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An Experiment of SCR System On-board Ship

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Abstract : IMO NO_x levels are generally possible to meet by means of primary on-engine measures. Further significant follow-on reductions are likely to require a secondary after-treatment technique. SCR(Selective Catalytic Reduction) technology is used almost exclusively for NO_x removal in stationary combustion systems. In order to develop a practical SCR system for marine application on board ship, a primary SCR system using urea was made. The SCR system was set up on the ship, "HANNARA" as a test vessel, employed a two-stroke cycle diesel engine as main propulsion, which is a training ship of Korea Maritime University. The purpose of this paper is to report the results about the basic effects of the below system parameters, The degree of NO_x removal depends on some parameters, such as the amount of urea solution added, space velocity, reaction gas temperature and activity of catalyst.

Key words : SCR system, Marine diesel engine, NO_x reduction rate, Ammonia slip, IMO regulation

1. Introduction

A diesel engine is utilized widely for industry and shipping because of its efficiency. However, diesel engine emits relatively high concentrated air pollution matters, which will become a competitive factor in the shipping as well as industry. In fact, the regulation has been already implemented from the year 2000.

Nitrogen oxides (NO_x) in particular is the main part of the regulation. IMO NO_x levels are generally possible to meet by means of primary on-engine measures. Further significant follow-on reductions are likely to require a secondary after-treatment technique.

Selective Catalytic Reduction(SCR) technology is used almost exclusively for NOx removal in stationary combustion systems. SCR system is currently the only available technology proven at full scale to meet the 90% NOx reduction levels. Accordingly, the use of an SCR

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system on board ship maybe provides the solution to minimize this primary pollutant without increasing fuel consumption.

Many studies of SCR system for marine application have been reported to improve the performance[1]-[4]. The effects are investigated from practical application through its trial use. In order to develop a practical SCR system for marine application on board ship, a primary SCR system using urea was made. The SCR system was set up on the ship, "HANNARA" as a test vessel, employed a two-stroke cycle diesel engine as main propulsion, which is a training ship. The purpose of this paper is to report the results about the basic effects of the below system parameters. The degree of NO_x removal depends on some parameters, such as the amount of urea solution added, space velocity, reaction gas temperature and activity of catalyst. The preliminary results from trial use are presented.

2. The SCR Process Using Urea

The selective catalytic reduction process is at present the only feasible secondary method for reduction of nitrogen oxides (NO_x) in exhaust gas from diesel engines. Ammonia is technically used either in its pure form or as a 25% aqueous solution. It is toxic and corrosive liquid, which is a problematic aspect. This difficulty can be circumvented when employing an ammonia carrier instead of neat ammonia as a reducing agent. For logistic and safety reasons urea ($CO(NH_2)_2$) was chosen. At room temperature urea forms non-toxic crystals, which can be easily dissolved in water.

The reduction of nitrogen oxides takes place by injecting a urea solution into the exhaust gas with a temperature of 300-450℃. When in contact with the hot exhaust gas, the water evaporates and subsequently the urea decomposes according to the following equation.

$$H_2NCONH_2 + H_2O \rightarrow 2NH_3 + CO_2$$

The mixing of NH_3 and exhaust gas is then subsequently passed through a catalyst where the NH_3 and NO_x react on the internal surface of the catalyst according to the following reaction schemes.

$$4NO + 4NH_3 \rightarrow 4N_2 + 6H_2O$$

$$4NO_2 + 8NH_3 \rightarrow 7N_2 + 12H_2O$$

The conversion of nitrogen oxides does not create any secondary pollution, as the products formed are only nitrogen and water vapor.

3. Experimental Arrangement

A schematic diagram of the overall experimental arrangement is shown in Fig. 1. A small part of the exhaust gas is diverged from exhaust gas receiver. The SCR system is installed in the funnel of boat deck due to the difficulty on the installation. The SCR system unit utilizing urea solution as reducing agent consists of the following components.

- Urea injection system

Storage tank, Liquid flow controller,

Injection nozzle

- Exhaust gas system
  Gas flow controller, Mixer, Electrical heater
- SCR reactor with catalyst elements
- NOx analyzer and data acquisition system

The urea solution is stored in the pressurized storage tank to 3 bar by compressed air at ambient temperature. From the storage tank the urea solution is injected directly into the mixer in which evaporation and decomposition will take place. In order to prevent from clogging with solid urea and achieve a proper mixing on the produced ammonia and exhaust gas, urea solution is injected with compressed air. Also air blow is carried out by compressed air among the tests to blow off the deposit of solid urea and the soot. The used catalyst measuring 152×152×150mm has a monolithic structure manufactured in wash coating type. Four catalyst cassettes are assembled at the upper and lower part in the reactor. The total catalyst volume is 0.0135 m^3.

Each flow controller controls mass flow rates of exhaust gas and supplied urea solution. Gas sampling is carried out at inlet and outlet of SCR reactor. Sampling gas is induced to a gas analyzer through a gas sample dilution probe. The specifications of the gas analyzer and the dilution probe are shown in Table 1 and Table 2, respectively.

Table 1 Paticulars of gas analyzer

Name	NH_3 Analyzer
Type	Model 17C
Measuring method	Chemiluminescence
Measuring output	NO, NO_2 NH_3, NO_x
Measuring ranges	0 - 20 ppm
Extended ranges	0 - 100 ppm
Sample flow rate	600 cc/min

Table 2 Specifications of dilution probe

Name	Gas Sample Dilution Probe
Type	SP2000H/DIL
Dilution Factor	20 : 1

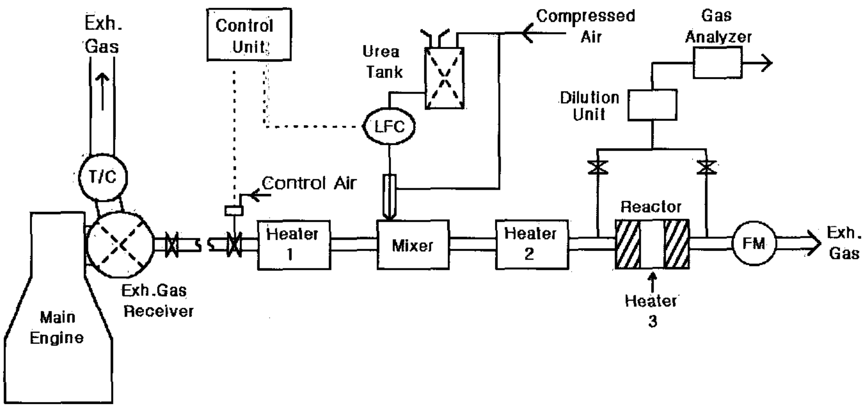

Fig. 1 Schematic diagram of experimental arrangement

4. Experimental results

The influences on the NO_x reduction rate are investigated in accordance with the variation of operation factors on the process for the SCR system, such as gas temperature, urea/NO_x mole ratio and space velocity. NO_x reduction rate and space velocity are defined respectively as follows.

NO_x Reduction rate (%) = [NO_x concentration at reactor outlet(ppm) / NO_x concentration at reactor inlet(ppm)] * 100

SV (h^{-1}) = Exhaust gas flow rate (Nm^3/h) / Catalyst volume (m^3)

The tests were carried out while the main engine was operated at 180 RPM, torque 11.2 ton · m on the average.

Table 3 Ship and engine specifications

Kind of ship	G/T 3500 Ton class Training vessel
Engine type	MAN B&W - 6L35MC
Bore / Stroke	350 / 1050 mm
Output / Speed	4,000BHP/200RPM(MCR) 3,400BHP/189.5RPM(NCR)
Comp. ratio	12.96
Mean Eff. Press.	14.6 bar at MCR
Turbocharger	BBC-VTR-354A-32

Table 4 Characteristic values of fuel oil

Specification	Bunker B oil
S.G. at 15/4 ℃	0.9209
Viscosity	46 cSt at 50℃
Flash point	92.7 ℃
Sulfur	2.45 %
Water & sediment	0.1 %

The specification of main engine is shown in Table 3. And heavy fuel oil was used as shown in Table 4. The process computer acquired all measured data when the stable condition is maintained after 20-30 minutes.

Fig. 2 illustrates that the NO_x reduction rate varies with gas temperature in the SCR reactor for three different space velocities. The urea solution was used as a 20% aqueous solution, and was supplied with constant amount as urea/NO_x mole ratio 1.0 at SV 10,000 h^{-1}. 1 mole of urea solution makes 2 mole of NH_3. As shown in Fig. 2, the NO_x reduction rate increases with the gas temperature increase. When the space velocity is at SV 10,000 h^{-1} above, it is possible to obtain high degree of NO_x reduction rate, and the difference according to the space velocity is small. When the gas temperature is above 400℃, it is shown that the NO_x reduction rate is high at any space velocity.

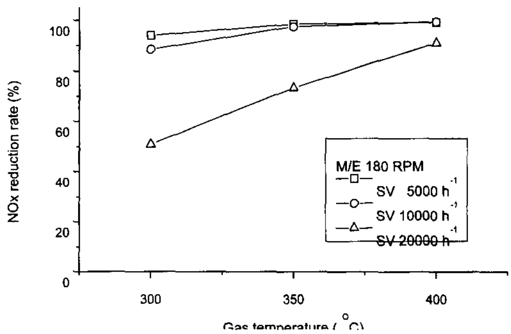

Fig. 2 NO_x reduction rate at various gas temperature

From the above, it is obvious that the gas temperature in the SCR reactor is the most important factor for NO_x reduction. The space velocity is secondary.

Generally keeping high temperature of exhaust gas, it is not desirable due to need of heater and increase of the fuel consumption.

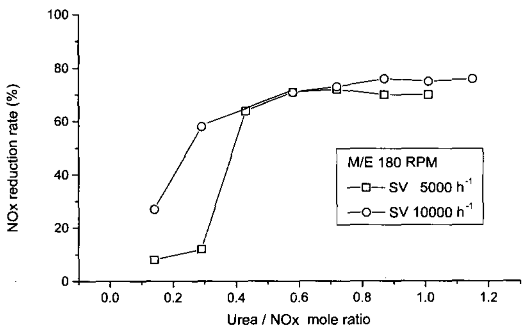

Fig. 3 NO_x reduction rate at various urea/NO_x mole ratios

Fig. 3 illustrates that the NO_x reduction rate varies with the urea/NO_x mole ratio at the gas temperature 300℃ for two different space velocities. The NO_x reduction rate increases with an increasing mole ratio. But the increase of the NO_x reduction rate decreases gradually and is limited as maximum about 80% when the mole ratio is above 0.6. The difference between two space velocities is found hardly for NO_x reduction rate. It seems that the NO_x reduction of this primary SCR system has unfortunately a limitation due to unsuitable design of the mixer. The decomposition of the urea solution depends on mixing pattern, staying time and gas temperature in the mixer. Actually, it is found that some amounts of solid urea as well as the soot left in the mixer and reactor after the tests. In case of this primary SCR system the flow distance from urea solution injection nozzle to reactor is designed to be relatively short. It was supposed that a part of the urea solution did not become to ammonia during the passing in the system, and emitted as it was from the system. From the above, it is obvious that the optimal design of the mixer is important in order to achieve high degree of NO_x reduction.

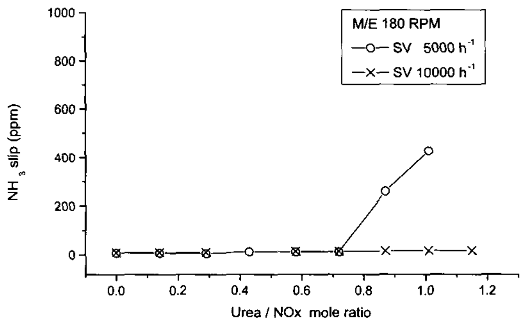

Fig. 4 NH_3 slip at various urea/NO_x mole ratios

Fig. 4 illustrates the results of the NH_3 slip measured at the same time in case of Fig. 3. NH_3 slip means the amount (ppm) of unused ammonia in the exhaust gas at the reactor outlet. From the figure it can be seen that at SV 10,000 h^{-1} the NH_3 slip did not occur in spite of increase of the mole ratio. But at SV 5,000 h^{-1} the NH_3 slip occurred when the mole ratio is above 0.7, and increased almost in proportion to the mole ratio. Because the stay time in case of SV 5,000 h^{-1} is longer than SV 10,000 h^{-1}, urea solution decomposed effectively to NH_3. But the NO_x reduction rate increases hardly. From the above described if the mole ratio increase in order to high degree of NO_x reduction rate at SV 10,000 h^{-1}, the consumption of the urea solution increase, and at SV 5,000 h^{-1} the NH_3 slip increase only without the increase of NO_x reduction rate.

Consequently it is confirmed that the mole ratio and the space velocity have to be controlled adequately for optimal operation of the SCR system. For the NO_x reduction, it is desirable that the space velocity is chosen as low as possible. But the low space velocity means that the space volume of catalyst becomes larger.

5. Summary

When the urea is used as reducing agent, the design of mixer is very important to decompose urea to ammonia. The optimal range of space velocity depending on catalyst volume maybe exists. The NO_x reduction rate sensuously depends on the mixer and space velocity. The optimization of the space velocity will achieve the high degree of the NO_x reduction as well as the small space of installation.

In the design of the SCR system, the gas temperature is basically important factor, because the higher the gas temperature is, the higher the degree of NO_x reduction rate is. When the gas temperature is high, the space velocity can be selected highly. Accordingly the installation space of the SCR system as well as catalyst volume maybe takes small space. However the heater is required to keep the gas temperature high and it makes fuel consumption high. It is necessary to study about the new method, which does not need heater. For example in case of two-stroke engine, a gas exchange system without mixing between scavenging air and exhaust gas during gas exchange process will be one of the new method, because the exhaust gas temperature becomes low due to the scavenging process.

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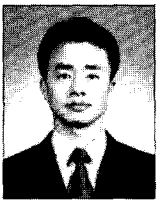

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