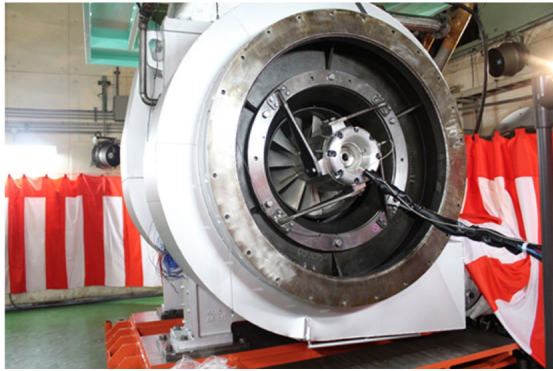


Energy Savings through Electric-assist Turbocharger for Marine Diesel Engines



KEIICHI SHIRAISHI*1

YOSHIIISA ONO*2

YUKIO YAMASHITA*3

MUSASHI SAKAMOTO*3

The extremely slow steaming of ships has become the mainstream on the back of the recent energy-saving trend. Turbochargers (super chargers) for marine diesel engines are generally driven only by exhaust gas energy. Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd. has developed an electric-assist system for large turbocharger for marine diesel engines, and verified high energy saving advantages in the low-load operating range of the engine. This paper reports the effect of an electric-assist system for turbocharger rotors with test results in two- and four-stroke engines.

1. Introduction

The ratio of fuel oil costs in ship operational costs has become nearly 50% with the recent price hike in fuel oil and the advancement of shipping operation streamlining. As a result, the reduction of fuel consumption in the total ship operational costs has become an important issue for shipping companies.¹ Many ships have begun to adopt high-efficiency propellers, waste-heat recovery systems of propulsion (main) diesel engines, friction reduction systems that generate bubbles under the ship hull, etc. Slow steaming is the easiest way to reduce fuel oil consumption. The ship's speed is proportional to the cube root of main engine output power. Therefore, the fuel cost will be reduced in proportion to the square of the speed reduction rate per operational distance assuming that the fuel oil consumption ratio of the main engine remains constant. For this reason, slow steaming at 30% or lower engine load is not uncommon these days.

Under such low-load operation, energy saving through waste heat recovery from the main engine is difficult, and the poor performance of a turbocharger driven by scarce exhaust gas energy becomes evident. For this reason, the two-stroke engine requires the combined use of the turbocharger and electric auxiliary blower under low-load operation. In addition, four-stroke engines tend to show a rather high exhaust gas temperature with air shortages under low-load operation, which may result in decreased reliability, increased fuel consumption, and more smoke caused by poor combustion.

The authors have verified the effect of increased air flow rate by electrically assisting the turbocharger rotation to improve engine performance under low-load operation in engine operating tests. As a result, a significant energy saving effect can be expected by reducing fuel oil consumption.

2. Outline of Hybrid Turbocharger

The power generating technology that leads the expanded exhaust gas after the turbocharger into a boiler to generate steam and drive a steam turbine has become common as an energy saving system of ships with marine diesel engines. This energy saving system utilizes waste heat and has been adopted in many ships while scarcely affecting the diesel engine performance. As shown in

*1 Senior Manager, Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*2 Mitsubishi Heavy Industries Marine Machinery & Engine Co., Ltd.

*3 Nagasaki Research & Development Center, Technology & Innovation Headquarters

Figure 1, for active heat recovery, a turbo compound system where high temperature and high pressure exhaust gas is partially extracted to a small exhaust gas turbine (power turbine) combined with a steam turbine to drive a generator and generate electricity (much like the steam turbine described above) is mainly used in large container vessels, etc. In this case, the exhaust gas amount extracted to the turbocharger turbine becomes small compared with a system without a power turbine, and the exhaust gas temperature and pressure are adjusted higher to gain power sufficient to compress enough air.

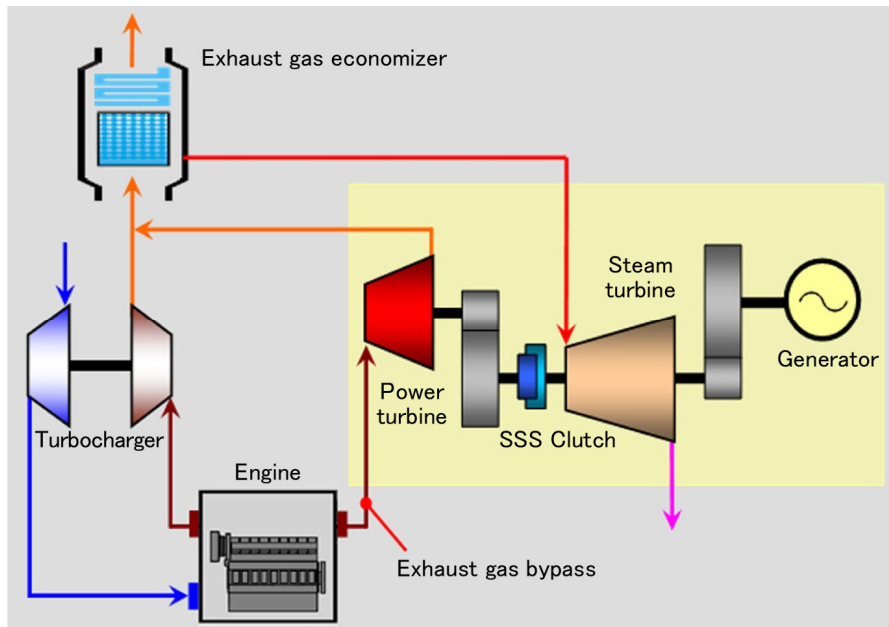


Figure 1 Turbo compound system (waste heat recovery system)

The turbocharger is generally constructed with the exhaust gas turbine and compressor placed at the both ends of a shaft. The turbine converts the exhaust gas energy to rotational energy, and drives the compressor to send compressed air to the engine. The rotational energy is huge, accounting for up to 50% of the engine output power. In the case of a hybrid turbocharger, a generator is coaxially and directly connected to the shaft, and the rotational energy is partially used for electrical generation. All of the exhaust gas exhausted from the engine enters the hybrid turbocharger turbine, and its energy is converted to the rotational energy of the turbocharger rotor. Some of the exhaust gas is used for the generator, and the exhaust gas temperature and pressure at the turbine inlet must be raised to ensure sufficient energy to compress the air. In other words, a hybrid turbocharger and an ordinary turbocharger with a power turbine affect the engine in a similar manner.

A turbocharger with higher efficiency gains more rotational energy from the exhaust gas energy, and compresses the required amount of air using less rotational energy. Therefore, the turbocharger allows more energy to be used for electric power generation. Recent high-efficiency hybrid turbochargers can supply sufficient amounts of air with sufficient pressure to the engine after using approximately 13% of the rotational energy for electrical generation.

A sectional view of the hybrid turbocharger is shown in **Figure 2**. A permanent magnet 3-phase AC synchronous generator is supported with the robust cast-iron shell. The rotor of this generator and the rotor of the turbocharger are directly connected with a diaphragm type flexible coupling. Even in the case of the large MET83MB model turbocharger, the maximum rotational speed is 10,000 rpm or higher, and the frequency of electric current approaches 700Hz. The current is rectified to DC current by a converter and converted by an inverter to 60Hz constant electric power to be connected to the electric power grid onboard. **Figure 3** shows an external view of the onboard inverter and converter. This converter is not a simple rectifier with diodes, but a synchronous rectifier with switching devices (IGBT) as shown in **Figure 4**. With the mode change of generating to motoring, the turbocharger rotor can be accelerated. In other words, an electric-assist function is possible, and the system has the advantages shown in the following chapter under low-load operation for both two- and four-stroke engines.

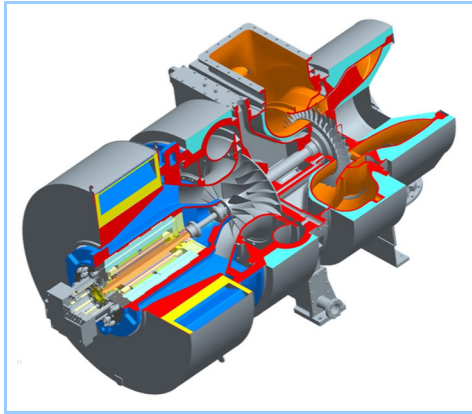


Figure 2 Sectional view of hybrid turbocharger



Figure 3 External view of inverter (left) and converter (right)

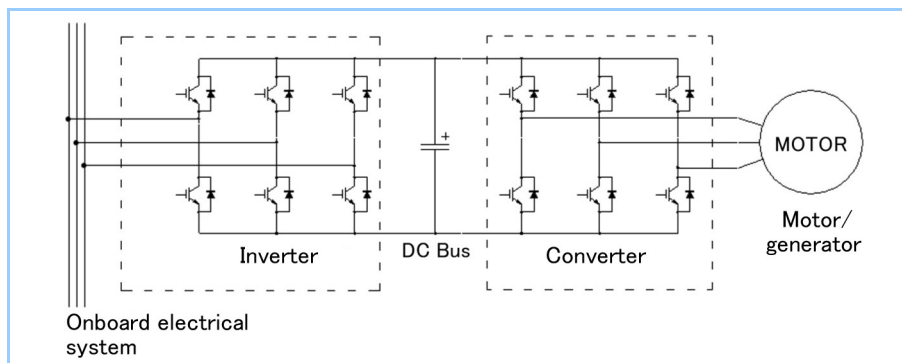


Figure 4 Bi-directional inverter/converter

3. Electric-assist Turbocharger in Two-stroke Engine

3.1 Problem of Electric Auxiliary Blower

In the uniflow scavenging air model two-stroke diesel engines, which is the main configuration of large-commercial-ship propulsion plants, the scavenging air flows into the cylinder when the piston is pushed down by combustion pressure, and moved down below the scavenging ports. At this timing the exhaust valve located at the cylinder upper position is already opened, and the air scavenges exhaust gas. The piston then moves upward to compress air. The scavenging air pressure should be raised enough to effectively replace the combustion gas in the cylinder with air. The turbocharger has the function to raise the scavenging air pressure, but the turbocharger alone cannot raise the pressure sufficiently under low-load operation with a small amount of exhaust gas energy. An electric auxiliary blower is provided at the compressor outlet of the turbocharger, and it is operated when the engine load is 30% or below.

The auxiliary blower performance, reliability and economic efficiency had not been very important because the engine operation at such a low load had been limited to the time of departing and arriving in port. Slow steaming has become the main stream of shipping for the reduction of fuel oil cost, and the continuous operation of the auxiliary blower is sometimes required. The auxiliary blower generally consists of a centrifugal blower and an induction motor operated at a constant speed, and it automatically turns ON and OFF with the change of engine scavenging air pressure. Therefore, the blower has a low efficiency and consumes a comparatively larger amount of electric power, while also requiring periodic maintenance. Although hysteresis, the scavenging air pressure difference to start and stop the auxiliary blower, is provided, the engine must be operated by avoiding the blower ON/OFF load range for the reliability of the motor.

3.2 Advantages of Electric-assist Turbocharger

The generator in a hybrid turbocharger can be used as a motor to work instead of an auxiliary blower by increasing the turbocharger rotational speed (variable speed operation) and increasing the scavenging air pressure of inlet air to the engine. The advantages compared with the auxiliary blower are as noted below:

- (1) Low electric power consumption with high efficiency

- (2) Continuous operation at the optimum scavenging air pressure at any engine load
- (3) Fuel oil consumption reduction of the engine

Next, the results of verification testing by operating real engines are shown below.

3.3 Test Results

The MET66MAG-VTI hybrid turbocharger is provided with a generator with a maximum output of 470kW, and it has an electric-assist function to accelerate the turbocharger rotor with external electric power. The turbocharger is mounted on a Mitsubishi type 7UEC60LSE-Eco two-stroke diesel engine, and operational testing was conducted. The test results of electric-assist are shown below.

Table 1 shows a comparison of engine fuel oil consumption and consumed electric power at 20% and 25% loads between a conventional auxiliary blower and the electric-assist turbocharger. At 20% load, the auxiliary blower consumed 86kW of electric power, and generated 0.46bar of scavenging air pressure. Next, the auxiliary blower was stopped and electric power was supplied to the motor/generator in the turbocharger. The consumed electric power was 66kW, which was 23% less than the blower, when the scavenging air pressure became the same 0.46bar. In addition, the fuel oil consumption of the engine with the hybrid turbocharger was reduced. The reason is believed to be the lower resistance of the air flow at the same scavenging air pressure and the increased air flow rate as the turbocharger outlet air did not go through the auxiliary blower.

The authors observed the change in performance by applying higher electric power than the auxiliary blower consumption to the hybrid turbocharger. When 100kW of electric power, which exceeded the auxiliary blower consumption by 16%, is applied at 20% load operation, the scavenging air pressure was raised to 0.54bar, and the fuel oil consumption of the main engine was reduced by 5.1 kg/h (1.85 g/kWh). On the other hand, 3.8 kg/h of fuel oil for the diesel generator is needed to generate the consumed extra 14kW compared with the auxiliary blower. The net fuel oil consumption reduction shrinks to 1.3 kg/h. The maximum reduction of total fuel oil consumption by applying what amount of electric power will be clarified in additional testing considering the effect of engine load, environmental temperature, etc.

Table 1 Results of electric-assist hybrid turbocharger

	20% Load (2760kW)			25% Load (3450kW)		
	86	—	—	103		
Auxiliary blower electric power (kW)	86	—	—	103		
Assist electric power (kW)		66	100		79	131
Scavenging air pressure (bar G)	0.46	0.46	0.54	0.66	0.66	0.73
Turbocharger rotational speed (rpm)	5860	6250	6700	6880	7250	7600
Flow rate change of main engine fuel oil (kg/h)	ref	-2.8	-5.1	ref	-1.4	-10.6
Flow rate change of diesel generator fuel (kg/h)	ref	-3.9	+3.8	ref	-4.7	+5.5
Total flow rate change of fuel oil (kg/h)	ref	-6.7	-1.3	ref	-6.1	-5.1
Converted main engine fuel consumption rate (g/kWh)	ref	-2.4	-0.5	ref	-1.8	-1.5
Change of gas temperature at turbocharger outlet (°C)	ref	-3	-27	ref	-8	-30

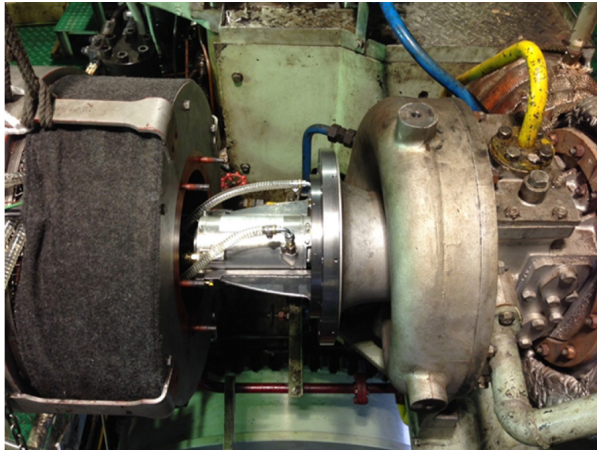
4. Electric-assist Turbocharger in Four-stroke Engine

In the case of a four-stroke engine, an auxiliary blower is generally not installed for low-load operation as air is naturally aspirated in the intake stroke with the descending piston. However, in addition to the fuel oil consumption increase, the degraded reliability resulting from increased thermal load of the engine must also be considered under low-load continuous operation. Furthermore, domestic vessels sometimes cause problems from transient black smoke when frequently leaving and arriving in port.

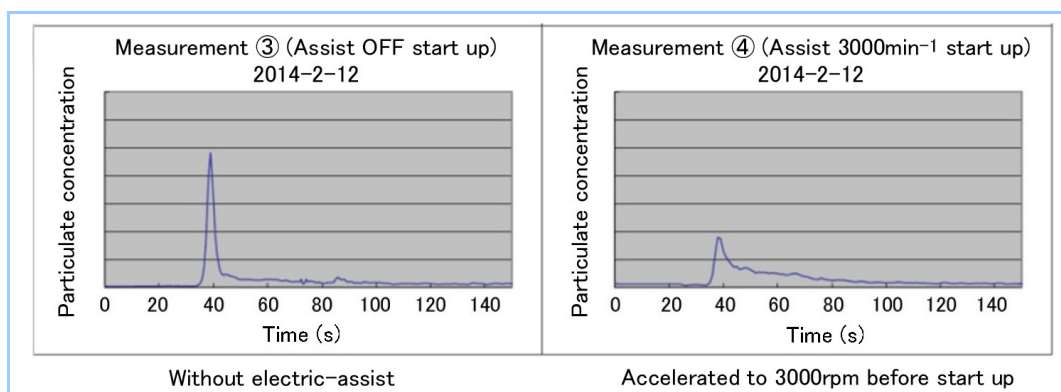
As such, the authors conducted verification testing to understand the effect of electric-assist on the turbocharger rotor used for a four-stroke engine using a test engine (660kW) of Akasaka Diesels Limited. **Figure 5** shows the high-speed motor installed on the turbocharger. This shows the general use high-speed motor connected to the turbocharger rotor for the test purposes, and it will not be sold on the market in this condition. **Table 2** shows the change in the fuel oil consumption ratio when the turbocharger rotor is assisted with the motor at the load of 25% and 35%. The results showed a greater reduction in the fuel oil consumption ratio of the engine than the applied electric power to the motor.

Table 2 Change in fuel oil consumption ratio with electric-assist turbocharger

	Assist electric power (Output ratio to engine [%])	Turbocharger rotational speed (rpm)	Boost pressure (bar G)	Fuel consumption reduction ratio (%)	Net fuel oil consumption reduction ratio (%)
25% Load	0 kW	14611	0.20	ref	ref
	1.3 kW (0.70%)	16000	0.25	2.7	2.0
184 kW	5.3 kW (2.90%)	18000	0.32	5.7	2.8
38% Load	0 kW	19240	0.37	ref	ref
	3.5 kW (1.40%)	21000	0.45	4.1	2.7
258 kW	5.9 kW (2.30%)	21810	0.49	4.2	1.9

**Figure 5 High-speed motor installed on turbocharger for four-stroke engine**

Next, the engine start up test was conducted by accelerating the turbocharger to the rotational speed of 3000rpm with the motor before start up to reduce the amount of black smoke generated at engine start up. **Figure 6** shows a comparison of particulate concentration in the exhaust gas between the cases of with and without motor acceleration. The particulate concentration in the exhaust gas was reduced to half or less by turning the turbocharger to pressure the intake air manifold of the engine before start up.

**Figure 6 Particulate concentration in exhaust gas for cases of with and without motor acceleration at engine start up**

5. Development of Electric-assist Turbocharger

If a ship equipped with a hybrid turbocharger also utilizes slow steaming for fuel oil cost reduction, exhaust heat recovery by generating electricity using a generator integrated in the turbocharger is not often carried out. Rather, the electric assist function, which is efficient under low-load sailing, will be executed more often. The amount of electric power required to operate the electric-assist function is almost the same as that of the auxiliary blower, and much less than the generated electric power of a hybrid turbocharger. As such, only the electric-assist function allows a smaller motor and inverter. The authors have developed an electric-assist turbocharger that only accelerates the turbocharger rotor. The drive shaft, which corresponds to the motor rotor, is directly connected to the turbocharger rotor. **Figure 7** shows an exploded view. The motor has no bearings,

which differs from conventional hybrid turbochargers, and lubrication and coupling are not required, thereby reducing maintenance costs. A cooling water supply is also unnecessary because the motor is air cooled by installing it at the inlet side of the compressor. **Figure 8** and the upper part of the top page of this report show the application of this motor installed on the large MET83MA turbocharger as a test. The turbocharger was verified to be able to start running by electric power only from a stand still condition, and the stator coil temperature was below the allowable limit even when accelerating the turbocharger rotor with the maximum electric power on a test bench.²

This electric-assist turbocharger provides a high-efficiency assist function substituting a conventional auxiliary blower by applying minimal changes to the standard turbocharger. In addition, the motor can be retrofitted to an existing turbocharger. Authors have already completed the fundamental drawings to convert six turbocharger models from MET48 through MET83 to electric-assist turbochargers.

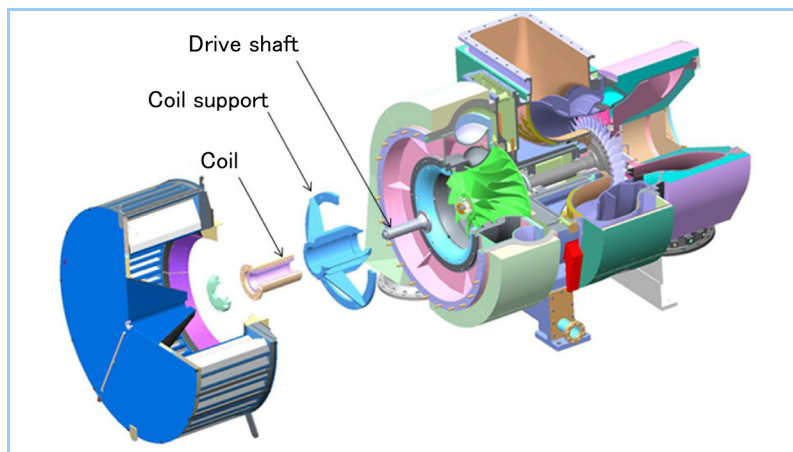


Figure 7 Exploded view of electric-assist turbocharger



Figure 8 Drive shaft and coil installed on MET83MA turbocharger

6. Conclusion

The electric-assist turbocharger was verified to reduce fuel oil consumption and black smoke at engine start up by testing the engine using the hybrid turbocharger with electric-assist function. The system can supply sufficient pressurized air substituting the auxiliary blower in the two-stroke engine, and control the turbocharger rotational speed. Further fuel oil consumption reduction and reliability improvement are expected by setting the optimal electric-assist power adjusted to the engine model and operating condition. The turbocharger with electric-assist function only was developed by connecting the drive shaft with magnets, and a bench test was conducted. This turbocharger is small in size and low in cost compared with the hybrid turbocharger, and is expected to expand future demand with its electric-assist function equal to that of a hybrid turbocharger. We would like to express special thanks to Akasaka Diesels Limited and Calnetix Technologies LLC for their cooperation in the testing of the four-stroke engine.

References

1. NYK Report 2014, Our Course (www.nyk.com/ir/library/nyk/pdf/2014_nykreport_04.pdf)
2. Shiraishi, K. et al., Electro-assist Turbo for Marine Turbocharged Diesel Engines, Proceedings of ASME Turbo EXPO 2014, GT2014-25667