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Effect of Auxiliary Injection Ratio on the Characteristic of Lean Limit in Early Direct Injection Natural Gas Engine

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Abstract*— *the direct injection natural gas engine is well known as the new generation CNG engine with lean combustion and high power. Extension of lean burn region for this engine is the effective method to decrease the combustion temperature for reducing NOx emission and increasing thermal efficiency. In this study, auxiliary injection is to enhance the mixing duration and lean boosting is to increase supply energy in the lean burn region. As the results, use of auxiliary injection is extended the lambda to λ = 1.5, but power is reduced because of the decrement of supply energy. To compensate power for extending lean limit and lower gas temperature, the combination between auxiliary injection ratio with lean boosting is also evaluated in this article. The results are shown the lean limit extended and decreased NOx emissions without decreasing power.

Index Terms—**Auxiliary injection ratio, Characteristic of lean limit, Direct injection, Lean boosting, Mixing duration, Power compensation, Supply energy.**

I. INTRODUCTION

The Direct Injection Natural Gas Engine has known as the fourth generation of the gas injection method, its merits can be easily enumerated such as high power and high efficiency in comparison with Port Injection Natural Gas Engine. For heavy-duty Compressed Natural Gas (CNG) engine with early Direct Injection (eDI type), CNG fuel injects directly into the cylinder at the early stage of compression stroke, consequently the turbulence intensity of mixture into the cylinder is intensively increased in comparison with Port Injection (PI type), and the result in the lean limit is able to be extended to λ=1.4. Meanwhile power is lowered by supply energy reduced at lean burn region.[1] At present, the emission standards are more tightened than before so the eDI engines have to extended the lean limit. The mixing rate of mixture is an important factor can be extended the lean limit of conventional engine. Two technical methods can be considered to increase the mixing rate of mixture in the vicinity of spark plug at spark timing. The first is the control of injection patterns such as injection timing, direct injection pressure during compression process. This method may be less effective in mixing due to short mixing duration. The other one is auxiliary injection, the small portion of fuel supply in the intake port during intake process and main fuel inject into the cylinder during early stage of the compression process directly. It means that the mixing duration start from the intake process till the burning membrane develops. It may lead to the mixing rate is better and the result in the lean limit will be extended more than eDI type.[2, 3] However, the engine power will be reduced because the air mass into cylinder decrease when auxiliary injection ratio enhance. To overcome this drawback, the method is supposedly effective that is the use of supercharging. The enhancement of air mass flow rate before entering into the cylinder is by increasing boost pressure, this means that the supply energy is raised at the same air excess ratio (λ) and the result is both of power output, thermal efficiency and lean limits are enhanced significantly.[4, 5] In order to more extend the lean limit without power loss in comparison with the auxiliary injection, the combination of auxiliary injection with lean boosting can be seen as the effectiveness method to improve the characteristic of lean limit, because the supplied energy is equal or over in comparison with non auxiliary injection at lean burn region.[6, 7] In this study, the major objective is to examine the effect of auxiliary injection ratio on the characteristic of lean limit such as power, thermal efficiency and NOx emissions. Experiments in this study will carry out by a research single cylinder CNG engine with two injectors. In addition, its result is compared with non-auxiliary injection at lean limit.

II. EXPERIMENTS AND METHODS

A. Experimental setup

A single cylinder diesel engine was modified into a direct injection spark ignited natural gas engine. The specifications of the engine are listed in Table 1.

Table I: Engine specifications

Engine type	SOHC
Number of cylinder	Single cylinder
Bore x stroke	123mm x 155mm
Displacement	1842cc
Compression ratio	10.5
Injection type	DI & PI
Injection pressure	30 bar & 4 bar
Fuel	CNG

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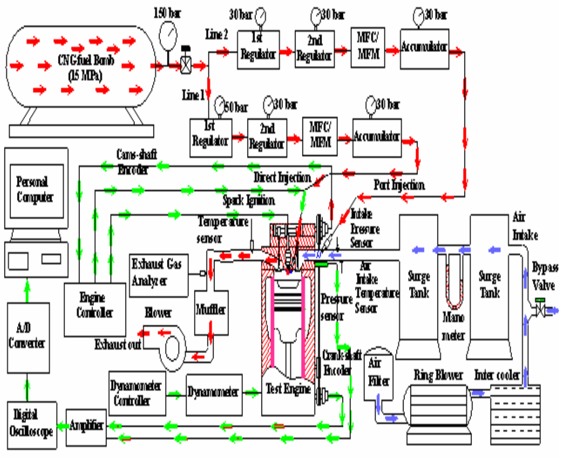

Fig1. Schematic diagram of experimental setup

Fig. 1 represents a schematic diagram of the experimental setup. It consists of the DING engine, an AC dynamometer, a CNG supply system, intake/exhaust systems, a cooling system, a supercharging system for lean boosting, an engine controller unit, data acquisition units and several measuring devices. The test engine has $\varepsilon = 10.5$ of the compression ratio, the displacement volume of 1842 cc, 123 mm x 125 mm in the bore and stroke, respectively. The engine has two injectors and its position shows in the Fig. 2, the one is low pressure injector inserted on the intake pipe for auxiliary injection, other one is high pressure direct injector installed on the cylinder head close to spark plug. The CNG in the commercial high-pressure gas bomb pressurized to 150 bars is decompressed to 30 bars and 7 bars through the primary and secondary pressure regulators. And decompressed gases are finally supplied to the engine via a direct injector and a port injector, respectively.

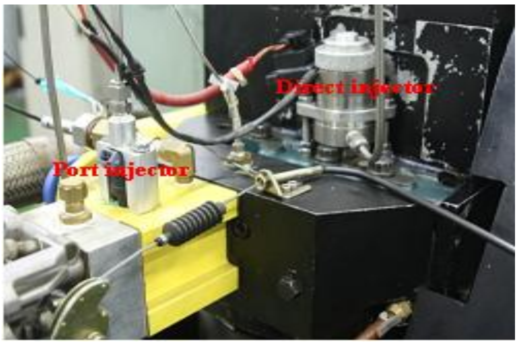

Fig. 2 Location of port and direct injectors

Both of the two injectors are controlled by an engine controller. Flow mass of fuel is measured by using a thermocouple type of flow meter (Bronchus, P-113AC-HAD-55-V). Between the CNG flow meter and the gas injectors, a 3.8 L accumulator is installed to minimize pulsation caused by fuel injection. The supercharging system for lean boosting consists of an electrical ring blower operated with external power, an intercooler of water type, and air filter. Two surge tanks (104 L per tank) are installed at the front and rear of the air flow meter to eliminate any pulsation of the air stream during engine operation. A piezoelectric transducer (Kistler 6061-B) is inserted on the cylinder head to measure in-cylinder pressure. Coolant water is supplied to the modified cylinder head, the block, and the oil cooler separately.

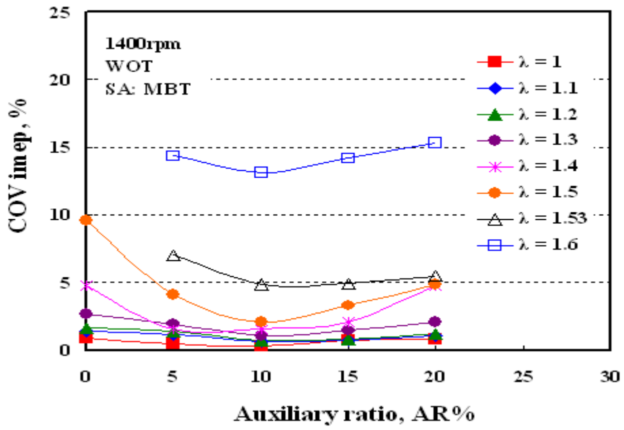

Fig. 3 COV imep as a function of auxiliary ratio, AR(%)

B. Experimental method

The experiment variables are the auxiliary injection ratio, lean boosting pressure and lambda (λ). For extension of lean limit by auxiliary injection, auxiliary injection ratio (AR) varies in two cases as follow: To study the effect of auxiliary injection ratio on extending lean limit, the auxiliary ratio change from AR = 0% to AR = 20% by ΔAR = 5%. In case of increasing supply energy when extending lean limit, the auxiliary ratio change from AR = 10% to AR = 30% by ΔAR = 10%. Lean boosting pressure fixed at 1.3 bar and 1.5 bars. Air excess ratio is increased from stoichiometric air-fuel ratio up to the misfire occurrence. For each experiment, engine speed set to 1400rpm and MBT at where the maximum torque occurs, and the intake and coolant temperature fixed to 262K (25^{o}C) and 353K (80^{o}C), respectively. Injection pressures were 7 bars and 30bars for auxiliary injector and direct injector, respectively. The auxiliary injection ratio (AR) is defined as follow:

$$AR = \frac{m_{fp}}{m_{fd} + m_{fp}} \times 100(\%)$$

Herein: $\dot{m}_{fp}$ and $\dot{m}_{fd}$ (kg/s) are fuel mass flow rates of the port and direct injectors, respectively.

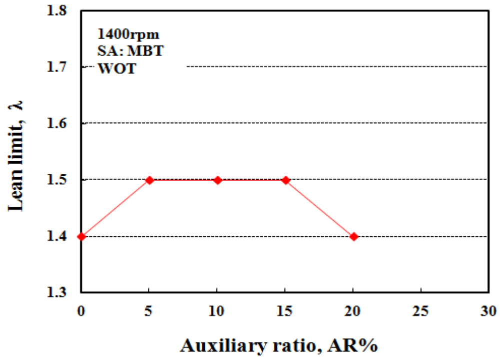

Fig. 4 Lean limit as a function of auxiliary ratio, AR(%)

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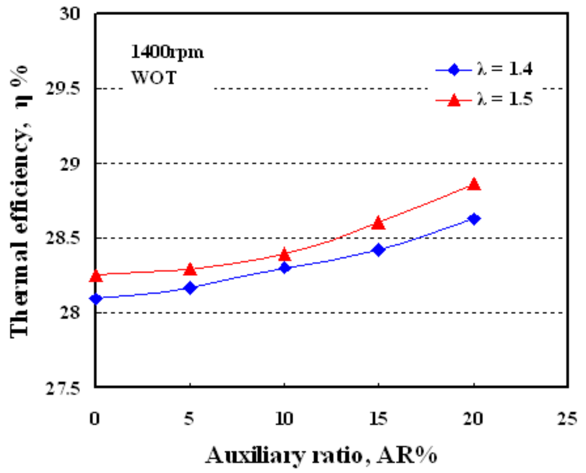

Fig. 5 Thermal efficiency as function of auxiliary ratio, AR (%)

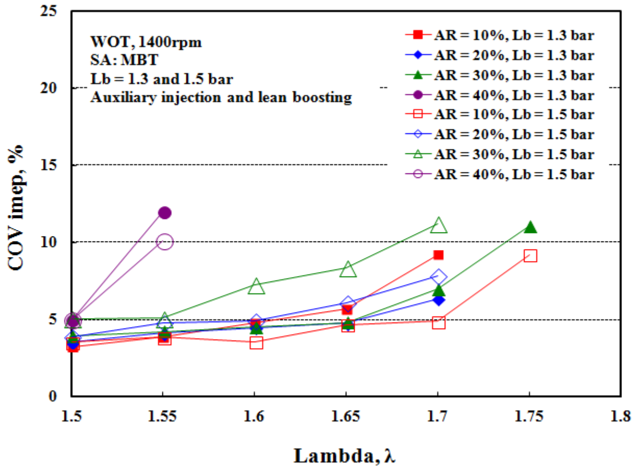

Fig. 7 COVimep versus lambda, λ

III. RESULTS AND DISCUSSIONS

A. Effect of auxiliary injection ratio on lean limit

Cyclic variation occurs when the in-cylinder pressure varies from cycle to cycle due to the changing rate and incompleteness of burning generated by asymmetrically distribution of mixture temperature and concentration. In most cases, cyclic variation is larger under low loads and high dilutions for conventional SI engines. However, the use of auxiliary injection ratio has improved the weakness and extended lean limit. Figure 3 presents COVimep as a function of auxiliary ratio, AR(%) in conditions such as engine speed equal to 1400rpm and Wide Open Throttle (WOT). Normally, the value limit of COVimep is below 5% and like this the CNG fueled engine can be operated stably without appearing unstable combustion. For λ = 1.5 without auxiliary injection (AR = 0%), COVimep of is higher than that of 5% as shown in the figure. However, the use of auxiliary injection ratio, the COVimep has the tendency is remarkably reduced and its values are below 5%, even the engine can be stably operated at λ = 1.53 if the conditions pertaining to stable combustion unbreakably.

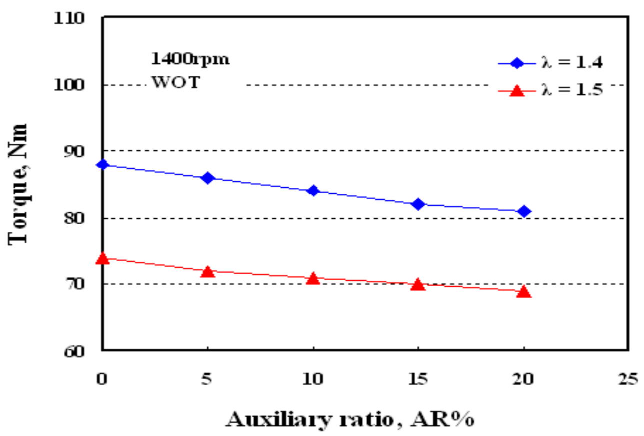

Fig. 6 Torque as a function of auxiliary ratio, AR (%)

As depicted in figure, the COVimep value is smaller than 5% in the range of AR = 10~15%, but these values are larger than that of 5% when auxiliary injection ratio overcome AR = 20%, and then the result in the misfire phenomenon start to observe slightly. Fig. 4 presents the lean limit (λ) with respect to auxiliary injection ratio at WOT condition. As mentioned previous figure, the lean limit were extended from λ = 1.4 to λ = 1.5 due to the combustion duration is decreased. This change can be explained by the fact that as the flow motion into cylinder has been enhanced, so burning rate and thermal efficiency raise irrespective of reducing in fuel supply. Contrary to the lean limit is went back to λ = 1.4 when auxiliary injection ratio enhances to AR = 20%. The main cause of this case is due to the decrease in supply energy when the both of lambda and auxiliary injection ratio increase, the effect of the decreased supply energy on thermal efficiency and torque is different in the lean burn region. Fig. 5 showed the thermal efficiency as a function of auxiliary ratio at lean limit such as lambda of λ = 1.4 and λ = 1.5. For two lambdas, the tendency of thermal efficiency is augmented when increasing auxiliary ratio, it is because the flammability of mixture is significantly improved in the lean burn region. Especially, the thermal efficiency of λ = 1.5 in comparison with λ = 1.4 is increased slightly. This can be traced back to the effect of the heat loss reduction is increased with using higher ratio of auxiliary injection, it is a result of combustion acceleration due to auxiliary injection addition to the temperature of combustion gas are increased due to the decreased intake flow mass. Above results demonstrate that auxiliary injection is an effective as method of achieving lean limit expansion and increasing thermal efficiency in a direct injection natural gas fueled spark ignition engine. The decrease of supply energy when increasing auxiliary ratio in the lean burn region has the effect on torque is more powerful. The figure 6 represents the torque as a function of auxiliary ratio for both of lambda (λ = 1.4 and λ = 1.5). The torque tends to decrease linearly, because the supply energy is rapidly decreased regardless of increased thermal efficiency.

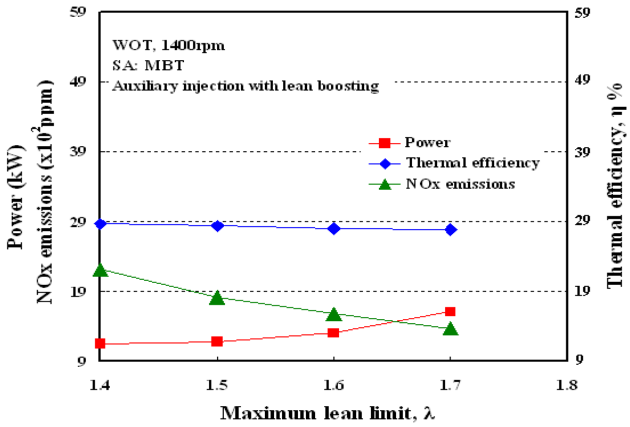

Fig. 8 NOx emissions, thermal efficiency and power as function of maximum lean limit, (λ)

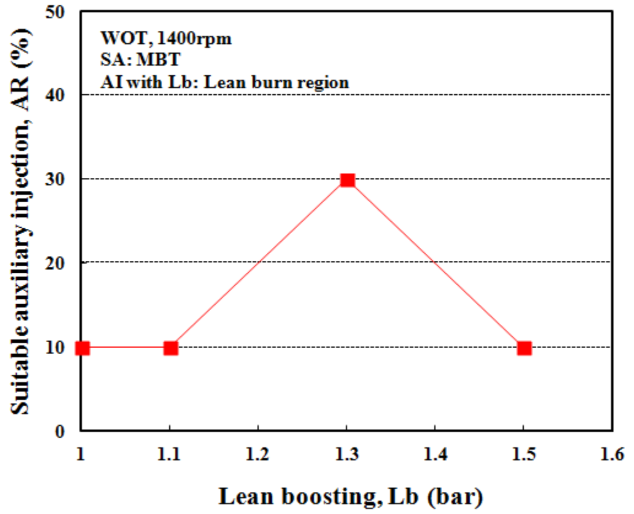

Fig. 9 Auxiliary injection ratio required to lean boosting

B. Lean limit characteristic with auxiliary injection ratio and lean boosting

Fig. 7 illustrates the variation of COVimep versus lambda for six couples of combination between auxiliary injection and lean boosting (such as AR = 10%, 20%, 30%, and lean boosting of Lb = 1.3 bar and 1.5 bar). As depicted in the figure, the tendency of COVimep enhancement is observed when lambda increases at each couple value of auxiliary injection and lean boosting. The results are clearly indicated that the lean limit extended from λ = 1.5 to λ = 1.7 when auxiliary injection ratio increases in the range of AR = 10% ~ 30%. In this case the main reason to extend lean limit that is supply energy is increased significantly in comparison without supercharging. However, the effect of auxiliary injection ratio on COVimep compares to supercharging is evident, because the rate of COVimep exceed the limited value of 5% is rapid %, when auxiliary injection ratio over 30%. But the essence of increasing COVimep is in the decrease of the CNG fuel quantity of direct injector, in other words, the increment of auxiliary injection ratio will be reduced the CNG fuel quantity by direct injector. Fig. 8 indicates NOx emissions, thermal efficiency and power as function of maximum lean limit in case of using auxiliary injection with lean boosting. The NOx emissions are significantly reduced according to the increase of lean limit expansion. The thermal efficiency has the slight decreased tendency when lean limit expands. But it can be seen as almost same because its difference is not so much. The power has the tendency increased due to the increase of intake air mass rapidly as the lean boosting becomes greater. When auxiliary injection is adapted with lean boosting simultaneously, the decrease of NOx emissions is around 38% and power is increased by 29% approximately. Fig. 9 indicates auxiliary injection ratio required to lean boosting at larger lean limit. In this case, the suitable auxiliary injection is established the base of the maximum value of air-fuel equivalence ratio with COVimep below or equal 5%, and thus the value of COVimep equal 5% is reputed as the limit to determine suitable auxiliary injection. As depicted in the figure, the operating region close to lean boosting of Lb = 1.1 bars, auxiliary injection ratio equal 10% is suitable to large lean limit because of the decrease of air mass flow rate into cylinder. When engine operates with higher lean boosting (from Lb = 1.1 to λ= 1.3) need to enhance auxiliary injection to AR = 30%, because can take full advantages of auxiliary injection such as larger mixing duration and flammability of mixture. However, at lean boosting equal 1.5 bar, auxiliary injection must to reduce to AR = 10%, it is because the burning rate of both auxiliary injection limit (AR = 15%) and lean boosting limit (Lb = 1.4 bar) is reduced (as depicted in Fig.3-6, 4-2 and 4-4). The variation of auxiliary injection according to lean boosting will be affected engine performance, therefore, the next step is going to report the engine performance with the combination of auxiliary injection and lean boosting.

IV. CONCLUSIONS

Effects of auxiliary injection ratio on the characteristic of lean limit in early direct injection natural gas engine have investigated with two cases such as: varying auxiliary ratio to extend the lean burn region, and combining auxiliary injection ratio with lean boosting is to enhance supply energy at extending lean limit. The conclusions of this study summarized as follows: Using the auxiliary injection extended the lean limit to λ =1.5 due to the increase of the mixing duration. The stable region of engine operation is found in the auxiliary injection ratio around AR = 10%. The thermal efficiency is slightly increased due to combustion promotion by increased mixing duration, although power is reduced rapidly because of supply energy decrement. The combination between auxiliary injection and lean boosting has enhanced the supply energy at lean burn region and the result in the lean limit is extended in comparison with only auxiliary injection. Especially, NOx emissions is decreased around 38% but the power has trend is increased in comparison with early direct injection only, in addition thermal efficiency seems to be unchanged during lean burn region. It is due to the mixing duration and supply energy are increased as the auxiliary injection combines with lean boosting. For obtained results can be seen that the combination of auxiliary injection with lean boosting is one of the useful methods to extend lean limit without power loss for a direct injection natural gas engine. To clearly know about extending lean limit without power loss, the next study will present the combination between auxiliary injection and lean boosting at similar supply energy.

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