Development of the New Generation Turbocharger RHZ Series

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In recent years, awareness of reducing CO_2 and fuel consumption has increased as a measure against global warming, and various technological developments such as improving the efficiency of internal-combustion engines and cleaning exhaust gas are being promoted. Under such circumstances, the Miller cycle is a technology that has been adopted in automobile engines. In order to meet the needs of our customers, IHI has developed the RHZ series, which can be used with Miller cycle engines, low-viscosity oil (oil grade 0W-12), has high performance, good transient response, and a lightweight, compact design. This paper introduces the merits of the RHZ series to engines and the technologies that support them.

1. Introduction

Countermeasures against global warming are increasingly required to suppress the escalation of natural disasters due to climate change, and the government and automotive users are becoming more and more conscious of the need to reduce carbon dioxide (CO_2) emissions and fuel consumption.

Therefore, automakers, which are customers of the IHI Group, are developing technologies to satisfy environmental regulations and levels of fuel consumption and drivability required by automotive users. In addition to technologies to improve the efficiency of conventional internal-combustion engines and make them produce clean exhaust gases, not to mention reducing the cost of these technologies, they are developing new technologies, including those for hybrid vehicles (HV), electric vehicles (EV), and fuel cell vehicles (FCV).

Given this, automotive internal-combustion engines are seemingly becoming obsolete. However, EVs become twice as heavy and expensive as internal-combustion engine vehicles if they have the same distance to empty due to the increased weight of the batteries and there are still many other challenges to solve. For this reason, it is safe to say that internal-combustion engines will remain in use for a while yet.

Amidst such a situation, looking at trends in internal-combustion engines, the development of downsizing turbocharged engines, which were the mainstream, having been adopted by European automakers, is on the decline and a shift to rightsizing turbocharged engines, which achieve an appropriate engine displacement for the vehicle class, without forcibly lowering the displacement is proceeding. The fuel consumption assessment modes have changed, and the "Worldwide harmonized Light vehicles Test Procedure (WLTP)" and "Real Driving Emission (RDE)," which is an exhaust gas regulation for driving on actual roads, have been introduced. High-load driving in urban areas is increasing, and it is becoming difficult to address this situation with downsized engines, which are less efficient at high loads. Therefore, rightsizing turbocharged engines, which provide high efficiency at low- and medium-speed ranges when combined with a Miller cycle with an optimized displacement, have been adopted. At the same time, engine oils are becoming increasingly less viscous for further reduction of fuel consumption, and in 2015, low-viscosity oils, such as 0W-12, were standardized in SAE J300[1]. Accordingly, turbochargers are required to have the functionality to handle them.

IHI is developing turbochargers for FCVs and turbochargers for internal-combustion engines. There is an ongoing shift from diesel engines to gasoline engines, especially for internal-combustion engines, because exhaust gas regulations are becoming more and more stringent. For this reason, IHI is developing turbochargers with a variable geometry system (VGS) for gasoline engines, which are used at higher temperatures than diesel engines.

This paper introduces the RHZ-series turbochargers, which can be used with a Miller cycle engine and low-viscosity oil (0W-12) and has a compact design and high performance.

2. Miller cycle engines and turbochargers

This section first describes Miller cycle engines, which are attracting attention as a fuel consumption reduction measure for automotive engines, and then it describes turbochargers.

Conventional gasoline engines (Otto cycle) have the same duration on the intake, compression, expansion, and exhaust strokes (i.e., compression ratio = expansion ratio). However, the Miller cycle is a heat cycle having a longer duration in the expansion stroke (expansion ratio) than in the compression stroke (compression ratio) with an adjusted intake valve closing time.

Miller cycle engines are classified into the late closing and early closing according to the opening and closing timing of the intake valve. Details are given in literature[2] in References and other literature, but to give the conclusion first, turbochargers have good compatibility with the early closing Miller cycle engines.

Figure 1 shows the engine operating lines and compressor maps. This shows the operating lines and compressor maps for turbochargers mounted on a conventional gasoline engine (Otto cycle) and a Miller cycle gasoline engine. From **Fig. 1** it can be seen that Miller cycle engines require a higher tip speed, enhancement operational range and a compressor with a higher pressure ratio than conventional Otto cycle engines.

The transient response time (time until the turbocharger energy is transmitted to the engine) is an important factor in improving the drivability and reducing the turbocharger size is important to improving the flexibility in the engine layout. The requirements for turbochargers, which involve various factors, are classified as follows:

(1) Able to contribute to reducing engine fuel consumption with a wide operating range (wide range), high pressure ratio, and high efficiency.
(2) Good transient response with a low-inertia rotor assembly and low-friction bearing. Also, turbochargers must be able to be used with a low-viscosity oil.
(3) Lightweight and compact design.

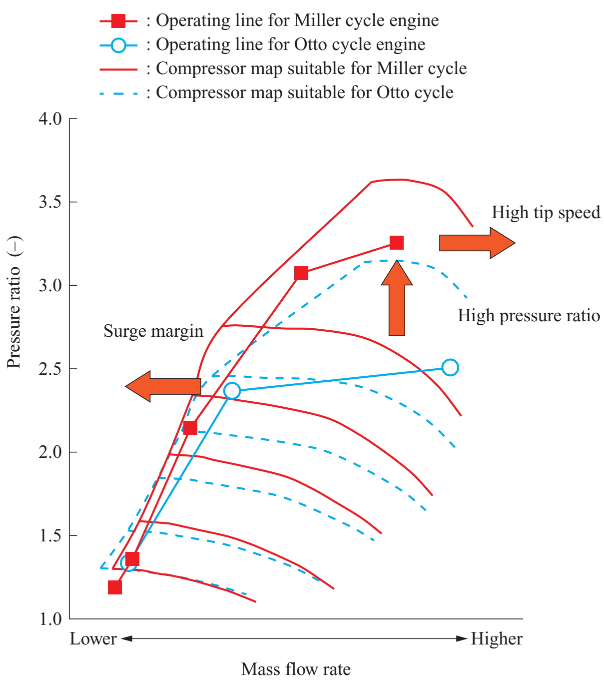


Fig. 1 Engine operating line and compressor map

3. Development of RHZ series turbochargers

Given these points, IHI is developing new models for its RHZ series. **Figure 2** shows the lineup for the RHF series and the lineup planned for the RHZ series. It compares the vehicle output power among different turbocharger models. The RHF series used to cover a wide range of vehicle outputs with one model and sometimes was not competitive due to over-engineering and high cost. Therefore, the RHZ series lineup was increased to enable optimal application (sweet spot matching) for different engines. This paper introduces the RHZ39, which is the flagship model.

3.1 Reduction of fuel consumption with increase in compressor impeller tip speed — Benefits which the RHZ series gives engines

To know what benefits can be obtained by mounting an RHZ39 turbocharger on a Miller cycle engine, as compared to an existing model (RHF4), the engine performance was estimated with a displacement of 2.0 *l* and power of 80 kW/*l*.

Figure 3[3] shows a comparison of fuel consumption at representative operating points. This shows the brake mean effective pressure (BMEP) in relation to the engine speed and the percentage of the specific fuel consumption (SFC) of the RHZ39 to that of the RHF4 in the Worldwide harmonized Light vehicles Test Cycle (WLTC), which is a next-generation fuel consumption measurement mode. As can be seen from **Fig. 3**, the SFC is lower at almost all operating points, showing reductions in fuel consumption.

Figure 4[3] shows the engine performance and turbocharger performance. Compared with the RHF4, the RHZ39 has a higher pressure ratio with an increased compressor impeller allowable tip speed of up to 630 m/s, having a great effect on the engine performance. This means that using the high pressure generated by the turbocharger, the Miller cycle engine can reduce CO_2 emissions without reducing the rated power or system dynamic response.

In addition to the increased allowable tip speed, the Miller cycle engine has 20% lower inertia with a compact compressor and turbine wheel, and has 40% lower mechanical loss with an optimally designed bearing, leading to an improvement in response by 0.36 s (engine operating range

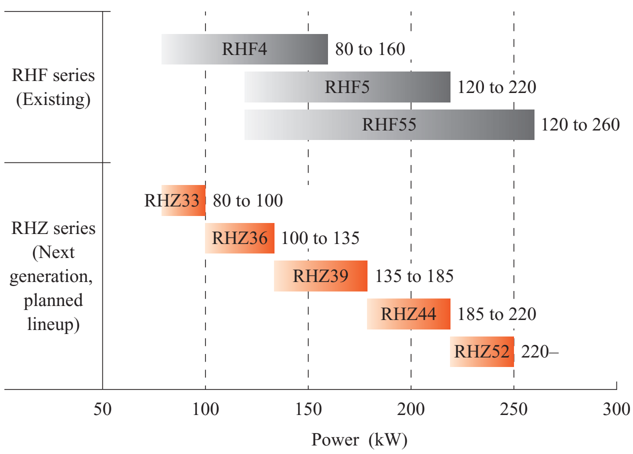
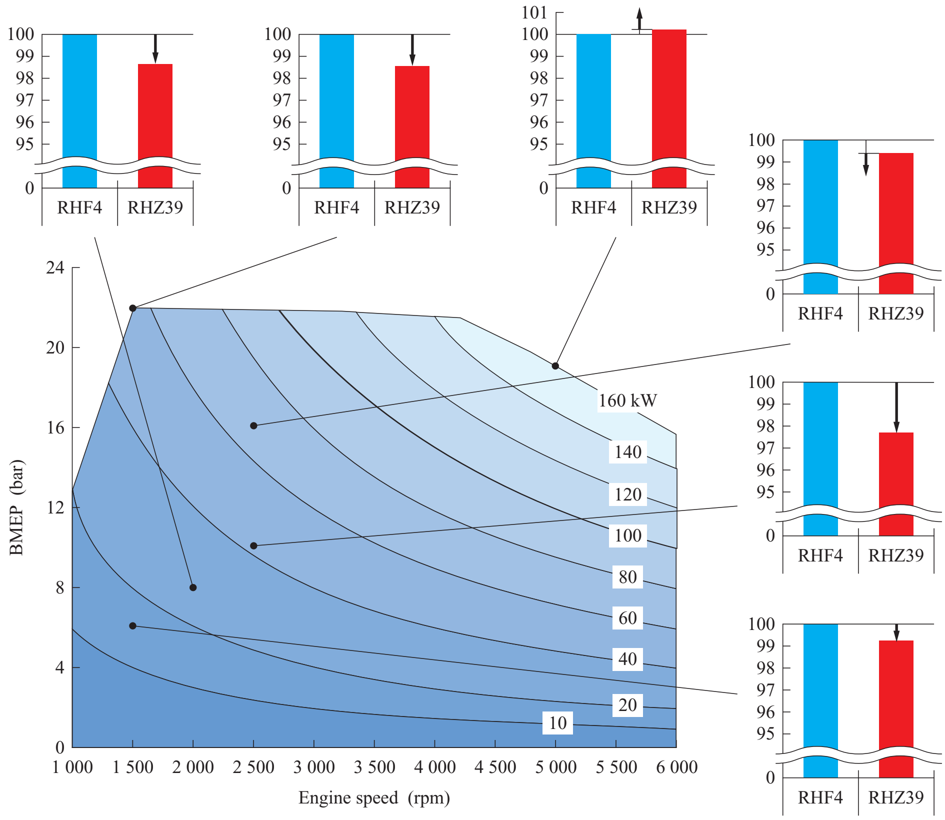
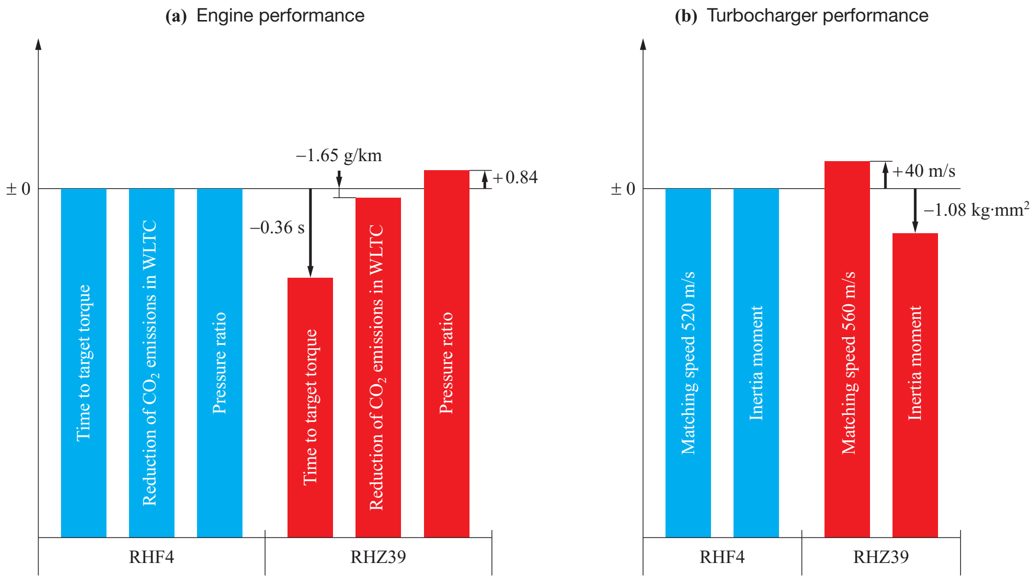


Fig. 2 Comparison of lineups between RHF series and RHZ series



(Note) The vertical axis of the bar graphs indicates the specific fuel consumption (%).

Fig. 3 Comparison of fuel consumption at representative operating points (WLTC)(3)



(Note) This shows the results of engine simulation.

Fig. 4 Engine performance and turbocharger performance(3)

from a torque at a BMEP of 2 bars and an engine speed of 2 000 rpm to a torque that is 90% of that torque).

As just described, the RHZ series can contribute to reducing engine fuel consumption with a wider operating range, higher pressure ratio, high efficiency, lower inertia, and optimized bearing. The following describes the representative items developed for the RHZ series to achieve this.

3.2 Path to achieving a wide range, high pressure ratio, and high efficiency

As previously described, turbochargers are required to have a wide range, high pressure ratio, and high efficiency so that they can be used with Miller cycle engines, which, however, often forces a tradeoff with strength. In addition, Miller cycle engines consume less fuel than Otto cycle engines, but produce less exhaust gas whose temperature is lower, which means that turbochargers are required to have a larger energy output with a smaller energy input when used with Miller cycle engines. Therefore, design optimization using model-based development (MBD) and new technologies were required.

Thus, a ramped hub using a new technology was adopted for compressors. **Figure 5** shows the ramped hub. The blade base on the outlet side of the compressor impeller tends to be subject to a higher stress if arranged on the side where an adequate surge margin can be ensured and the performance can be improved. At the same time, if the thickness is increased on the back face of the impeller, the stress on the boss (turbine shaft insertion part) increases, but with a ramped hub, the thickness is increased with the blade base on the outlet side of the compressor impeller inclined, thereby ensuring a wide range with a suppressed increase in the stress on the boss.

Figure 6 shows the compressor maps for the existing model (RHF4) and the RHZ39. The horizontal axis indicates the compressor flow rate in the standard state, and the vertical axis indicates the compressor pressure ratio. The contours in the figure indicate the iso-efficiency lines for the RHF4 and RHZ39, along with the operating points for the case where a turbocharger is mounted on a Miller cycle engine. From **Fig. 6**, it can be seen that the surge margin, high pressure ratio, and high efficiency at the normal operating points have increased.

Figure 7 shows a cross-sectional view of the turbine wheel. With regard to turbines, the cross-sectional shape of the blades was changed from one in which the blades extend straight radially to one in which the blades are bent. This reduced the loss at the inlet of the turbine wheel (vortex flow on the hub side), which provides smooth flow at the outlet, thereby reducing the loss at the diffuser. Also, the volume of the housing was reduced, thereby increasing the kinetic energy of the exhaust gas at the turbine inlet.

Figure 8 shows a comparison of the turbine power between the existing model (RHF4) and the RHZ39. From **Fig. 8**, it can be seen that the power (performance) of the RHZ39 is higher than that of the RHF4.

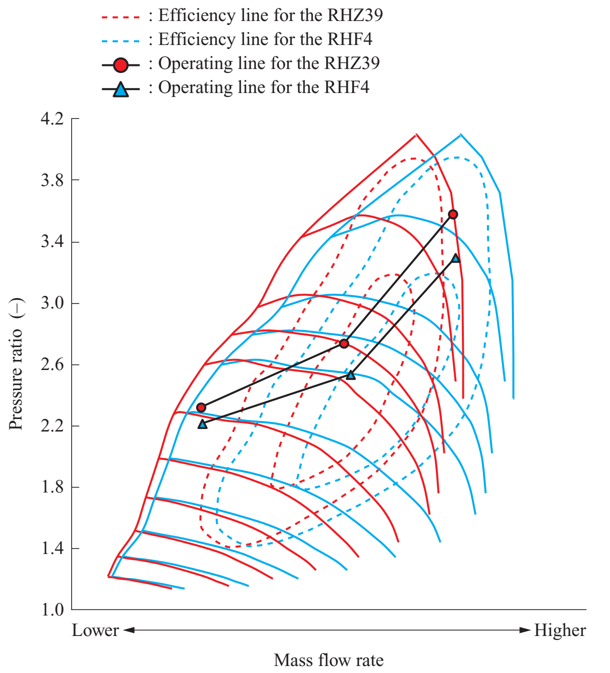


Fig. 6 Compressor map of existing model (RHF4) and RHZ series

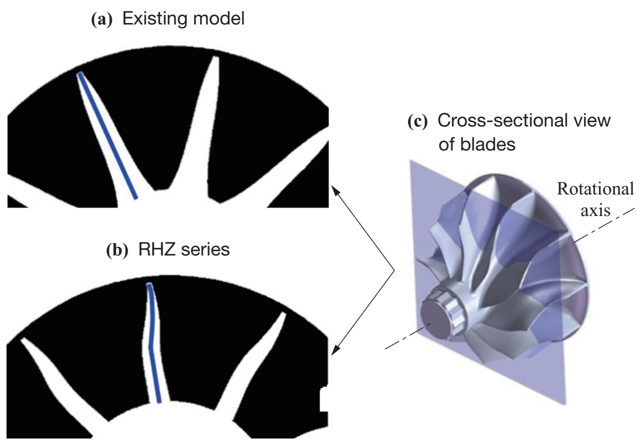


Fig. 7 Turbine wheel cross section

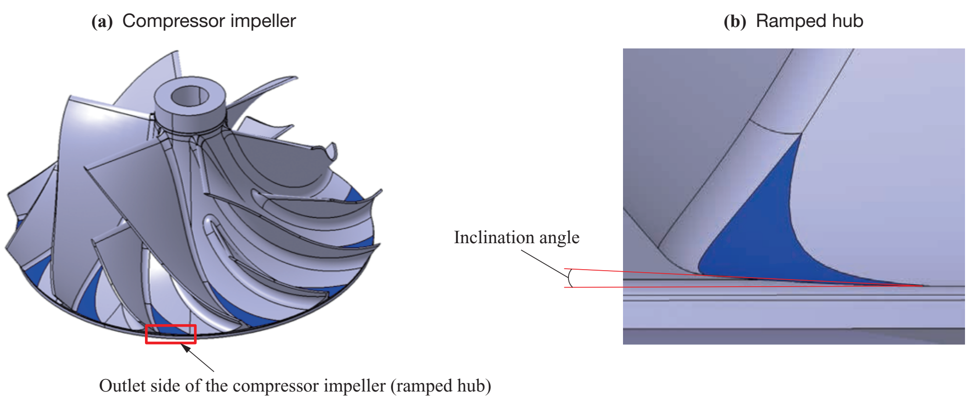


Fig. 5 Ramped hub

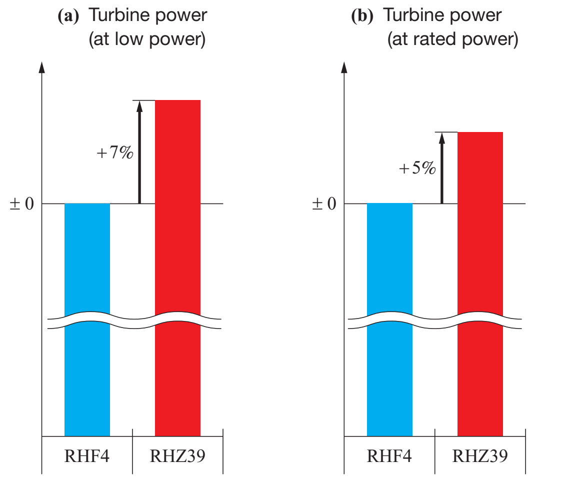


Fig. 8 Turbine power of existing model (RHF4) and RHZ39

3.3 Low rotor assembly inertia and low bearing friction

When mounting a turbocharger, transient response is important to eliminating the turbo lag (time lag from the demand for acceleration via accelerator pedal operation to when the vehicle starts to accelerate). Therefore, the RHZ series has a shorter shaft length than the RHF series and it employs a mixed flow compressor impeller and turbine wheel with reduced diameters, thereby reducing the inertia by 20% with a higher tip speed. **Figure 9** shows comparisons of the inertia and bearing loss. In **Fig. 9-(a)**, the vertical axis indicates how much the total inertia of the compressor and turbine was reduced from the existing model.

In addition, **Fig. 9-(b)** shows the mechanical (bearing) loss. At a turbocharger speed of 150 000 rpm, the bearing loss was reduced by 40%. The bearing loss was reduced by decreasing the shaft diameter.

Decreasing the shaft diameter also increased the bearing speed to 630 m/s when converted to an impeller tip speed. This may be a disadvantage in terms of rotational stability because the shaft stiffness decreases as the shaft diameter decreases, but the total rotor length was decreased, from the existing model, to compensate for the stiffness, thereby achieving a good balance between mechanical loss and rotational stability.

In addition, the bearing material was changed. Details are given in literature(4) in References. For the RHZ series which uses low-viscosity oil, the material containing aluminum (Al), silicon (Si), manganese (Mn), and Zinc (Zn) as additive elements was used as the bearing material so as to ensure adequate seizure resistance and heat resistance for the bearing. This improved the heat resistance by 100°C over the existing model.

3.4 Lightweight, compact design

Another remarkable point is that the RHZ series has a compact design. Being compact and lightweight leads to reduced fuel consumption. The RHZ series has achieved this with a reduced distance between the back faces of the turbine and compressor (Lb).

Figure 10 shows a comparison between the RHF4 and RHZ39. As shown in this figure, the RHZ39 has a smaller Lb than the RHF4 by 10%.

Figure 11 shows a comparison of the distance between the back faces of the turbine and compressor Lb between the

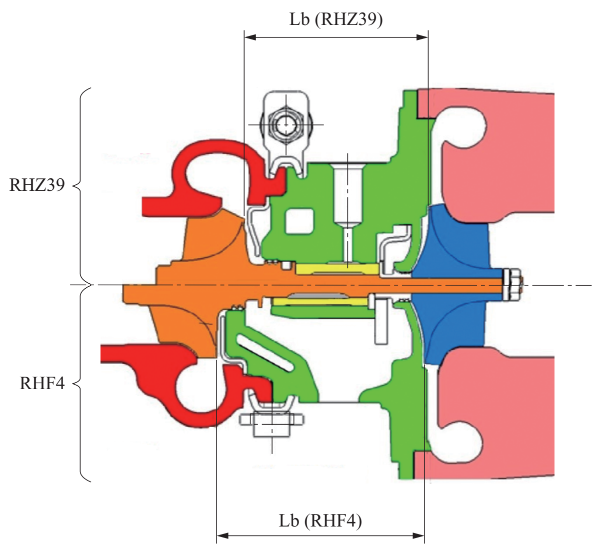


Fig. 10 Comparison between RHF4 and RHZ39

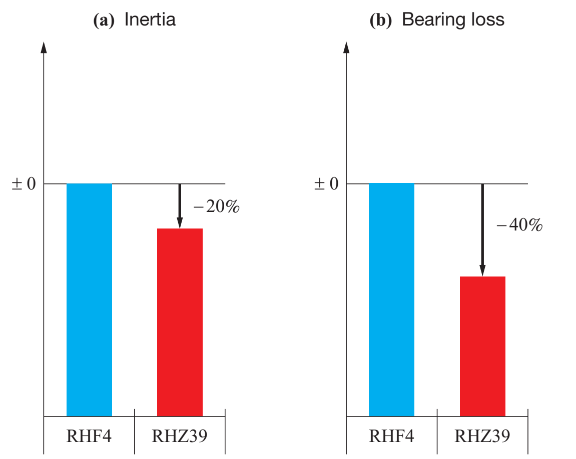


Fig. 9 Inertia and friction loss comparison

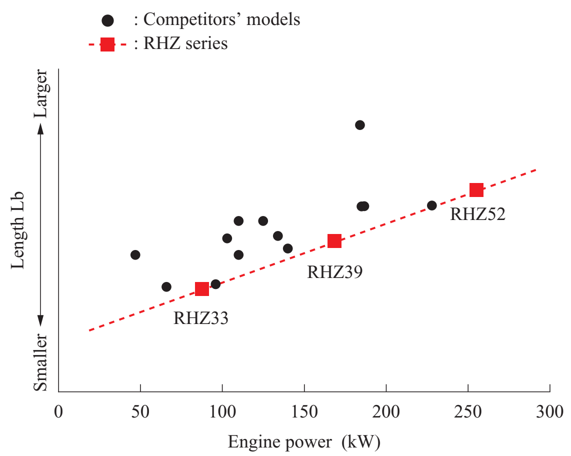


Fig. 11 Comparison between RHZ series and competitors' models regarding length Lb

RHZ series and competitors' models. From this figure, it can be seen that the RHZ series has a more compact design than competitors' turbochargers in the same power range.

Enhanced analytical accuracy of shaft vibration, enhanced criterion accuracy for bearing clearance, and the latest tolerance analysis technology, all of which are based on our long accumulated know-how, has enabled limit design and provided a shorter shaft length. Although there was a concern that the reduced shaft length could deteriorate manufacturability, adequate manufacturability was able to be ensured through cooperation with the production department and suppliers.

4. Conclusion

This paper has introduced the RHZ series, which is a new generation of compact, lightweight turbochargers with high performance and transient response that can be used with Miller cycle engines and low-viscosity engine oils (oil grade 0W-21), by exemplifying the RHZ39.

The high pressure generated by these turbochargers allows Miller cycle engines to have reduced CO_2 emissions without reducing the rated power and system dynamic response.

To address environmental regulations that are becoming more and more stringent year by year, the IHI Group will work together to develop new technologies with the aim of realizing a CO_2 emission-free, recycling-oriented society and making social contributions.

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