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Formation of Oxides of Nitrogen in a Diesel Engine

(In the Case of Swirl Chamber Type)*

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Similarly to other combustion systems, reduction of oxides of nitrogen emitted from diesel engines is one of the urgent problems to be solved from the viewpoint of photochemical smog. However, their formations are not fully understood yet and the effects of engine variables on their emissions are still not well known. In this paper, the tendency of the nitric oxide emission has been investigated with a swirl chamber diesel engine, by systematically changing some engine parameters. As the result, the following facts have been revealed: Some factors effective to flame cooling suppress the nitric oxide formation at lower fuel-air equivalence ratios, while they have less effect at higher ratios. In the latter range, the nitric oxide decreases with this ratio, which is attributable to the increase in the local fuel-overrich zone somewhere in the combustion space, and its decrease is largely dependent on the outflow of gas from the swirl chamber into the main chamber.

1. Introduction

Oxides of nitrogen from several power plants are presently recognized as major pollutants to form photochemical smog⁽¹⁾⁽²⁾, their reduction being nowadays one of the urgent problems to be solved in combustion technology. Previous investigations have for the most part dealt with the spark-ignition engines, and they have well prepared useful knowledges in relation to chemical kinetics^{(3)~(5)}. As regards the inhomogeneous burning, however, the situation is worse; in fact, there are only limited studies concerning details of their formation in diesel engines^{(6)~(8)}. Among them, McConnell's work⁽⁶⁾ is important, in which he studied the effects of some engine parameters including the type of combustion chamber, the method of scavenging, injection timing, and fuel-air ratio. At present, it is widely known that a divided chamber diesel engine emits less oxides of nitrogen than an open chamber engine. This is worth notice with respect to their reduction, which is sometimes attributed to fuel-overrich state occurring inside the prechamber, although the detailed reason for it has not been fully revealed yet.

The objective of the present paper is to arrive at better understanding of the formation of oxides of nitrogen in the pre-chamber engine and finally to discover some means for reduction. To this end, the effects of some parameters of combustion

chamber were systematically evaluated with a swirl chamber engine and the results were examined.

2. Experimental apparatus and procedure

The test engine used was a water-cooled four-cycle single-cylinder engine (Yanmar Diesel ST-95 type modified) having a cylinder diameter of 95 mm and a stroke of 115 mm. The swirl chamber employed was basically Ricardo's Comet Mark III type and was composed of two demountable parts, as shown in Fig. 1, for providing facilities for alteration of some parameters such as the direction of injection or the dimension of connecting passage. In the ordinary setup, the piston has two cup-shaped depressions on the top as illustrated in the figure.

Fig. 1 Cylinder head and piston

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Since there are many parameters to be examined, the following conditions were selected as the standard operating conditions to begin with; the direction of fuel injection was 15° from the center of the chamber toward downstream of the swirl, compression ratio 16.4, the volume ratio of swirl chamber to total compression space 50 %, the area ratio of connecting passage to piston surface 1.0 %, the injection nozzle single-orifice pintle-type Bosch DN8S1 (geometrical spray angle 8°), and the opening pressure of nozzle 120 kg/cm^2 . Injection pump was Bosch A-type PE1A70B101 having a plunger diameter 7 mm and a stroke 8 mm, and the fuel employed was heavy oil "A" of a specific weight 0.845 and a cetane number 45. All tests were carried out at a constant engine speed of 1500 rpm.

The measurement of air flow rate was conducted by using an orifice placed at the inlet of a large surge-tank (180 litres). The injection timing was detected dynamically during the run by use of a small piezoelectric element fitted on the injector needle. The concentrations of smoke and oxides of nitrogen in the exhaust were measured by using a Bosch smokemeter and a Horiba AIA-2 type non-dispersive infrared analyzer respectively. The latter one was introduced in the experiment on the assumption that all of the emitted oxides of nitrogen are nitric oxide NO.

3. Experimental results and considerations

3.1 General

Figure 2 gives the results obtained under the preceding conditions, showing the influences of fuel-air equivalence ratio ϕ and injection timing on nitric-oxide fraction in the exhaust NO, brake mean effective pressure p_e , brake specific fuel consumption b_e , and exhaust discoloration S . Consistently to the current understandings, in the fraction of NO, there is a maximum point somewhere in ϕ for a fixed injection timing. Advance of injection increases the maximum fraction of NO and shifts the corresponding equivalence ratio toward fuel leaner side. Another characteristic of NO

which deserves consideration is that the NO versus ϕ curves are less sensitive to the timing change at large ϕ than those at small ϕ , and that they appear to tend asymptotically to a straight line. This tendency suggests that in the swirl chamber engine the injection retardation is hardly effective for reduction of NO under full load condition. As regards the engine performance, the lowest specific fuel consumption is recorded at an injection timing of 8° before top dead center at middle and full loads. Injection advance from this timing causes a loss of output simultaneous with some deteriorations in both NO and smoke, while the retarded injection beyond the optimum to 2° before top dead center more or less improves smoke and NO. Further retardation, however, resulted in fluctuations of running or sometimes in misfiring at idling or low loads.

3.2 Formation of NO

To elucidate the obtained results, the tendency of NO formation will be briefly reviewed. It is a well-known fact that the NO concentration increases quickly with temperature. However, the rate of NO formation is very slow compared with those of reactions to form other combustion products. Consequently, the amount of NO can be kept small as far as the residence time is sufficiently short. The decomposition of NO once formed also proceeds slowly and NO appears to be practically frozen during combustion. Obviously, the concentration of oxygen present in the burning zone has a close connection with NO formation. Summing up these matters, temperature, residence time, and concentration of oxygen available are the main factors affecting NO formation.

3.3 Range of small ϕ

In this range, the fraction of NO in the exhaust rapidly increases with ϕ , as observed in Fig. 2. Once this tendency is written in the form of $(\text{NO}) \propto \phi^n$, the index n in this expression amounts to approximately three at the injection timing 8° before top dead center. In an ideal case where each of the lumps of flame may follow quite identical history during combustion irre-

spective of the dimension of flame, the index n should be only unity since there is no other reason conceivable than that NO is proportional to the fuel quantity. The observed large value of n should be thus attributed to the elevated level of temperature and/or the increased residence time resulting from the increasing fuel amount. As may easily be conceived, advance of the injection increases both the temperature level and the residence time, which brings about an increase of NO at low ϕ . For convenience, we shall designate this range of ϕ as "air excess region" hereafter.

Fig. 2 Influences of equivalence ratio and injection timing

Fig. 3 Courses of pressure and rates of heat release ($\phi = 0.80$, injection timing 8° before top dead center)

3.4 Range of large ϕ

In this range, the concentration of NO decreases with ϕ . This curve looks as if it were interrupted by a limit line, and the greater the equivalence ratio the less becomes the dependence of NO on injection timing. In order to make this clear, the rates of heat release in the swirl and the main chamber were calculated from the measured pressure-time relations, principally based on instantaneous energy balance in each chamber and the calculation of flow rate through the passage by the pressure difference*.

The result of calculation under full load condition is given in Fig. 3, showing that only a quarter of total heat is evolved within the swirl chamber, and that the combustion therein terminates as early as 20° after top dead center. The greater part of the remainder of the fuel burns in the main chamber lasting until 50° after top dead center. Taking this observation into consideration, it may be possible to state that the swirl chamber soon falls into deficiency of oxygen, the only course for the remaining fuel to be able to burn being to find oxygen present in the main chamber. The overrich state being reached sometimes in the swirl chamber will not only suppress directly further formation of NO but also cool down the NO forming part by heat absorption due to evaporation or to thermal cracking of fuel. For this reason, we will use the "locally overrich region" to de-

Fig. 4 Influence of temperature of cooling water

scribe the range for such a state to be reached. In the later stages of burning, high expansion speed associated with piston motion keeps the content from getting to higher temperature levels in the main chamber despite a lot of heat release, slowing down further evolution of NO. Thus it is conceivable that when ϕ is large the formation of NO is only possible in the earlier stages of burning before reaching such a deficient state of oxygen. In any case at high loads, there is great possibility of an overrich state being reached locally, and this may be one of the reasons why NO emission from the divided chamber engine is less in quantity than in the case of an open chamber engine. Finally, the fact that NO is less sensitive to the injection timing at higher ϕ may be tentatively explained as follows: At an early timing, the outflow of rich mixture into the main chamber is checked by the incoming stream of air, while at a retarded timing it is promoted by the inverse effect. For this reason, the injection timing does not produce much difference in the states of burning in the main chamber. Since the swirl chamber may soon get to an overrich state, only a slight change is brought about in the NO formation between earlier and later injections.

4. Effects of some factors

4.1 Main chamber

Figure 4 shows the influence of the temperature of cooling water on NO emission. A considerable effect is observed in an

*) Denoting the pressure, the temperature, and the weight of gas, of the main chamber as p_1 , T_1 , and G_1 respectively and those of the swirl chamber as p_2 , T_2 , and G_2 respectively, we may write the heats released in each chamber Q_1 and Q_2 in the following form:

$$dQ_1 = d(c_v G_1 T_1) + dI + A p_1 dV_1, \quad dQ_2 = d(c_v G_2 T_2) - dI$$

where c_v is the specific heat at constant volume, dI the enthalpy conveyed from the swirl chamber to the main chamber, V_1 the volume of the main chamber, and A the thermal equivalence of work. By assuming the gases to be an ideal air, we obtain

$$p_1 V_1 = G_1 R T_1, \quad p_2 V_2 = G_2 R T_2$$

where R is the gas constant for air, and V_2 the volume of the swirl chamber. Further, the relation of $dG_1 = -dG_2$ has to hold. Since dG_1 may be related to p_1 , p_2 , and the effective flow area of the connecting passage, and dI to dG_1 and the temperature, all unknowns may be solved by giving the measured pressures p_1 and p_2 .

Fig. 5 Influence of depression in the piston crown

intermediate range of ϕ between 0.3 and 0.7, but there is not any noticeable change at the extreme ranges of either low or high equivalence ratios. At a very small ϕ , NO formation is rather irrelevant to the contact of flame with the cylinder head, since the combustion may take place mainly in the swirl chamber. Another result pertaining to the state of the main chamber is given in Fig. 5, which compares the case of the conventional piston with depressions with that of a simple flat-topped piston. The flat-topped piston gives lower concentration of NO over wide ranges of ϕ than the conventional one. This may be interpreted by the decreased temperature level associated with closer contact of the flame on the piston surface.

Judging from these results, not only the combustion in the main chamber but also the hot gas issued from the swirl chamber are related to NO formation, which suggests a possibility of reducing NO to some extent by means of assisting flame-cooling in the main chamber.

4.2 Fuel injection

In a spherical swirl chamber, the best performance is usually experienced when the spray is directed downstream of the swirling motion. Without sticking to this, the direction of injection was much varied keeping the other conditions fixed. In Fig. 6 the obtained result is given, showing that there is a considerable change of NO. However, it is interesting to note that this change is very small at higher equivalence ratios except for the case of -15° direction; in other words, alteration of the direction of injection usually leads to a change of NO only on the fuel-lean side. According to a high-speed photographic study on the flame developments⁽⁹⁾, the mixture and the subsequent flame appear to accumulate in the middle part of the swirl chamber when the spray is directed against the swirl, while they are distributed in the peripheral zones in the case of injection directed downstream of the swirl. Since the flame may be well kept from cooling down by the walls of the chamber, a

Fig. 6 Influence of direction of fuel injection

higher temperature level can last for longer period in the former case than in the latter case. This favors production of NO compared with the case of peripheral injection, explaining why more NO is caused at lower or middle loads in the central injection. In the case of -15° direction, the NO level is much lower than that of other cases. In this case, an excessively over-rich state might have been locally produced in the swirl chamber. This situation resembles the charge stratification proposed by Witzky⁽¹⁰⁾, in which a local over-rich part is attained by directing the spray against the swirling motion. This method, however, is not advantageous at least for the engine performance when applied to the swirl chamber diesel engine.

In the next place, the effect of the type of injection nozzle is given in Fig. 7. This result was obtained by replacing the nozzle with a Bosch throttle type DN4SD24 (spray angle 4°). The result shows that this substitution lowers NO over wide ranges of ϕ . As has been recognized widely, a throttle type nozzle may realize lower injection rate, and accordingly it appears to give an effect similar to injection retardation. However, this fact does not fully explain the reduction of NO attained at large ϕ , judged from the previous experience that the injection timing did not

Fig. 7 Influence of injection nozzle

Fig. 8 Influence of area ratio of connecting passage f/F

produce any great change in this range. Consequently, this behavior should be attributed to something else in the state of outflow of mixture into the main chamber, as will be more closely discussed later. Incidentally, the combined effects of the substituted nozzle and the flat-topped piston are also presented in the same figure.

4.3 Area of connecting passage

The experimental results at varying area ratio of the connecting passage f/F are given in Fig. 8. These were obtained at a fixed injection timing in the original setup using again the pintle nozzle and the depressed piston. As is observed from the figure, the concentration of NO is much affected by f/F in the range of ϕ larger than 0.4. The highest curve of the NO versus ϕ relation is recorded at $f/F = 0.8\%$, and a rapid decrease from this curve is associated with the enlargement of the passage. Quite opposite to this, the lowest smoke level is also reached at 0.8% , showing an inverse relation between improving the performance and reducing nitric oxide.

The explanation of the behavior of NO at reducing f/F may require the following matters to be taken into account; (a) the improved mixture formation and combustion in the swirl chamber due to elevated intensity of swirl, (b) the tendency toward a constant volume combustion in the swirl chamber⁽¹¹⁾, which might prepare higher levels in pressure and temperature, and (c) the increased energy level in the outflow of gases into the main chamber. Among these items, the first one (a) seems to be less important than the others, as suggested by weaker dependence of the direction of fuel injection at higher loads. Moreover, the effect of swirl should be discounted by the fact that the stronger the swirl the more apt the injected fuel is to be blown onto the wall. For this reason, the other items (b) and (c) appear to serve better for the explanation of the effect of f/F . Since the prechamber engine in principle uses a large quantity of energy of the out-

Fig. 9 Influence of volume ratio V_a/V_c

flow into the main chamber in assuring the mixing and combustion therein, the insufficient energy by use of large f/F will lead to a retardation of burning, thus lowering the temperature level and the NO level. On the contrary, a decrease in f/F not only increases the outflow energy but also tends to clog the stream of gases through the passage. The latter favors an increase in the temperature level in the swirl chamber, producing a greater amount of NO. However, at a very small area ratio, the outflow energy becomes again insufficient and as a consequence the burning is delayed in the main chamber.

In contrast to the large influence encountered in the locally overrich range, the extent of variation with f/F is narrow in the air-excess region. The plausible explanation of this would be the decreased importance of the outflow energy.

4.4 Volume of swirl chamber

As has been made clear, the change in the state of gas motions gives essential influences on NO formation. Similar effect may be associated with the case when the volume ratio of the swirl chamber V_a/V_c is varied. Figure 9 presents this effect obtained at a fixed injection timing and compression ratio. The reduction of the volume ratio from 50% to 30% at the same area ratio $f/F = 1.0\%$ considerably decreases NO, quite consistently with the expected decrease in the outflow energy. In this experiment, the diameter of the swirl chamber was changed from 37.0 mm to 31.2 mm . Since this change does not seem to alter greatly the relative position of the spray and the swirl, the state within the swirl chamber will not be influenced so much. For this reason, the reduction of NO may be inherent in the decreased outflow energy. However, the engine performance is sacrificed to some degree, probably due to the same reason.

In the next place, the broken curve in Fig. 9 gives the result obtained when the decreased outflow energy was recovered by

reducing the area of connecting passage, which was determined on the relation of $(f/F)/(V_a/V_c) = \text{constant}$. Over a wide range of ϕ , the concentration of NO is recovered almost to the same degree as the earliest case of $V_a/V_c = 50\%$ and $f/F = 1.0\%$. Thus it may be stated that the volume is not significant to NO so far as the level of gas motions is kept at an identical degree.

4.5 Compression ratio

It can be expected that compression ratio will give some effects on NO. Figure 10 shows test results pertaining to this, attained at two different compression ratios. The swirl chamber being the same, there was a slight discrepancy in the volume ratio of the swirl chamber; they were 46% and 55% for the compression ratios 15.1 and 18.0 respectively. The results show that lowering the compression ratio by such an extent never reduces NO and sometimes increases it at retarded timings of injection. It is also noted that NO is more affected by the injection timing at higher compression ratio than otherwise; that is, earlier injection gives higher peak concentration of NO at higher compression ratio, and so does later injection at lower compression ratio. This tendency reminds us of two possibilities: One is that high compression ratio reduces ignition delay leading to a lower rate of heat release in the earlier stages of burning; the other is that it brings about immediate expansion and quenching of the combustion products during the expansion stroke. These facts make the situation too complicated for us to obtain a clear explanation of the observed tendency. However, it may at least be stated that the effect of compression ratio is not very significant in reducing the NO emission.

5. Discussion

Taking into consideration the collected results of surveying the oxides of nitrogen, the general tendency will be discussed and summarized as follows.

In some cases, factors effective to cooling the flame tend to suppress NO, as experienced when the coolant temperature and the form of the main chamber were varied. Similar but reverse effect was encountered when the spray was kept from hitting the walls in the swirl chamber. However, these behaviors could be met only in the case of low equivalence ratios and were not significant at high equivalence ratios. The reason for this will be due to an immediate arrival at the deficiency of oxygen, in which only an insufficient time is allowed to form NO. As a consequence, no remarkable change appears to come out by a small difference in the temperature level. In contrast to this situation, there is plenty of residual oxygen at low ϕ , and the NO formation proceeds gradually for a longer time, so that a slight change in the state of flame cooling may be apt to produce greater difference in NO.

In the locally overrich region, NO is

Fig. 10 Influence of compression ratio

less sensitive to the injection timing and direction, and it depends rather on the rate of injection, the area of connecting passage, and the volume of swirl chamber. By taking these facts into consideration, the following explanations may be proposed concerning the action of prechamber in the locally overrich region.

(a) The swirl chamber gets to a fuel-overrich state soon after ignition, not giving sufficient duration to form NO.

(b) The swirling motion and the expansion of gas due to combustion well stir up the content existing in the swirl chamber, making the NO formation be less swayed by the state of mixture formation.

(c) The state of burning in the main chamber is substantially related to the formation of NO. This is closely influenced by the outflow energy.

As explained above, an immediate mixing and quick arrival at an overrich state, as compared with the contrary conditions, will give less sensibility to the details of the state of mixture formation occurring in the swirl chamber, and entering the gas into the main chamber and the subsequent burning produce more important difference in yielding nitric oxide. As a consequence, NO is more affected by the factors relating to the outflow energy such as the area ratio of the connecting passage and the volume ratio of the swirl chamber.

As has been referred to earlier, the divided chamber system can reach a locally overrich state at a relatively low equivalence ratio, and this provides us with an inherent means of achieving lower level of NO than an open chamber system.

6. Conclusions

As the result of the present study concerning the emission of oxides of nitrogen in the swirl chamber diesel engine, the following conclusions have been obtained:

At lower fuel-air equivalence ratios, some factors favorable to lower the temperature levels such as retarding the injection and cooling the flame reduce the formation of oxides of nitrogen. However, their effect comes to be of less importance at higher equivalence ratios. In this range, the concentration of oxides of nitrogen decreases with the equivalence ratio, and this behavior is attributable to the increased fuel-overrich zone present locally in the swirl chamber. The emission of nitric

oxide in this range is mainly concerned with the factors relating to the outflow of gas into the main chamber such as the area of connecting passage and the volume of the swirl chamber.

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