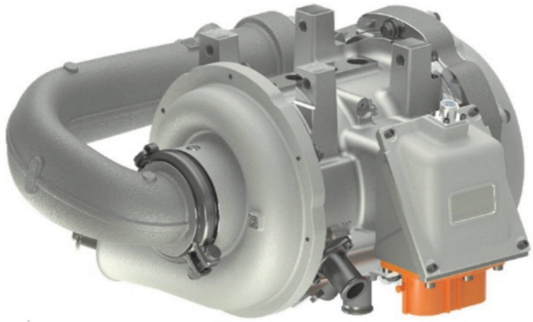
Development of Air Compressors for Fuel Cells



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In response to the expanding fuel cell market, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. has newly developed an electric centrifugal air compressor (motor output: 45 kW) for Fuel Cell (FC) systems with a net output exceeding 200 kW, in addition to one (motor output: 30 kW) for FC systems with a net output of 150 kW. Available in two configurations, a two-stage (two-stage compressor) type and an expander (single-stage compressor + turbine) type, this product has improved efficiency and can meet diverse customer requirements. In the development of this product, new technologies have been introduced, such as a lightweight and highly rigid rotor with a hollow journal, oil-free air bearings, a high-efficiency compressor, and a high power density motor with an improved motor stator/rotor design. This report introduces these efforts.

1. Introduction

Amid the global trend toward decarbonization, automobiles have been increasingly electrified. Electric vehicles (EVs) are a promising option, but their increased weight and long recharging times due to larger batteries have become issues. Particularly for commercial vehicles, which require high output, the weight of the battery limits payload capacity, and the long charging time reduces their usability. In addition, a smaller driving range due to reduced battery performance is a problem in cold climates.

On the other hand, fuel cell (hereinafter referred to as FC) systems that operate on hydrogen can be refueled in a short time, and are well-suited for commercial vehicles and heavy-duty trucks. In recent years, output of FC systems has been increasing, and systems with a net output of over 200 kW have appeared. In addition, the use of hydrogen fuel results in zero CO_2 emissions, and can be derived from renewable energy sources to further reduce environmental burden. At the same time, development of hydrogen stations is essential for the widespread use of FC vehicles, and costs and regulatory compliance are issues to be addressed. Still, the advantages of FC will be maximized as the infrastructure is developed.

Against such a background, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (hereinafter referred to as MHIET) has developed an air compressor for FC systems with a net output exceeding 200 kW, contributing to improved efficiency and lower environmental impact by FC vehicles and generators.

2. Demand for air compressors for FCs with net output exceeding 200 kW

In the past, air compressors were auxiliary equipment that supplied required compressed air flow. However, with the recent increase in output of FC systems, air compressors are no longer auxiliary equipment but are viewed as part of the main equipment that determines performance and economy of the entire FC system. In other words, efficiency, reliability, and lightweight of the air

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compressor are directly linked to an increase in output and system efficiency in vehicles and generators equipped with FC. The air compressor has become a core component of the FC system.

To increase output of the FC system, increasing motor output of the air compressor and compressed air flow rate is essential. However, increasing air flow rate also leads to issues such as a greater power consumption and increased load on the bearings and motor components. Therefore, advanced technology to increase output while maintaining efficiency and reliability is needed. Accordingly, MHIET has conducted various analyses of the following needs for air compressors for FC systems with a net output exceeding 200 kW.

(1) Available in two types: two-stage and expander

Two types of FC systems are used on the current market, a two-stage compressor type (hereafter referred to as "two-stage type") and a compressor + power recovery turbine type (hereafter referred to as "expander type"). As such, flexibility to match the customer's system configuration is needed. In response, MHIET sought to create a design that could be used as either a two-stage type or an expander type on the same platform.

(2) Higher power density motor

For increased air compressor output, a higher output from the motor is needed. Generally, this higher motor output is addressed by enlarging the motor. In this development however, increasing motor power density by improving the motor cross-section and reinforcing cooling, without changing motor size, was targeted. As a result, a compact design that minimizes impact on the customer's system configuration/layout was possible.

(3) Higher efficiency

Net and gross output of the FC system assumed by MHIET is shown in **Figure 1**. The air compressor and inverter consume power supplied from the gross output of the FC system, and their power consumption is estimated to be approximately 20% of gross output, depending on the system efficiency. Therefore, reducing power consumption of the air compressor and inverter is considered to greatly contribute to increasing net output of the FC system and improving system efficiency.

Loss analysis of an inverter and air compressor is shown in **Figure 2**. Since aerodynamic loss is the largest factor affecting efficiency of air compressors, reducing such loss is essential. To efficiently compress a large flow rate of air, a design that reduces aerodynamic loss and optimizes the amount of cooling air was attempted. In addition, SiC-MOSFET power devices were employed in the inverter to improve the conversion efficiency, thereby increasing the energy efficiency of the entire system. In this way, higher efficiency of the air compressor and inverter is considered to directly lead to improvement in the overall efficiency of the FC system.

(4) Improved reliability

The air compressor uses oil-free air bearings. Ensuring the durability of these bearings is extremely important, so the rotor weight was reduced to decrease bearing load, which in turn contributed to improved reliability. The air compressor is expected to operate at a maximum of 800 Vdc, so the insulation design and thermal protection of the motor stator (hereinafter referred to as "stator") are important. In addition to insulation reinforcement, a temperature feedback function with a thermistor to control the temperature during operation was added to ensure reliability of the stator.

As indicated by these approaches, today's air compressor is, as a core component of the FC system, an element whose high efficiency, power density, reliability, and compactness determine the performance of the entire FC system. MHIET contributes to the performance improvement of high-power FC system by developing high-power/high-efficiency air compressor.

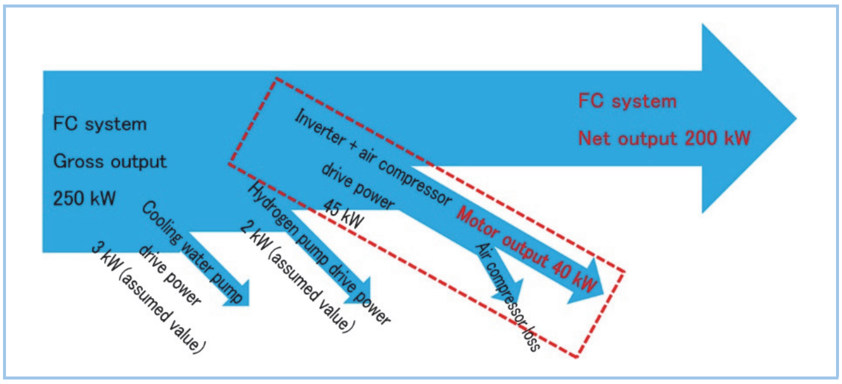

Figure 1　Schematic diagram of FC system net/gross output

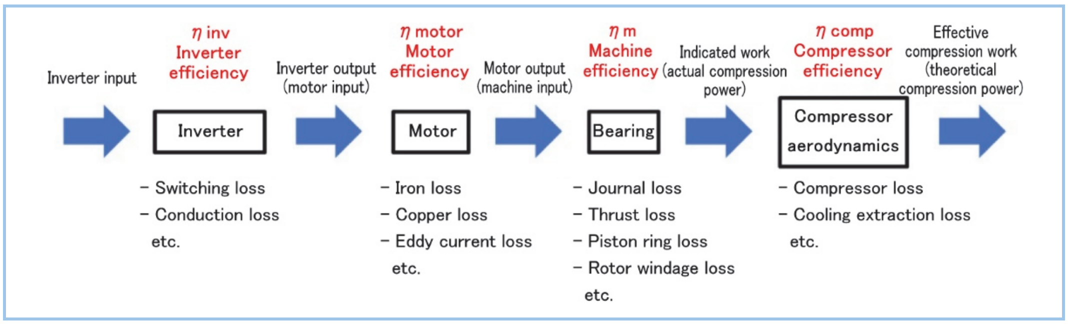

Figure 2　Loss analysis of inverter and air compressor

3. Air compressor (rated output 45 kW) for FC systems with net output exceeding 200 kW

The air compressor developed at this time incorporates new technical devices to realize the needs described in the previous chapter. Features of the air compressor for FC systems with net output exceeding 200 kW are shown in **Figure 3**. This chapter introduces the elemental technologies used and details the technical features and improvements of each.

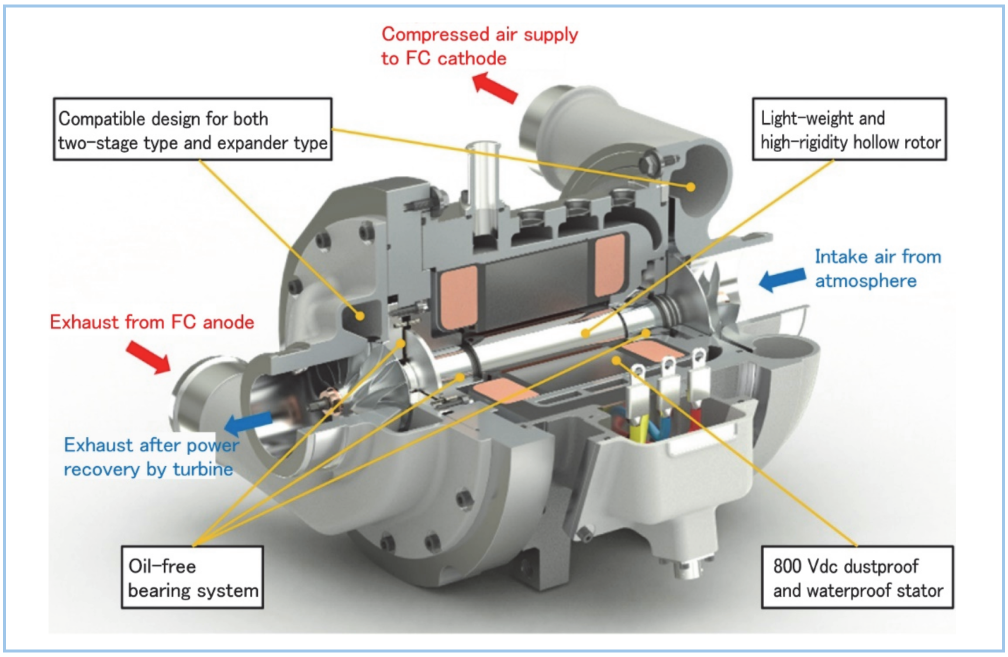

Figure 3　Features of air compressor for FC systems with net output exceeding 200 kW

3.1　Compatible design for application in both two-stage type and expander type

The air compressor developed this time is available in two configurations, a two-stage type and an expander type. Outer appearance of each type is shown in **Figure 4**. Operating range of the two-stage type and of the expander type, as well as the assumed operating points (rated and partial-load) for an FC system with a net output exceeding 200 kW are shown in **Figure 5**.

Components of the developed air compressor are shown in **Figure 6**. Based on the concept of separating fixed sections from variable sections, standard parts for the stator, rotor, and surrounding housing and individually optimized aerodynamic parts such as the compressor wheel were used so the same platform could be used for either a two-stage type or an expander type. The two-stage type can be used for a wider operating range while the expander type can be used in a limited operating range with high efficiency. By adopting both types, the most appropriate type can be used for each application to satisfy diverse customer requirements in a flexible manner.

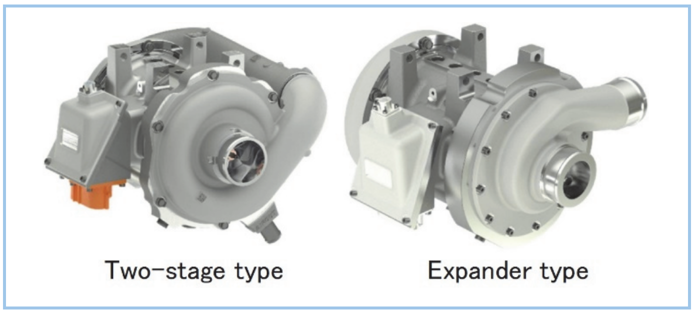

Figure 4 Air compressor (output 45 kW) for FC systems with net output exceeding 200 kW

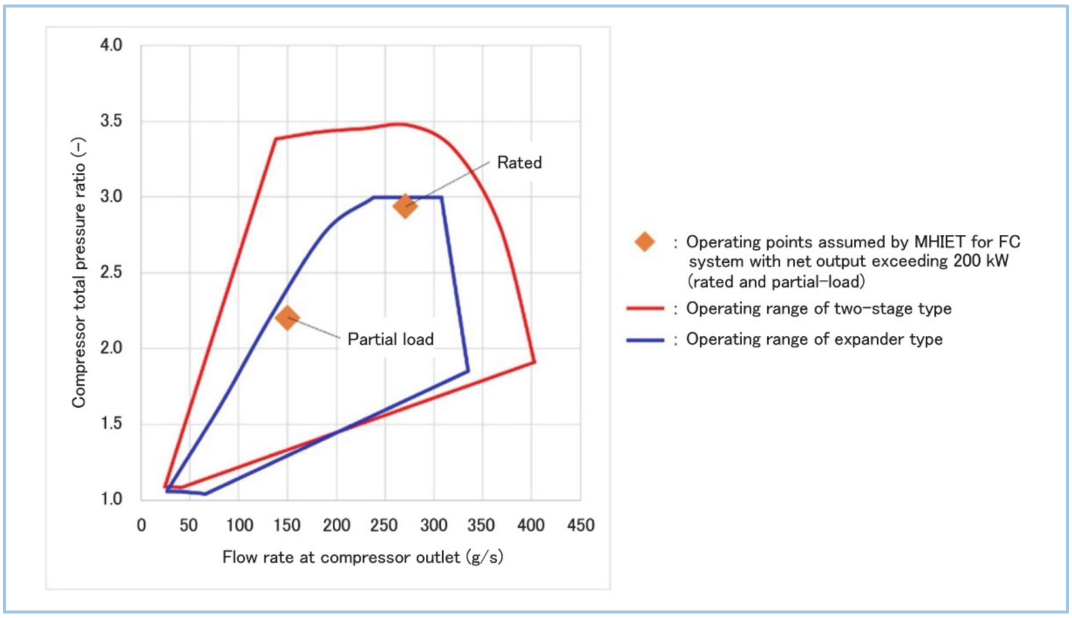

Figure 5 Operating range of the two-stage type and the expander type

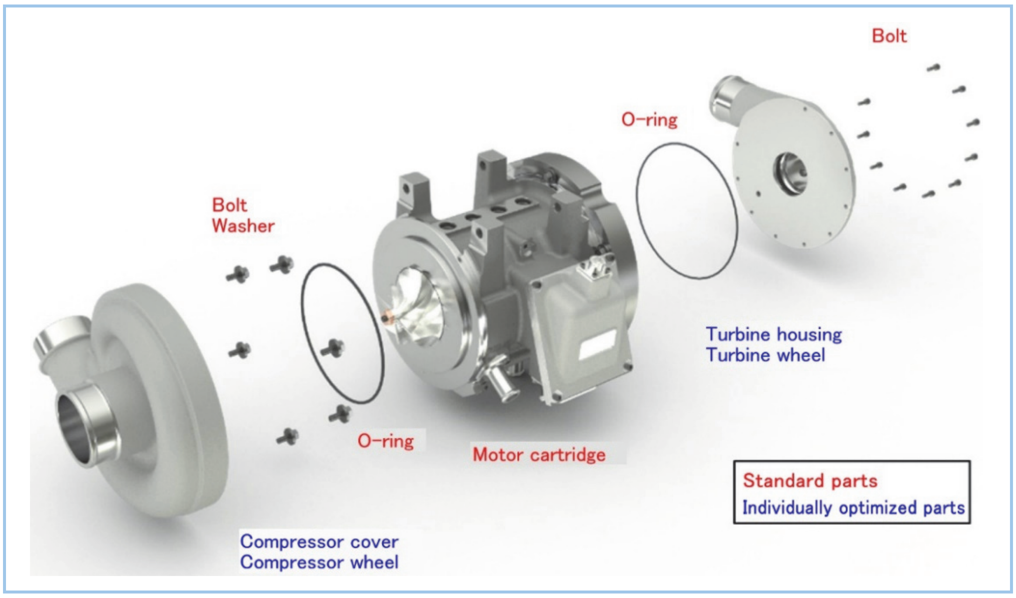

Figure 6 Separation of fixed sections from variable sections of air compressor

(1) Two-stage (two-stage compressor) type

The two-stage type has compressors placed at both shaft ends of the motor and air is compressed in two stages. This design achieves a high pressure ratio without reducing aerodynamic efficiency by decreasing the pressure ratio per stage, thus enabling a large air supply flow rate. In addition, this type eliminates the need for an external cooling air supply, contributing to simplification of the overall design of the FC system. The two-stage type can be applied over a wide operating range, facilitating stable performance and is suitable for applications requiring versatility.

(2) Expander (single-stage compressor + turbine) type

The expander type has a single-stage configuration that incorporates a turbine for power recovery in addition to the compressor. This system recovers air energy discharged from the FC system, and can reduce power consumption. The effect of power recovery at the assumed operating points (rated and partial-load) is shown in **Figure 7**. Improvement in COP (coefficient of performance) from 0.68 to 0.82 at the rated point and from 0.70 to 0.80 at the partial-load point by improved power recovery in the turbine could be confirmed. This improvement in efficiency contributes to better energy efficiency of the entire FC system.

The expander type (single-stage compression + turbine) has a narrower operating range than the two-stage compression type, but is better suited for specific applications which require high efficiency. As such, it can satisfy the needs of customers who require maximum efficiency under limited conditions.

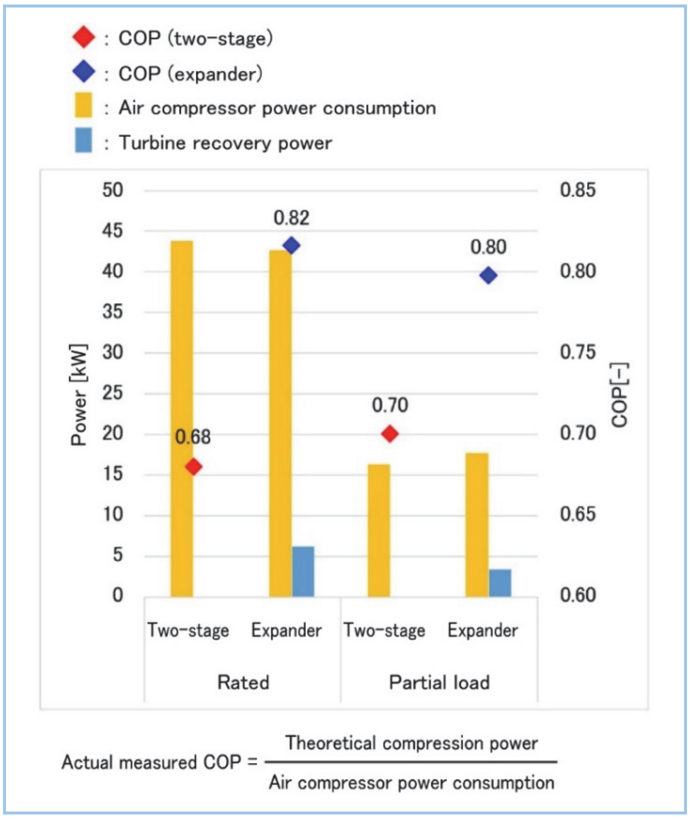

Figure 7 Results of power recovery

3.2 800 Vdc dustproof and waterproof stator and cooling design

Air compressors by MHIET utilize a stator with two-pole distributed concentric winding, which is suitable for high-speed rotation and can be produced in an automated manner. The winding specifications and stator/rotor cross-sectional shape design were improved to increase motor output. By optimizing the magnetic gap and improving the cooling capacity as described in the following sections, in addition to increasing the slot area and the magnet amount, output could be increased 1.5-fold compared to the previous model without changing the outside diameter or thickness.

As measures related to insulation to handle 800 Vdc, the thickness of the inter-phase and intra-slot insulation papers is increased to reinforce turn-to-turn insulation, phase-to-phase insulation, and phase-to-ground insulation, in addition to the winding enamel coating. Furthermore, the entire stator is molded after forming the coil ends to enhance the insulation effect. The molding process also contributes to the stator's dustproof and waterproof properties.

When increasing power density of the motor, the cooling function must be further strengthened to control heat generated from the increased motor current. The cooling design of the motor mainly uses high thermal conductivity molding materials to improve cooling efficiency. Heat transfer efficiency to the cooling water is improved by the molding process, successfully reducing the motor coil temperature significantly. By achieving effective heat dissipation, motor output could be increased while maintaining the motor size.

MHIET manufactures stators in-house, including the winding and molding processes. This allows MHIET to flexibly adjust motor specifications to meet customer requirements. This is a major advantage when responding to various operational conditions and requirements of our customers.

3.3 Higher efficiency achieved by optimized aerodynamics and self-developed inverter

In order to reduce aerodynamic loss, the newly developed air compressor utilizes the latest CFD (computational fluid dynamics) analysis to optimize the thrust balance and cooling air flow inside the air compressor, as well as the shape of the compressor, turbine, and intermediate piping. In particular, to adapt the compressor to the customer's required operating point, turbocharger technology is used to perform optimization so that the compressor efficiency peak point agrees with the operating point, which makes it possible to improve the energy efficiency of the entire FC system.

MHIET's in-house developed inverter is shown in **Figure 8**. This inverter, newly developed exclusively for MHIET air compressors, is equipped with SiC-MOSFET power devices to achieve high efficiency and high output. This inverter supports carrier frequencies from 20 kHz to 40 kHz, is adjusted to the changes in motor winding specifications according to customer requirements, and then is optimally matched with the motor. As a result, efficiency of the entire FC system can be maximized. In addition, the development of software that is compliant with AUTOSAR, a platform to achieve commonality of in-vehicle software, and ISO 26262, the international standard for functional safety related to vehicle electrical/electronics, is underway.

Figure 8 In-house developed inverter

3.4 Improved reliability by rotor weight reduction, air bearings adoption, and motor thermal protection

A rotor was designed, aiming for both weight reduction and strength assurance. As a result, a weight reduction of approximately 40% compared to conventional rotors was successfully achieved, by optimizing strength and rigidity of each part using the rotor dynamics technology gained through the development of turbochargers designed for vibration and strength, in addition to adopting a hollow structure. For example, by adjusting the material selection and shape design of each part in detail, decrease in rigidity due to weight reduction can be minimized and stability at high speeds could be achieved. In addition, by introducing production equipment in parallel with the designing processes, in-house production of rotors is possible, which further improves quality and enables a flexible response to design changes. Specifically, assembly, finishing including balancing, and magnetizing processes of rotors are performed in-house, ensuring strict quality control.

By adopting air bearings instead of oil-based, lubricating oil is not needed and compressed air with the high purity as required for FC systems can be supplied. FC stacks are extremely sensitive to impurities such as lubricating oil, and this oil-free design is an essential element to ensure reliability of the FC system. In addition, by applying a special lubricant coating to the surface of the bearing top foil to suppress wear during start/stop operations, high durability is maintained even in environments where start/stop operations are repeatedly performed.

The stator cooling was designed to improve the layout and shape of the cooling passages, in order to achieve uniform temperature distribution and prevent local overheating. In addition, a thermistor is installed in the stator section to provide temperature feedback to the inverter. By maintaining thermal protection for the stator, degradation of the insulation is prevented and long-term reliability of the air compressor can be ensured.

4. Conclusion

MHIET has newly developed an electric centrifugal air compressor (motor output: 45 kW) for FC systems with a net output exceeding 200 kW. This product is available in two configurations, a two-stage (two-stage compressor) type and an expander (single-stage compressor + turbine) type, each with specific characteristics that meet the needs of the customer. By combining elemental technologies such as a lightweight and highly rigid rotor, oil-free bearings, high-efficiency compressor, and an 800 Vdc dustproof/waterproof stator, this product can be used in various customer FC system configurations.

In this development, focus was placed on not only product design, but also the construction of production equipment to enable in-house production of rotors and stators. As a result, a pilot line with a production capacity of 2,000 units per year was established, as well as a product supply that provides high quality and allows flexible specification changes at the same time, has become possible.

From now, MHIET will promote the practical application of new technologies to improve the efficiency and reliability of FC systems through further research and development. Specifically, development of high-value-added products such as a two-stage compressor with a turbine that can handle 850 Vdc or higher and integrate the inverter and air compressor is planned. Through these efforts, MHIET will contribute to the evolution of FC technology and play an active role in support of the construction of a sustainable energy society.