion in the pre-chamber The specifications of the experimental engine are presented inTable 1, while the properties of the gas injected is shown in table 2.The reason for the use of the gases are;

i) to compare the oxidation influence of the injected gas. Inert N_2 and argon (Ar) were used, to compare with air.

ii) to compare the thermal influence of the gases, in which case the use of Ar with a heat capacity of about 50% of that of N_2 or air will enable thorough comparison.

iii) to check the contribution of the inertial effects of the injected gas on the combustion and emissions. In this caseAr which is heavier than N_2 and air could have a better effect than the other gases.

Table 1 Specifications of the test engine

Engine type	4 stroke, 4 cylinder, 1800cc displacement
Bore and stroke	83X83 mm
Maximum power	65 PS/4500 rpm.
Compression ration (original/modified)	23.5/22.5
Fuel Injection type/timing	Throttle/10° BTDC

Preliminary experiments established the suitability of the gas injection duration and the sampling positions. The sampling from the pre-chamber was correlated to the sampling from the exhaust port, since sampling at the pre-chamber disturbs the combustion in the pre-chamber, especially when relative sizes are considered. Sampling was carried out at a distance of 10 mm from the exhaust valve along the manifold to avoid the influence of the exhaust pipe down stream and the high temperatures inside the pre-chamber. The sampling time recorder recorded the time at the start of sampling, and was driven by a solenoid valve and electronic control circuit specially designed for this purpose. Before sampling was done, the engine was run until steady state operations awere attained, then gas is injected at the set durations, and allowed to stabilize before sampling. All the concentrations were corrected against the dilution effects of the injected gas into the cylinder.

Present experiments were carried out at an idling condition with an engine speed of 2000 rpm, and a fuel-air equivalence ratio of 0.18. Argon, and nitrogen were injected and the results compared with those for air injection. The difference in heat capacity which could classify the emission reduction of NO_x as been due to the thermal mechanism or not, or the improvement of combustion as been a result of improved kinetics of the medium when gas is injected can be elaborated. This is by the use of Ar which is heavier than either air or nitrogen. The absence of oxygen was simulated by the use of argon and nitrogen, while the absence of nitrogen is dictated by the results for injection of argon. Engine rotational speed was controlled by means of an eddy current dynamometer. The compression power was calculated to be about 246W, and vary slightly with load within the magnitude of 10%.

Sampled gas was collected in sampling bags for future analysis of the concentrations of NO_x, HC, CO and CO_2 by means of gas chromatography and gas analyzers.

To determine the concentration of PM, a sampling filter (quartz filter) was installed into a holder along the sampling line. The mass difference between the new filter and the used filter (after sampling) gives the mass, where by using the mass flow rate of the exhaust at a given time the concentration corrected to the atmospheric conditions were established. After measuring the mass difference, the filter was dissolved in dicholoromethane in order to extract soluble organic fractions from the dry soot.

Experimental procedures were as described in the previous work [6]. High speed video system with a capacity of 40500 frames per second was employed to visualized the propagation of combustion in the cylinder. The recording rate was 9000 frames per second, part of which are presented in this paper.

DISCUSSION OF THE RESULTS

Influence of the Modifications on the pressure characteristics

Before undertaking the necessary experiments, it was necessary to evaluate the influence of the modification on the combustion process of the chamber. This was carried out by measuring the pressure of the unmodified chamber and the modified when the engine is motored. This is because it is difficult to set a pressure pickup at higher temperature qual to those of burning gases in the cylinder. Figure 2 shows the pressure characteristics of the two chambers in MPa against crank angle. It can be seen that by virtue of the modification, peak pressure and the time at which the peak is observed are different from the original chamber. While the occurrence of the peak is delayed for 8° c.a., its magnitude is reduced from 3.6 MPa to 2.7 MPa. This is due to the induced pressure drop due to the slim and long passageway. This leads to a delay in the pressure build up in the chamber, and when it is about to reach the maximum, the opening of the exhaust valve releases the gases, therefore resulting into reduction of the peak.

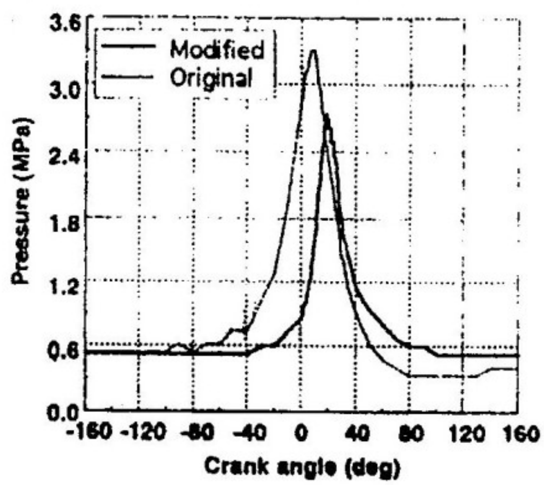


Fig. 2 Pressure of original and modified pre-chamber pressure (motoring)

Effects of gas Injection into chamber type 1

The results of emissions of PM, NO_x, CO and HC are shown as a function In Fig. 3(a), the emissions fraction of PM indicates a reduction when all of gas injection timing expressed as the time at which gas injection starts. Presented results are in fraction of what would have otherwise been the emissions when no gas was injected. It is expressed as a fraction of the normal emissions of the cylinder taken as percentage. In each setting, data were collected five times and an average of the five results were taken at five times data collection after steady state of the running of the engine was realized. Initially conditional sampling technique was used to verify the use of the current method of sampling, and the data seems to represent the actual tendencies of the engine.

Table 2 Properties and induced kinetic energy of the test gases

	Kinematic viscosity ($10^{-4}m^2/s$)	Specific heat (kJ/kg°C)	Molecular weight	Density (kg/m^3)	Gas injected (mg/cycle)	Kinetic energy induced (J)
Air	0.358	1.025	28.84	0.722	289	6.99
N2	0.355	1.055	28.0	0.699	251	6.09
Ar	0.317	0.519	40.0	1.035	401	9.7

Reference state: P=10^5 Pa t=200 °C Volume injected 5ml/cycle Injection velocity 220 m/s (average)

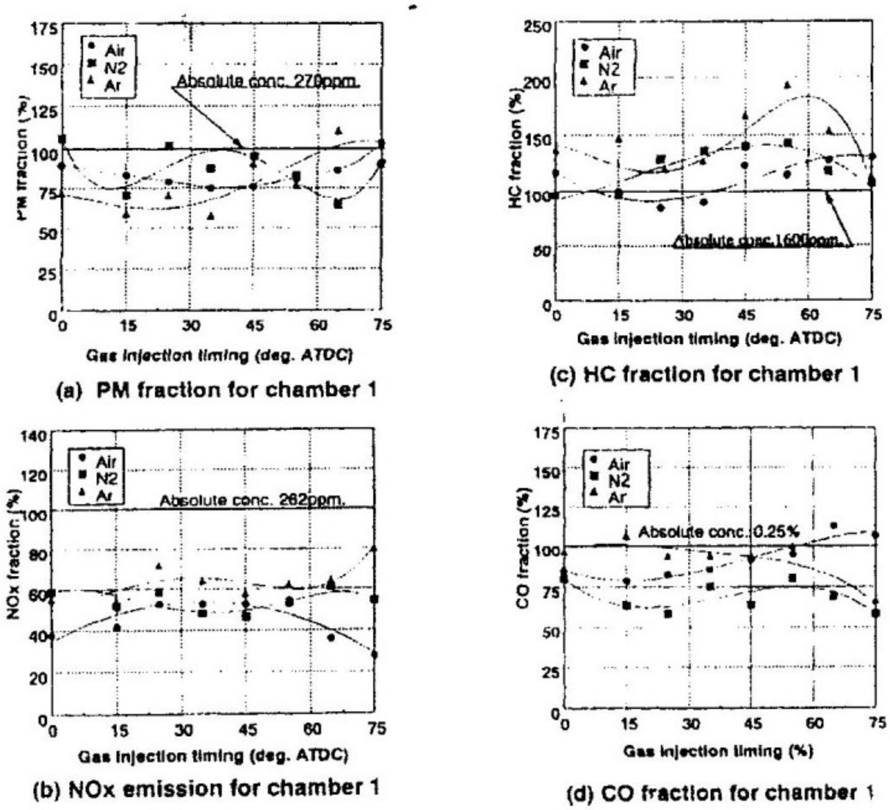


Fig. 3 Chamber 1 emissions (air, N_2 & Ar)

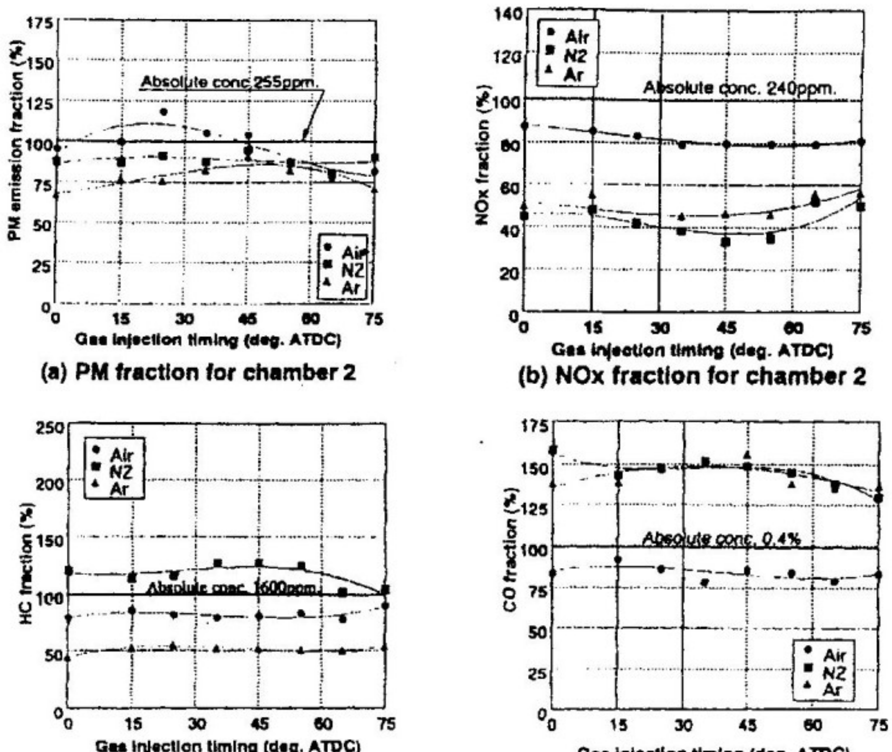
the gases are injected during combustion. In order, Ar is best followed by air and finally nitrogen coming last in the list. Nitrogen indicates no substantial reduction in PM emissions fraction with the exception of beyond 45° ATDC. Changing the argon injection timing shows that up to 30° ATDC there is a reduction of up to 60%, beyond which the effect dies off. It suggests that gas injection has less impact at the beginning but has significant influence on the last part of the combustion process. From Fig. 3(b) it can be seen that with the timing range of 15 to 55° ATDC, a reduction to a fraction of around 60% is attained. This can be seen as been a result of the shifting of the center of peak pressure which then would delay the combustion process. The weaker swirl induced by this chamber could explain its weakness on the reduction of the two polluting species.

HC emissions on the other hand show a gradual increase when nitrogen and argon are injected, whilst weakly increasing tendencies are observed by the injection of compressed air. Tendencies of the emission of HC and CO look similar, suggesting the oxidation process of the unburned fuel or combustion partial products would have taken place. From Fig. 3(d) CO reduction of up to a fraction of 60% was realized with N_2.

Effects of gas Injection into chamber type 2

Fig.4 (a) through (d) shows the emissions fractions of the chamber 2 for PM, NO_x, CO and HC. Figure 4(a) shows the emissions of PM for chamber type 2. Argon followed by nitrogen and air being the last in the order of effectiveness in the reduction of PM. Towards the end of combustion, gas injection leads to oxidation of PM during the last part of the combustion process in the chamber. Air, however shows a substantial increase especially when compressed air was injected at 30° ATDC. Injection at TDC seems to be effective (only a fraction of about 60% realised), but in the last stages it is worse. Looking into Fig. 4(b), the order is similar in terms of effectiveness in NO_x reduction. In this case while N_2 and Ar cause a reduction of up to 40%, air gives only 80% reduction. For the case of air, at an injection timing of 55° ATDC and beyond, results in a pronounced reduction in emissions reduction.

HC and CO as seen in Fig.4(c) and (d) respectively indicate an increase respectively. Only with HC, air and argon seemto reduce emissions to fractions of about 80% and 50% respectively. Argon and nitrogen on the other hand indicate a substantial increase to a fraction of about 150%.

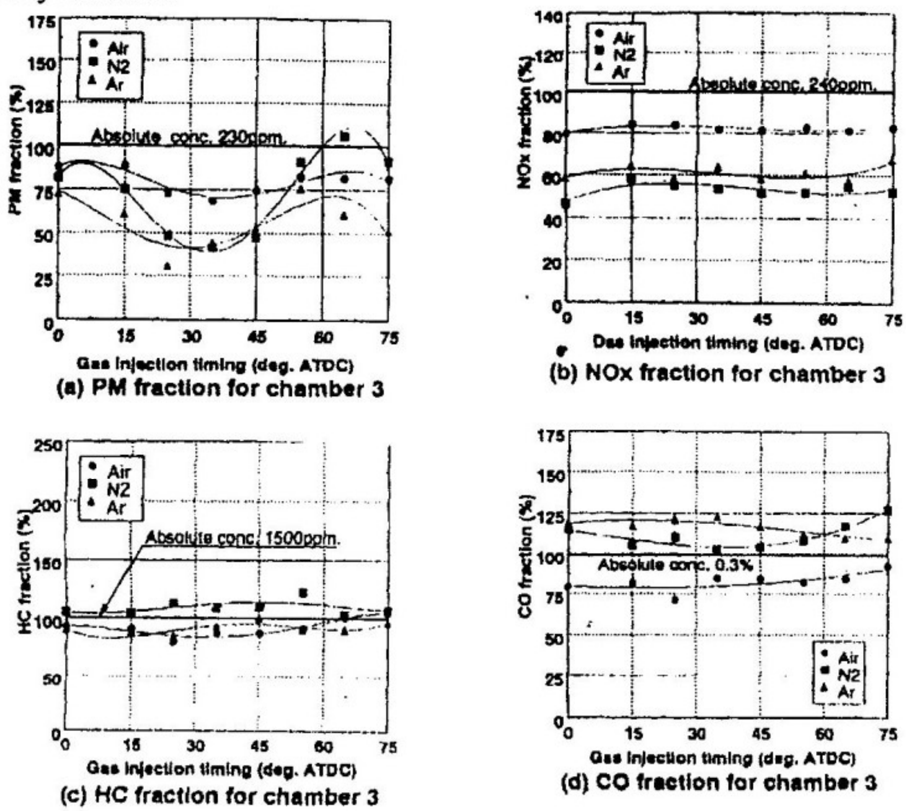


(a) PM fraction for chamber 2
(b) NOx fraction for chamber 2
(c) HC fraction for chamber 2
(d) CO fraction for chamber 2

Fig. 4 Chamber 2 emissions (air, N_2 & Ar)

Effects of gas Injection into chamber type 3

Figure 5(a) though (d) shows the emissions results of HC, NO_x CO and PM under compressed gas injection into chamber type 3. From (a), the injection of the three types of gases show that within a band from 25° to 45° ATDC, PM fractions are substantially reduced, with Ar and N_2 showing equal capabilities in reducing PM especially in the best region of gas injection. Air on the other hand is not so effective as compared to the other two gases. It is possible, however, to have a reduction higher than 10%. From Fig. 5(b), NO_x reduction is well pronounced for all gases although it is best for N_2 followed by argon and finally air. From the orientation of the chamber, it is observed that by injecting a gas tangentially, homogenization of the fuel-air mixture is well done, followed by thermal quenching of the combustion gases. In Fig. 5(c) however, the emissions of HC seem to remain almost unaffected by gas injection, although a reduction to a magnitude of 20% was observed. This phenomenon coupled by the increase in CO suggests a chemical reaction which consumes HC. By this way, a possibility of reduction of NO_x by HC would explain the CO increase observed in Fig. 5(c). Figure 5(c) shows slight increase of the CO emission from the normal operation. If compared to Fig. 4(c) for chamber type 2, it is apparent that there is a slight depression of the CO emission fraction. This is due to the role played by HC which would also affect the emissions of CO, as this kind of reactions involves a number of hydrocarbon fragments and the hydroxyl radical.



(a) PM fraction for chamber 3
(b) NOx fraction for chamber 3
(c) HC fraction for chamber 3
(d) CO fraction for chamber 3

Fig. 5 Chamber 3 emissions (air, N_2 & Ar)

Table 3 summarizes these results in abstract form for the three types of chambers tested. The letters in the table are; A for the best emissions reduction, N for no effect and B for bad in terms of emissions reduction.

Visualization of the Combustion Process in the Pre-chamber

Visualization results for chamber type 1 was reported in the previous paper [6], hence it is not repeated here. Figure 6 shows the combustion flames for (a) chamber types 2 and (b) type three. Physical assessment of the flame and flow show that, for type 3 flow and subsequently burning is more vigorous than chamber type 2. In chamber type 2, the gas injection opposes the direction of swirl, hence the whole mass of the injected gas lumps itself and it is never distributed over the whole chamber.

Table 3 Summary of results for the chambers

	Chamber 1			Chamber 2			Chamber 3		
	Air	N_2	Ar	Air	N_2	Ar	Air	N_2	Ar
PM	A	A	A	B	A	A	A	A	A
NO_x	A	A	A	A	A	A	A	A	A
HC	N	B	B	A	B	A	A	N	N
CO	N	A	N	A	B	B	A	B	B

Key:
A- Best in emissions reduction
N- Not very effective in reducing emissions
B- An increase in emissions observed.

Consequently, although the flame is brighter at the start of combustion, less luminosity is noted as burning proceeds on. The combustion duration is shorter with type 3 than type 2. This is because of the enhanced mixing due to the supported swirl [7]. In both cases however, combustion commences at 14° ATDC while fuel injection was performed at 10° BTDC. Combustion in chamber 3 ends at almost 54° ATDC while in chamber 2 it continues up to 67° ATDC. Since swirl motion is weaker for the case of chamber type 2, flame propagation seems to concentrate at the center of the chamber, unlike for the case of chamber type 3. The proceeding of combustion seem to be more premixed in characteristics than heterogenous. This could explain the reason for less emissions of PM from chamber 3.

It follows from these results that simultaneous reduction of PM and NO_x from diesel engine by compressed gas injection is a result of induced kinetic energy which could be converted into turbulent energy. This transformation assists in improving the homogeneity of the fuel air mixture. It is possible that such reduction could also occur in direct injection (DI) diesel engine.

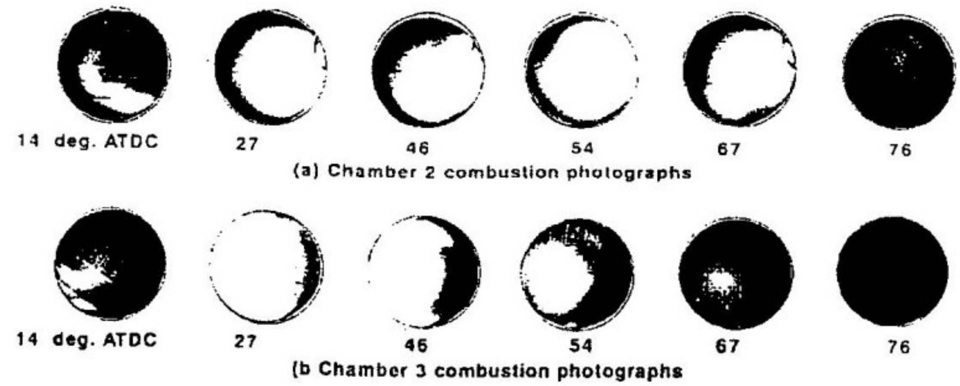


Fig. 6 Direct photographs for chambers 2 and 3 for TDC air injection

CONCLUSIONS

It has been confirmed that the mechanism of reduction of emissions of NO_x and soot is not driven by the presence of oxygen alone, but factors such as, total energy input of the injected gas, gas injection timing, relative orientation of the gas injection and the local thermal quenching of the combustion flame. At present it is not possible to explain precisely how this phenomenon occurs. Further experiments would shed light on the details of the mechanism.

From this discussion, it can be concluded that;

According to the chamber types, chamber type 3 is more effective in reducing pollutants from this engine. Chamber type 3 follows and then finally chamber 1. This is due to enhanced local mixing of fuel and air, driven by the high diffusion rate of the induced gas when it is injected in the direction of swirl.

Chamber type 2 and 3 are equally most effective in reduction of NO_x. This is thought to be through the reduction of the Zeldovich thermal NO_x which is a result of thermal substraction from the high temperature combustion gases.

Similar to NO_x, CO emission reduction was observed mostly in chamber type 2 and 3. The possible explanation is that since the state of combustion is lean, gas injection improves the availability of oxygen and hence its participation in the oxidation process of the fuel as well as the partial products of combustion like carbon monoxide.

Visualization results indicated that combustion in chamber type 3 is more pronounced and vigorous. This is a resultant of suppressed diffusion combustion which would otherwise have favoured an increase in soot emission, even when compressed gas is injected.

ACKNOWLEDGEMENT

The conduction of this research was possible by the support received from the Japan Society of Mechanical Engineers, under research grant number RC-107. Many thanks are due to Professor Shin Matsuoka for his support of the initial ideas and his valuable suggestions.

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The manuscript was received on 18th February 1997 and accepted for publication, after corrections, on 29th December 1997