The reduction requirement of environmentally impact material has been increasingly stringent. Furthermore, the reduction of greenhouse gas and black smoke has been discussed. Table 1 shows the comparison of environmental impact material reduction technology. Gas engine is only the effective solution of reduction all exhaust emissions simultaneously.

**Table.1 Comparison of environmental impact material reduction technology**

<table>
<thead>
<tr>
<th>No</th>
<th>Item</th>
<th>Description</th>
<th>NOx</th>
<th>SOx</th>
<th>PM</th>
<th>CO2</th>
<th>Tasks to be solved</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SCR</td>
<td>NOx deoxidation by the catalyst</td>
<td>◎</td>
<td>−</td>
<td>−</td>
<td>◎</td>
<td>Urea cost, maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>◎</td>
<td>Prevention of ammonia</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>◎</td>
<td>Leakage</td>
</tr>
<tr>
<td>2</td>
<td>Scrubber</td>
<td>Removing SOx by seawater wash</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>−</td>
<td>Purification of polluted seawater</td>
</tr>
<tr>
<td>3</td>
<td>EGR</td>
<td>Exhaust gas recirculation</td>
<td>△</td>
<td>◎</td>
<td>×</td>
<td>×</td>
<td>Engine durability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Efficiency drop, recovering</td>
</tr>
<tr>
<td>4</td>
<td>Emulsion</td>
<td>Combustion temperature decrease by emulsion</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Mass pure water production device,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Engine durability</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Efficiency drop, recovering</td>
</tr>
<tr>
<td>5</td>
<td>Gas engine</td>
<td>Operation by natural gas</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>◎</td>
<td>Fuel supply infrastructure, fuel storage in ship</td>
</tr>
</tbody>
</table>

We have two concepts for the development of marine gas engine. In developing marine gas engine with excellent exhaust emission properties, we have set the two concepts. The first concept is maximizing the engine performance while keeping low emission performance. The second concept is maximizing the yield strength with respect to the change of fuel calories and load variation, which is expected the engine work on the ship.

This paper introduces the new technology, which ensures the reliability for the marine gas engine with complying with environmental regulations.

2. Main particulars

The gas engine has been converted from 260mm bore marine diesel engine. The principal particular is shown in Table 2.

**Table.2 EYG26L principal particular**

<table>
<thead>
<tr>
<th>Engine name</th>
<th>6EYG26L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>4cycle water cooled</td>
</tr>
<tr>
<td>Cycle</td>
<td>Lean burn mirror cycle</td>
</tr>
<tr>
<td>Ignition</td>
<td>Spark Ignite</td>
</tr>
<tr>
<td>Bore</td>
<td>mm</td>
</tr>
<tr>
<td>Stroke</td>
<td>mm</td>
</tr>
<tr>
<td>Speed</td>
<td>min⁻¹</td>
</tr>
<tr>
<td>Fuel</td>
<td>Natural gas</td>
</tr>
</tbody>
</table>

This engine is designed as the main engine to be mounted on the electric propulsion ships. Combustion system employs a pre-chamber system with spark plug.
3. Experimental device

3.1 Fuel calorie control system

The test instrument used in this research is the fuel calorie control system to simulate the fluctuation of natural gas. Fig.1 shows the system. The system enables to control fuel calorie by mixing the standard natural gas in Japan (=13A) and the Air that increased the ratio of nitrogen.

Fig.1 Fuel calorie control system

3.2 Simulated load generator

The test instrument used in this research, can be simulated various patterns of load fluctuation. Fig.3 shows the system of load generator.

Fig.3 Load generator

4. Air control system

The bypass valve that returns air from compressor out of turbocharger to compressor in has the advantage that has high control response to load variations. On the other hand, the bypass valve can’t control air flow rate at low load because it isn’t possible to control the negative pressure in the supply manifold. Therefore EYG26L adopt the two valve system that has the throttle valve in addition to the bypass valve. Fig.4 shows the two valve system.

Fig.4 Two valve system

4. Air control system

Fig.5 shows the effect of throttle valve opening. Closing the throttle valve decreases the excess air ratio and enables THC emissions and fuel consumption to improve because it is possible to control the negative pressure in supply manifold and suitable air fuel ratio for gas engine.

Fig.5 Effects of pressure in supply manifold on THC and Fuel Consumption
5. Fuel control system

The fuel gas pressure for main chamber is controlled by the pilot pressure of mechanical regulator. On the other hand, the fuel gas pressure for pre-chamber is controlled by electrical valve to the target pressure. These systems enable the fuel gas pressure for main chamber and pre-chamber to control the optimum pressure at each load. Fig. 6 and Fig. 7 show the fuel control system for main chamber and pre-chamber.

The fuel gas pressure for main chamber is controlled by the pilot pressure of mechanical regulator. On the other hand, the fuel gas pressure for pre-chamber is controlled by electrical valve to the target pressure. These systems enable the fuel gas pressure for main chamber and pre-chamber to control the optimum pressure at each load. Fig. 6 and Fig. 7 show the fuel control system for main chamber and pre-chamber.

6. Air fuel ratio control for fuel calorie fluctuation

6.1 Main chamber

Fig. 8 shows the air control system in the main chamber.

\[
Q_{fuel} = \frac{W}{ETA \times H}
\]  \hspace{1cm} (1)

The mixture flow rate to the main chamber is defined by Eq. (2).

\[
Q_{mix} = \frac{273.15 \times P_1}{101.325 \times ETA \times V_i \times N_e}
\]  \hspace{1cm} (2)

The equation clearly suggests that the mixture flow rate stays constant if the volume efficiency, temperature in supply manifold and engine speed is same in that the pressure in supply manifold is controlled at each load by throttle valve or bypass valve. Fig. 9 shows the effect of fuel calories on calculated excess air ratio of main chamber with this control system. The excess air ratio is in main chamber constant with fuel calorie.

6.2 Pre-chamber

Fig. 10 shows the fuel control algorithm in the pre-chamber.

The fuel gas flow rate is constant against fuel calorie in that the fuel gas pressure to the pre-chamber is controlled. In this case, the simple model calculates the air fuel ratio in the pre-chamber. Fig. 11 shows the simple model. The pre-chamber is filled with fuel gas and scavenged gas at the beginning of compression stroke. The fuel gas and air is supplied to the pre-chamber in compression stroke. The simple model assumes that the gas compressed adiabatically.
Fig. 11 Simple model of air fuel ratio in pre-chamber

Fig. 12 shows the correlation between fuel calorie and calculated excess air ratio in pre-chamber. The calculated excess air ratio in pre-chamber becomes higher when fuel calorie is decreased.

When fuel calorie is decreased, assumed that the output and thermal efficiency is constant, the amount of fuel consumption is increased. This suggests that the control logic enables the excess air ratio in pre-chamber to control to be constant by estimating fuel calorie generated from the amount of fuel consumption, adding the function that correct fuel gas pressure to pre-chamber based on the amount of fuel consumption was added.

Fig. 13 shows the improved air fuel ratio in pre-chamber control logic.

Fig. 14 shows the correlation between fuel calorie and IMEP COV (=Coefficient of Variation). Correcting the fuel gas pressure to pre-chamber enables to improve IMEP COV, in case of low fuel calorie.

Fig. 15 and Fig. 16 shows the effect of fuel calorie on engine performance. Thermal efficiency and NOx emissions are constant against the fuel calorie changes.
Fig. 16 Effect of fuel calorie on NOx (O2=0%)

Fig. 17 shows NOx emissions in case of changing fuel calorie. NOx is constant at all times.

Fig. 17 NOx emissions in case of changing fuel calorie

7. AIR FUEL RATIO CONTROL FOR LOAD FLUCTUATION

7.1 LINEAR PREDICTION ALGORITHM

The linear prediction algorithm (Method based on the signal of the past, to predict the course of future linearizing the transition sequential) could be applied to a load fluctuation signal of electric propulsion in coastal shipping, optimizing the parameters such as order and weighting factor.

The Linear prediction algorithm is defined by Eq. (3). Predict value at ‘n’ are obtained by adding a weighted value of the ‘k’. 

\[ \hat{y}_n = \sum_{i=1}^{k} a_i y_{n-i} \]  

(3)

Fig. 18 shows the comparison of predicted load after one second and real time load. According to the comparison, it has been found that it is possible difference between the actual load and the load after 1second is predicted at +24.6kW (Error margin within 1.8% of ± against the rated power).

Fig. 18 Comparison of predicted load after one second and real time load

7.2 SYSTEM IDENTIFICATION EXAMINATION

It is necessary to understand the change factor of air fuel ratio and the influence level on air fuel ratio to calculate the amount of the operation in which the air fuel ratio change by the load fluctuation is controlled. Therefore, the factor that influences air fuel ratio in the system of the gas engine has been extracted. 6EYG26 does the fuel injection control with the gas injector for the speed governing and the output control, and influence an air fuel ratio. Moreover, the fuel gas pressure to main chamber that is operated by the regulator according to load, influence an air fuel ratio. The response characteristic of each restrictor was investigated based on this block diagram (system identification examination).

- The response characteristic of air fuel ratio by injection duration
- The response characteristic of air fuel ratio by fuel gas pressure to main chamber
- The response characteristic of air fuel ratio by pressure in the supply manifold
- The response characteristic of pressure in the supply manifold by throttle valve opening

7.3 DESIGN OF LOSD PREDICTOR

Based on the characteristics of the engine system obtained from the system identification test was designed load predictor. The load predictor estimates fluctuation of the air-fuel ratio
corresponding to the response characteristics of the factors causing the air-fuel ratio variation due to the load variation, controlling the air-fuel ratio by the bypass valve operation.

Fig.19 shows control block diagram of load predictor.

Fig.19 Control block diagram of load predictor

In order to estimate the improvement of the air fuel ratio control by the load predictor, it was subjected to the simulation analysis in case of using the load predictor, based on the step load data with test engine without the load predictor. Fig.20 and Fig.21 shows the result. Converging time of the air fuel ratio was improved about 50% (Without the load predictor: about 9.0seconds, with the load predictor: about 4.5seconds).

7.4 LOAD FLUCTUATION ANALYSIS OF THE ACTUAL SHIP

In order to verify the effects of load fluctuations of the actual ship, it was examined test conditions of load variation data for navigation data from electric propulsion ship with diesel engine. Fig.22 shows the route of the electric propulsion ship with diesel engine.

Fig.22 Route of the domestic vessels

Interval 2 of the interval 1-4 which load fluctuation is large in particular was surveyed the characteristics of load fluctuation. Fig.23 shows the frequency spectrum and load fluctuation width of interval 2. The load variation range was determined by calculating the load on one engine from the whole load of the ship. From analysis of the frequency spectrum of the load variation range, the load variation due to waves has been found that the periodicity is high.

Fig.23 Frequency spectrum and load fluctuation width

7.5 VALIDATION OF AIR FUEL RATIO CONTROL FOR LOAD FLUCTUATION

The simulated load generator makes the validation of load predictor by a test engine (Interval2 described in 7.4). Fig.24 shows the comparison of the air fuel ratio with load predictor
and without it. According to the comparison result, fluctuation of the air fuel ratio with load predictor is obtained improvement of about 36%.

Fig.24 Effect of load predictor at load fluctuation of electric propulsion ship

8. CONCLUSION

The YANMAR EYG26L is the new gas engine in the YANMAR engine product family. EYG26L has very high efficiency and durability because it is based on the diesel engine proven as marine use. EYG26L is equipped with the sophisticated control technology to accommodate the fluctuation of the load and fuel gas calorie that is the technical issue of the gas engine for LNG fuel vessels.

YANMAR will continue to develop the marine gas engine to provide the solutions to our customer in the future.

9. NOMENCLATURE

\[ Q_{\text{fuel}} \] : Flow rate of fuel [Nm³/h]
\[ W \] : Engine output [W]
\[ H \] : Fuel calorie [J/Nm³]
\[ ETA_{th} \] : Thermal efficiency [-]
\[ Q_{\text{mix}} \] : Flow rate of air fuel mixture [Nm³/h]
\[ P_1 \] : Pressure in supply manifold [Pa]
\[ T_1 \] : Temperature in supply manifold [K]
\[ ETA_v \] : Volumetric efficiency [-]
\[ V_s \] : Swept volume [m³]
\[ N_e \] : Engine speed [min⁻¹]
\[ P_{fp} \] : Pressure to pre-chamber [Pa]
\[ \lambda_m \] : Excess air ratio in main chamber [-]

\[ \hat{y}_n \] : Predicted value
\[ a_i \] : Weighting factor
\[ y_{n-i} \] : Value of past
\[ k \] : Order

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