Development of Mitsubishi KU Series Diesel Engine

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The Mitsubishi KU 44 high-power diesel engine has been developed for an output range between 10 to 17 MW, based on the operating results of the KU 30 and KU 34, more than 200 sets of which have been delivered to domestic and foreign plants. The design of the KU 44 basically follows the lines of the KU 30 and KU 34, but a BMEP of 2.55 MPa at an engine speed of 514 rpm has been achieved to realize good fuel economy. The KU series diesel engines now cover the output range from 3 to 17 MW since introduction of the KU 44.

1. Introduction

Mitsubishi Heavy Industries, Ltd. (MHI) Yokohama Dockyard & Machinery Works mustered all its technical process, and successfully manufactured a KU 30 type experimental engine in 1985.

In 1986 the first KU type engine, namely 14 KU 30 engine, was put into practical use for the first time, and started operation as a co-generation power plant in our MHI Nagasaki Shipyard & Machinery Works. With the increasing demand of co-generation power plants in recent years, approximately 200 units of KU 30 engines have so far been supplied (as of February, 1997), 150 units of them still operating. Later in 1996, the low NOx type 18 KU 34 engine, equipped with the stratified fuel-water injection system, was developed on the basis of the long-term experience and operating results of KU 30 engines to meet with the need of high power range, and is operating successfully.

On the other hand, the KU 44 high-power engine has been developed in KU engine series, and is expected to be put in market as a large-scale power plant by the end of 1997.

This paper describes the features and the results of verification tests for reliability of KU series, mainly of the newly developed KU 44 engines.

2. Outline of KU engine

2.1 Main general specifications

The main general specifications of KU series engines are listed in **Table 1**.

The newly developed single diesel engine has the thermal efficiency of 44.1% at generator terminal, much higher than the thermal efficiency of other motors with the same output range, and excels in the economy of the plant. In some plants, the total thermal efficiency of over 70% has been obtained due to heat recovery through hot water and steam.

To cope with the environmental control for diesel engines, the newly developed engine uses the fuel injection system capable of applying the stratified fuel-water injection system developed by MHI. The adoption of this system allows the NOx at the engine outlet to get reduced to below 450 ppm (O_2: 13%). The system is already employed in KU 30 and KU 34 engines, showing successful operation.

2.2 Operational record of KU series diesel engines

The supply record under operation of KU series diesel engines is shown in **Fig. 1**.

About 148 units are under operation as of December, 1996, with the longest operating time being 80 000hrs; and 44 units more are to start operation within 1997. The KU series diesel engines are all operated continuously with 100% output for co-generation plants, and excluding the maintenance terms 2 or 3 times a year, their operating rate in some plants exceeds 97%, contributing largely to the cutting down on the expenses of the plant.

2.3 Structural features

Fig. 2 shows the configuration of KU series diesel engine.

The KU 44 engine is based on the design concept of KU 30 and KU 34 diesel engines, with improvements made on the basis of rich experience and operational results. Described below are the main structures of KU 44 diesel engine.

(1) Frame

The frame is a mono block structure composed of cylinder block, intake air manifold, cam case, and cam shaft drive case, with the holes drilled as the lubricating oil passages to

Table 1 Specifications of KU series engine

Engine name	KU 44				KU 34				KU 30			
Cylinder diameter (mm)	440				340				300			
Stroke (mm)	580				400				380			
Number of cylinders	12	14	16	18	12	14	16	18	12	14	16	18
Type	Four-cycle, trunk piston and water-cooled, vee-type constant pressure turbocharged diesel engine with air cooler											
Output at generator Terminal (kW)	11 000	12 850	14 650	16 500	6 400	7 450	8 550	9 600	3 750	4 350	5 000	5 650
Mean effective pressure (MPa)	2.55				2.45				1.95			
Firing pressure (MPa)	19.0				18.0				15.7			
Thermal efficiency (at generator terminal, %)	44.1				44.1				44.1			
NOx (O_2 13%, ppm)	Below 1 200				Below 950				Below 950			

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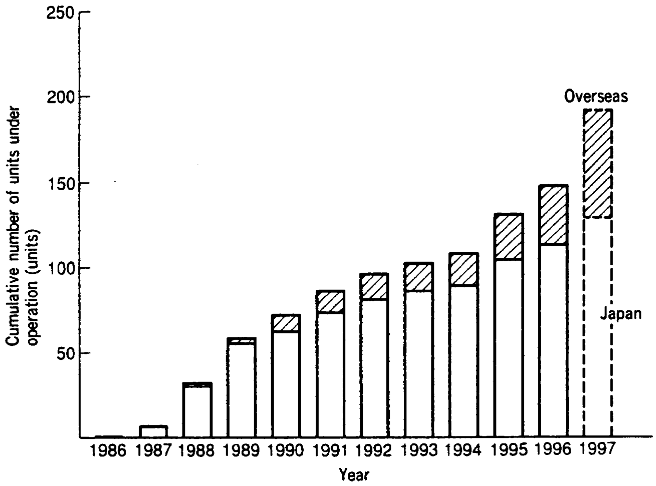


Fig. 1 Supply record under operation
The cumulative number of engines under operation in Japan and abroad is shown.

each section (making it pipe less), contributing to the reduction in number of parts and the improvement in maintainability.

The main bearing bolt adopts the tie-bolt system using the whole frame as a field of compressive stress instead of the conventional stud bolt system, drastically improving the reliability.

(2) Cylinder liner

The cylinder liner is made of special alloy steel at the upper part to withstand the high firing pressure, and of special cast iron partition structure at the lower part to provide excellent sliding property. Furthermore, the mating surfaces of cylinder cover, upper cylinder liner and lower cylinder liner are of tapered shape to provide high gas seal due to sufficient surface pressure.

The combustion chamber side of the upper cylinder liner is of special shape to prevent the polishing of the sliding surface with the piston, and this shape has been proved in KU 30 & 34 diesel engines to contribute to a drastic reduction in the consumption of lubricating oil. **Fig. 3 (a)** shows the structure of the anti-polish ring adopted in KU 34 diesel engine.

(3) Piston

The piston adopts the built-up type crown made of special alloy steel and piston skirt of nodular cast iron with high strength and toughness, while the piston ring sliding surface is subjected to special chrome-ceramic coating with high scuffing resistance.

(4) Connecting rod

Stamp forging is carried out at the large and small ends of the connecting rod, with the shape optimized through FEM analysis to allow thorough reduction of inertial mass. The horizontal partition structure with high reliability and stiffness is used for the large end, while special working is done on the contact surface to prevent fretting.

(5) Bearing

The bearing performance of the main bearing is improved by installing optimum counterweights to each crank throw. Furthermore, sufficient passage is made for the lubricating oil as a measure to prevent cavitation erosion in the bearing. The crankpin bearing has partial oil grooves to secure sufficient oil film thickness in order to prevent the wear due to the force of inertia of the crankshaft pin. [Fig. 3 (b)]

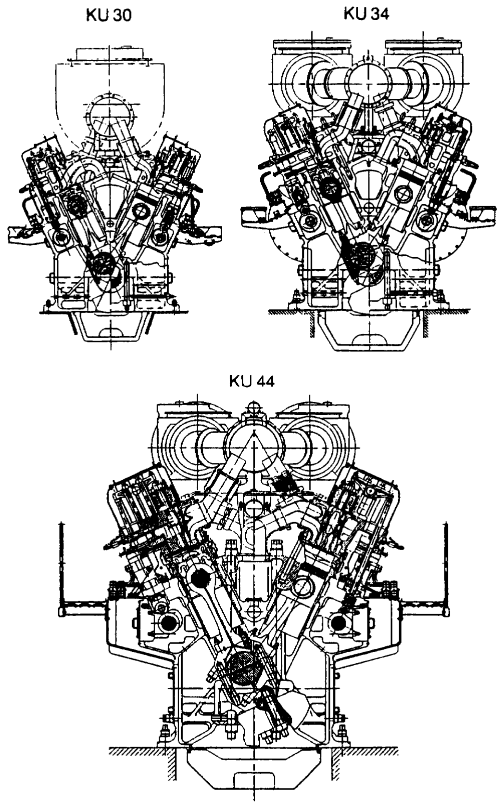


Fig. 2 Cross section of KU series diesel engine
The cross section of KU series diesel engine is shown.

(6) Cylinder cover

In order to reduce mechanical and thermal loads caused by high firing pressure the double-ceiling bore-cooling type cover made of special cast iron is used. [Fig. 3 (c)] Furthermore, the cylinder cover is sufficiently high, and has the shape capable of allowing appropriate flow of force to the gastight section of the cylinder liner, reducing the number of cover bolts to only 4 pieces.

(7) Crank shaft and cam shaft

The crank shaft, made of special alloy steel and subjected to stamp forging, has sufficient strength and stiffness due to fiber grain flow.

The cam shaft has fuel, exhaust and intake cams arranged in hydraulic shrink, each cam being adjustable at optimum timing. The running surface of cam is subjected to special surface treatment after carburized hardening to improve the reliability.

(8) Fuel injection system

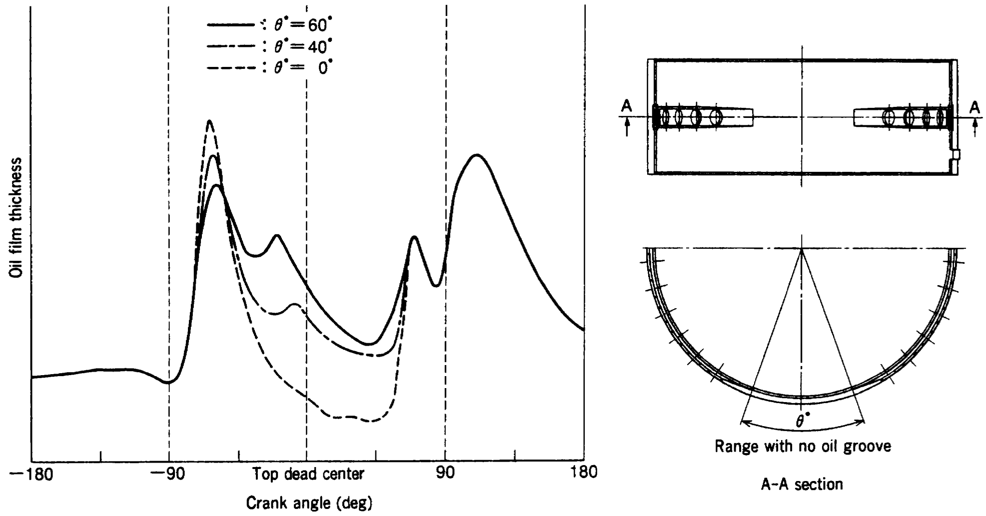
The fuel injection system has the injection pressure of 160 MPa, and has the injection period and heat receiving period shortened to improve the thermal efficiency.

The fuel injection pump is combined with the fuel pump driving device to make the structure simple.

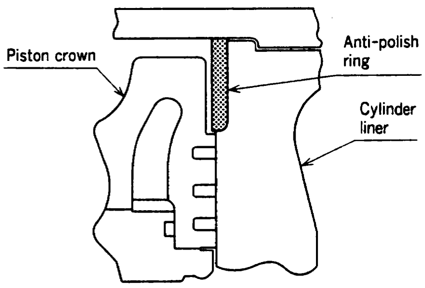
On the other hand, the plunger bottom has special structure so as to prevent the fuel drops from the plunger bottom of the fuel pump from getting mixed into the lubricating oil.

(9) Turbocharger

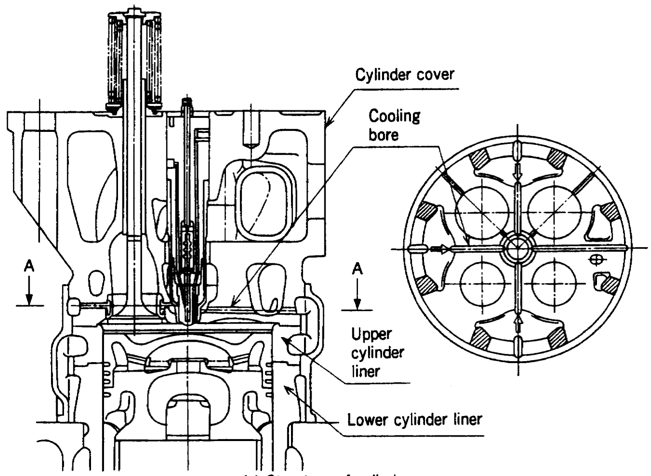
The newly developed diesel engine uses Mitsubishi high-



(b) Oil film thickness at crankpin bearing



(a) Structure of cylinder liner



(c) Structure of cylinder cover

Fig. 3 Structure of KU 44 diesel engine
Main structure of KU 44 diesel engine is shown. (a) Structure of cylinder liner equipped with anti-polish ring (b) Oil film thickness at crankpin bearing due to oil grooves (c) Double-ceiling bore-cooling type cylinder cooler.

performance, high pressure-ratio turbocharger MET-SH to ensure sufficient intake pressure at high output.

3. Verification of reliability

The KU 44 diesel engine has the highest speed of 514 rpm among the engines of the same level output, the mean effective pressure 2.55 MPa and the maximum firing pressure 19.0 MPa as the rated output. The high speed, high output and increased firing pressure not only cause the thermal load around the combustion chamber to increase, but also inflict remarkable influence on the strength and weight of all parts including the moving parts, calling for substantial verification at the time of design of each part. The KU 44 diesel engines have been developed on the basis of operational records of KU 30 and KU 34 series, and by making the effective use of evaluation technology. Described below is an example of reliability verification tests mainly of KU 44 diesel engines.

3.1 Temperature of main component parts of combustion chamber

The calculated temperatures of the main sections of combustion chamber such as cylinder cover, cylinder liner and piston crown are given in **Fig. 4**, where the temperatures are obtained through simulation after analysis of the actually measured temperatures of KU 30 and KU 34 engines, and are, therefore,

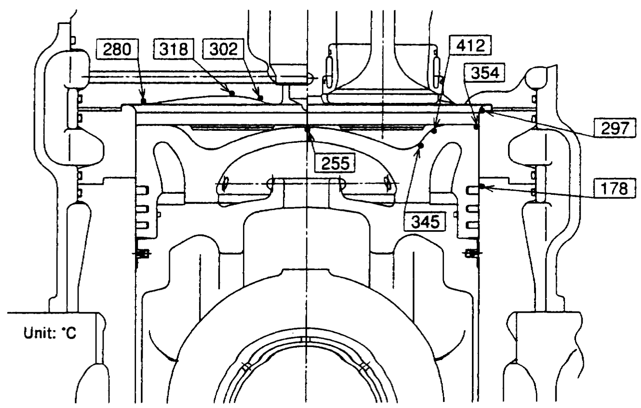


Fig. 4 Temperature around combustion chamber
Calculated temperatures around combustion chamber under full load are shown.

considered to be highly reliable. The temperatures conform to the record levels, and the temperature at top dead center of cylinder liner top ring is of favorable and appropriate level in view of corrosion resistance and lubricating performance.

3.2 Stress of main parts

The results of stress calculation of reciprocating parts including piston and connecting rod, and cylinder cover and

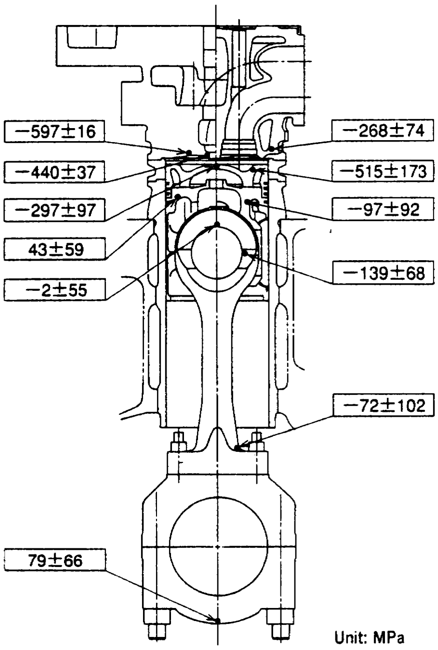


Fig. 5 Stress of main parts
Calculated stresses of main parts under full load are shown.

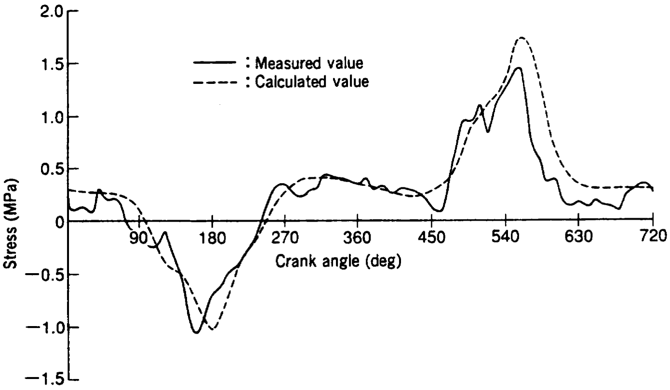


Fig. 6 Calculation and measurement stress of crankshaft
Comparison of simulated stress and measured stress is shown.

cylinder liner composing the combustion chamber are given in **Fig. 5**, indicating that the stress conforms to the record level of each material, ensuring substantially high fatigue safety factor.

On the other hand, it has been verified that the stress of fillet against deflection of crankshaft receiving rotational and bending force sufficiently satisfies the tolerance level by optimizing the fillet shape through FEM analysis. As for the stress during operation, it has been verified that the values obtained through the simulator of crankshaft analysis, developed by MHI, correspond well with the actually measured values. The calculated and measured values of stress at the crankshaft fillet of KU 34 diesel engine are given in **Fig. 6**.

3.3 Engine vibration

In order to study the engine vibration, analysis has been conducted on the characteristic frequency and vibration response to carry out evaluation of the engine including the installation stiffness. The stiffness of the engine body has been optimized to avoid the resonance of X-type and H-type vibrations at the rated speed of 514 rpm. Furthermore, the primary vibration response due to internal moment has been calculated to verify that the stress level conforms to the conventional record level.

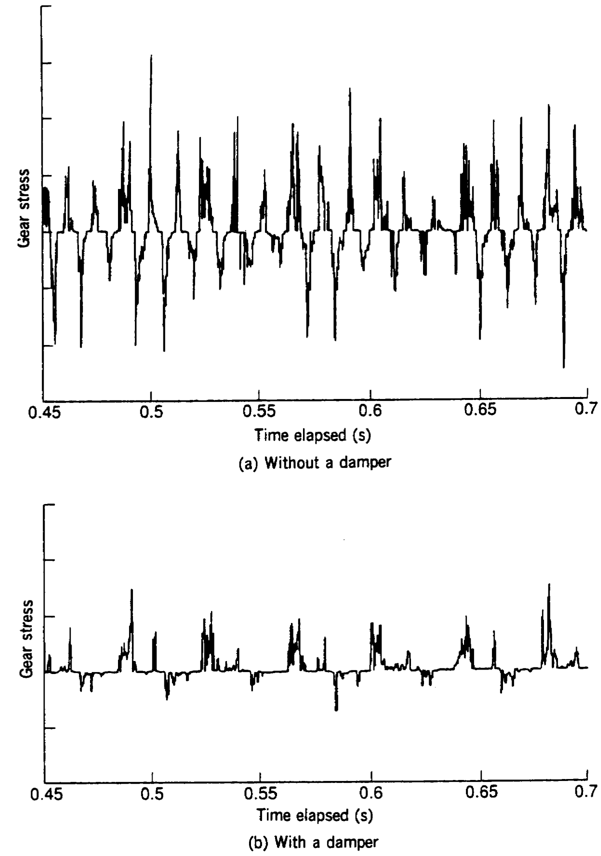


Fig. 7 Stress of camshaft gear
Comparison of gear stress with and without a damper by using non-linear time history analysis is shown.

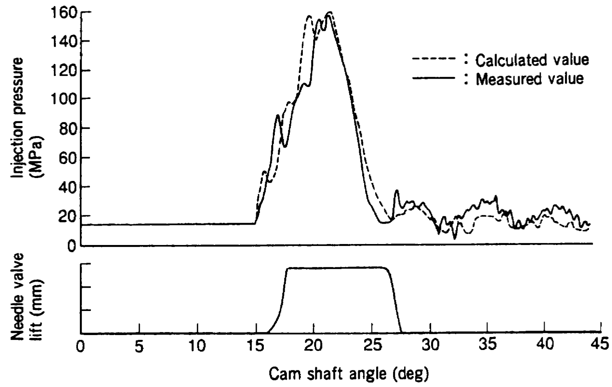


Fig. 8 Calculation and measurement of fuel injection system
Comparison between simulated and measured values is shown.

As for the cam shaft drive system, the reliability is verified through gear strength analysis using non-linear time history response analysis, a program developed by MHI. It has been decided, through the result of strength analysis using this program, to install a damper at the front end of the cam shaft. **Fig. 7** shows the comparison of calculated stress levels of the gear with cam shaft with or without a cam shaft damper, indicating a drastic reduction of gear stress by installing a damper.

3.4 Fuel injection system

Shortening of heat receiving period (main combustion period) is an important factor for reducing fuel oil consumption, which in turn calls for shortening the injection period by high-pressure, high-efficiency injection. And for this, the diameter and speed of the fuel injection pump plunger as well as the fuel injection valve and fuel injection pipe have been optimized. **Fig.** 8 shows the comparison of injection modes of simulation and measurement. The results obviously indicate that the target maximum injection pressure of 160 MPa and injection period of 20° (crank angle) have been achieved, with no secondary injection or cavitation occurred.

4. Conclusion

Description has so far been made on KU 44 engines, explaining mainly the features of KU engines and the results of reliability verification tests. With the KU 44 engines put on the market, a series of KU engines have been furnished to cover the output range of 3 to 17 MW per engine.

We are determined to make KU 44 diesel engines perfect at an early date in order to contribute to expanding the market for KU series engines and to meeting with the demands of customers through adequate follow-up of the operational records.