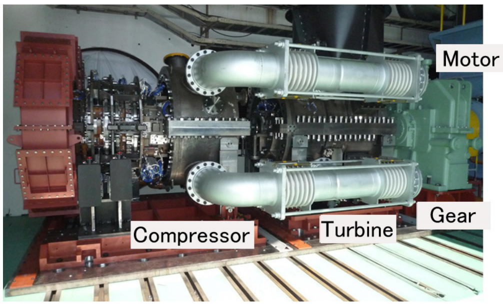
Development of Measurement Method for Verification of Multi-Stage Axial Compressor with Improved Performance



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Gas turbine power generation systems are clean and economical power generation facilities and have become more important because they are power generation facilities that can not only meet the base load but also follow fluctuation of electric power demand under a background in recent years where use of natural energy have expanded. Mitsubishi Heavy Industries, Ltd. (MHI) is currently developing elemental technologies for 1700°C-class gas turbines as a project subsidized by the New Energy and Industrial Technology Development Organization (NEDO) with the aim of further enhancement in the efficiency of gas turbines. For improvement in the efficiency of the gas turbine cycle of axial flow compressors for 1700°C-class gas turbines, it is necessary to increase the pressure ratio, enhance the performance and extend the stable application range. For the verification of compressor performance, eight-stage compressor model test equipment was developed. This paper describes the developed test facility in the subsidized project and the development progress of a measurement technology to which a 3D metal printer is applied.

1. Introduction

Gus turbines are required to further enhance their efficiency in order to reduce greenhouse gas emissions and to extend their operability following fluctuations in electric power demand as natural energy has been increasingly used in recent years(1). Gas turbine compressors are also required to attain enhancement in their efficiency, an increase in the pressure ratio and an extension of the operation range, and we are proceeding with research and development for all of these areas(2)(3)(4).

MHI developed elemental technologies for 1700°C-class gas turbines under a subsidized project of the Ministry of Economy, Trade, and Industry from fiscal 2004 to 2015, and have been continuing the development as a NEDO project since fiscal 2016 in order to develop new technologies(5). For verifying the effects of the newly developed technologies in advance of their application to actual machines and reflecting the results in the design of 1700°C-class gas turbines, we developed an eight-stage axial flow compressor test facility.

For enhancement of the compressor performance, it is important to grasp the internal flow in detail. Such detailed internal flow measurement was executed with use of a test machine also in the past. There was a concern with the conventional measurement method where the flow field was disturbed by the measurement equipment itself. Therefore we have developed a measurement method that uses a 3D metal printer in order to minimize the effects on the internal flow.

The 3D printer technology has been developing rapidly in recent years, and is also being increasingly applied to industrial gas turbines. 3D resin printers have been applied mainly to the manufacturing field as a tool for confirming the workability and assemblability in the design phase, as well as for processing in order to reduce the development lead time(6)(7). In addition, research and development of 3D metal printers is moving forward, with the aim of using them to manufacture gas turbine parts. As a result, we used a 3D metal printer and machine processing simultaneously to develop a compressor blade for measuring that contains a path for measurement. We applied the

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3D printed measurement blade to a compressor test to measure the flow field in detail under temperature and pressure conditions equivalent to an actual machine.

We used an eight-stage compressor that simulates the actual machine faithfully to implement a surge test in advance of operation of the actual machine in order to confirm its integrity through the verification of the operation range. In addition, detailed measurement of the compressor internal flow, which cannot be performed on an actual machine, and the verification of prediction accuracy of computer simulation (CFD: Computational Fluid Dynamics) were performed. This paper presents the details thereof.

2. Development of multi-stage axial flow compressor test facility

2.1 Background

An axial flow compressor, one of the main components of a gas turbine, is a turbo machine with multiple internal blades that rotate at a high speed to compress air, and therefore a complex unsteady flow field occurs inside. 1700°C-class gas turbines are required to increase their pressure ratio in order to improve the cycle efficiency. As the pressure ratio is increased, there is concern over increased loss because of the development of a boundary layer, the decrease in the stable operation range because of occurrence of reverse flow, separation, etc. and worsening of the startup characteristics. It is necessary to develop new compressor technologies for suppressing the development of the boundary layer and the occurrence of reverse flow, separation, etc. in order to enhance the efficiency, extend the stable operation range and improve the startup characteristics, while increasing the pressure ratio at the same time. We developed eight-stage axial flow compressor test equipment in order to verify the new technologies in advance of their application to actual machines and reflect the technologies in the actual design.

2.2 Multi-stage axial flow compressor test facility

Inside an axial flow compressor, the boundary layer on the end wall grows in downstream stages and causes blockage. A complex, unsteady flow field also occurs in the compressor because of this effect, such as interference between the blade rows, clocking (the difference of the stator vane mounting position on each stage in the circumferential direction), etc., brought about by the adoption of the multi-stage system. Conventionally, small-sized test equipment that has a certain number of extracted stages and is of a reduced scale was used for compressor verification tests. Although MHI also fabricated three-stage and four-stage compressor test equipment to perform verification tests in the past, it is necessary to implement verification tests using test machines with more stages in order to perform the verification of the medium and rear stages that are believed to be significantly affected by the upstream stages. Therefore, we fabricated an eight-stage test facility in order to understand the detailed internal flow under the multi-stage conditions and verify the increase in efficiency (**Figure 1** and **Table 1**).

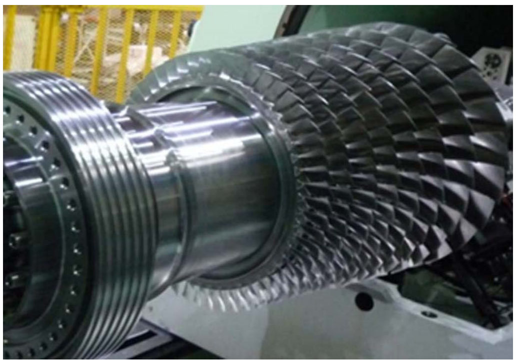

Figure 1 Eight-stage compressor rotor

Table 1 Compressor design specification

Stages	Inlet Guide Vane (IGV) + 8 stages (IGV and 1st to 3rd stator vane is variable)
Pressure ratio	7.14
Rotating speed	14400 (rpm)
Power demand	9100 (kW)

When implementing the test for verifying the aerodynamic performance of an actual machine, it is necessary to reduce the size of gaps including the rotor blade tip clearance according to the scale ratio. Therefore, the scale ratio was set as large as possible in consideration of the assemblability. Also for making measurement easier, a larger scale ratio is desirable. As a result of the determination of the scale ratio in consideration of the assemblability and the ease of measurement in this manner, the compressor power needed was approximately 9 MW. Because the largest power output of the existing motor is 4 MW, an air turbine was installed directly on the downstream side of the compressor in order to cover the insufficient power amount of 5 MW and assist the motor power (**Figure 2** and **Table 2**). The first stage stator vane of the turbine has a variable mechanism that drives and changes the stationary blade angle using an electric-powered actuator. By changing the throat area of the first stage stationary blade of the turbine, the compressor exit pressure can be adjusted and therefore the compressor test conditions can be set.

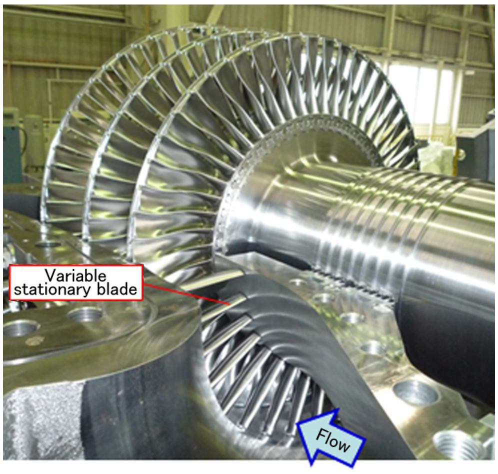

Figure 2 Power recovery turbine

Table 2 Turbine design specification

Stages	3 stages (1st stator vane is variable)
Expansion ratio	6.72
Rotating speed	14400 (rpm)
Power	6600 (kW)

The IGV and the first to third stage stator vanes were variable for which the angle can be adjusted individually by actuators. The compressor flow path had a bleeding chamber in order to verify the startup characteristics together with the variable stator vanes and then optimize the startup schedule. In addition, an emergency blow-off valve was installed in the exit chamber of the compressor. When the occurrence of a surge is detected by the pressure sensor installed on the casing, the blow-off valve is automatically and instantly opened in order to release the pressure and compressor from the surge condition. This allows a verification test of the compressor surge tolerance to be implemented safely without causing damage to the facility.

These valves, variable stator vanes and rotation speed are computer-controlled using a control device similar to that used for the control of power plants that MHI built. The automatic operation control following a pre-programmed operating schedule allows the easy setting of test conditions and the implementing of a test that faithfully simulated the operating conditions of a 1700°C-class gas turbine compressor. In addition, the control device always monitors operating conditions at various points of the test machine including the air temperature, air pressure, vibration of the axis, etc., as well as the operating conditions of auxiliary equipment including lubricating oil pressure, cooling air, cooling water, etc. The control device issues an alarm when an abnormality occurs with the test facility and trips and stops the machine when a limitation value is reached. This provides protection for the test facility and saves labor in the monitoring of operations during a test.

2.3 Measuring blade made with a 3D printer

There are multiple measuring points inside the compressor provided in order to understand the internal flow of the compressor in detail. In the past, typical internal flow measuring methods included wired pressure conduits or sensors that were attached to the blade, probes that were inserted into the flow path, etc. The wiring of the conduits or sensors on a blade surface caused the deformation of the blade and the disturbance of the internal flow. The insertion of a probe brought about the disturbance of the flow field caused by the probe itself and resulted in increased measuring error. With such a background, we installed a measuring blade made with a 3D metal printer in order to keep the effects on the internal flow field as small as possible while obtaining detailed internal flow data. The pressure was measured in the pressure measurement through-hole with a diameter of 0.4 mm drilled on the very thin compressor stator vanes with a thickness of approximately 1.5 mm. In addition, a hole with a diameter of 0.7 mm was provided on the blade in order to accommodate the thermocouple with a diameter of 0.5 mm for temperature measurement. The compressor blade had a three-dimensional shape for improved performance. A model that had measurement holes three-dimensionally following the blade shape was designed using 3D CAD

(Computer Aided Design) and formed with a 3D metal printer. In this manner, accommodation for pressure holes and temperature measurement could be provided inside the blade (**Figure 3**).

The stator vanes of the compressor test machine experience stress equivalent to an actual machine. The 3D printed measurement blade was strength-tested and its strength was confirmed to be equal to the conventional blade material before the application of the measuring blade to the test machine.

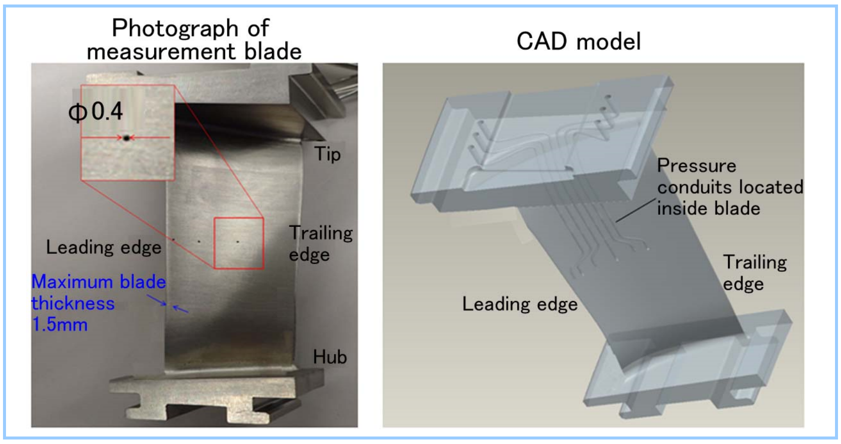

Figure 3 Static pressure measurement blade made with a 3D printer
(used as a set of two blades at three measurement points on each of the leading and trailing edge)

2.4 Test results

A test of the compressor was carried out and its overall performance was obtained (**Figure 4**). In addition, a verification test of the compressor surge tolerance that simulated a partial load operation was carried out to confirm that the surge tolerance was sufficient. The integrity and reliability of the compressor within the gas turbine operating range was verified and confirmed.

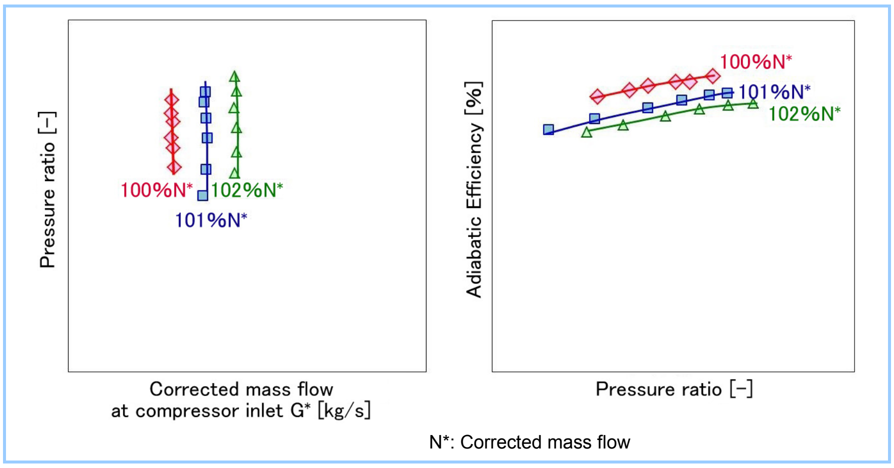

Figure 4 Compressor overall performance

The pressure and temperature at various stages were measured using a 3D printed measurement blade. It was confirmed that the load balance in each stage of the compressor and the distribution over the height direction was as expected (**Figure 5** and **Figure 6**).

The pressure distribution on the blade surface was understood in detail using the 3D printed measurement blade that had pressure measurement holes on the blade surface. The pressure distribution of the compressor blade surface in a partial load operation was measured and separation from the blade surface before the occurrence of a surge was confirmed through calculation (**Figure 7**). The presence or absence of separation from the blade surface is an important factor that determines the stable operation range of the compressor, but its prediction is difficult. The timing of separation from the blade roughly conformed to the results of CFD prediction and its prediction accuracy was confirmed.

The verification data obtained through this test will be used to improve CFD analysis codes in order to further enhance CFD prediction accuracy and will be applied to the development of 1700°C-class compressors.

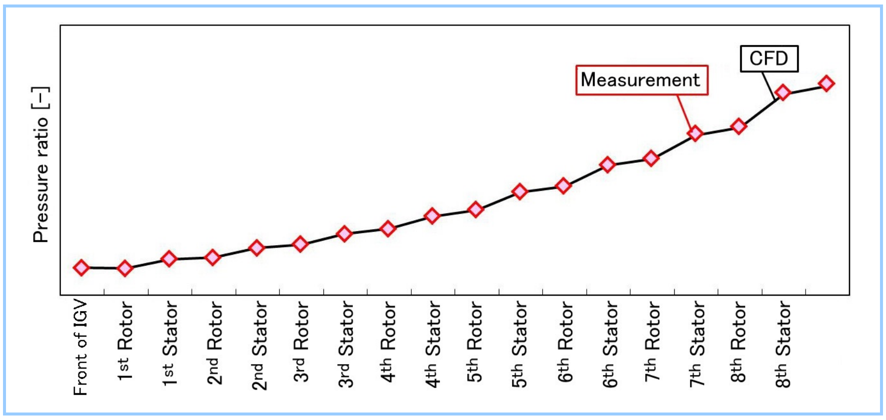

Figure 5 Stage pressure ratio

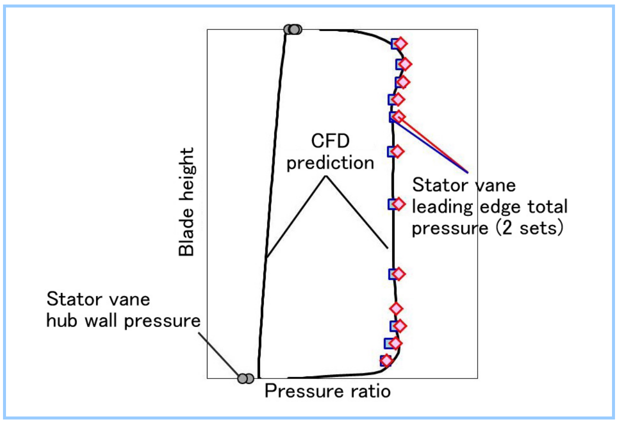

Figure 6 Leading edge total pressure and wall pressure of measurement blade made with 3D printer

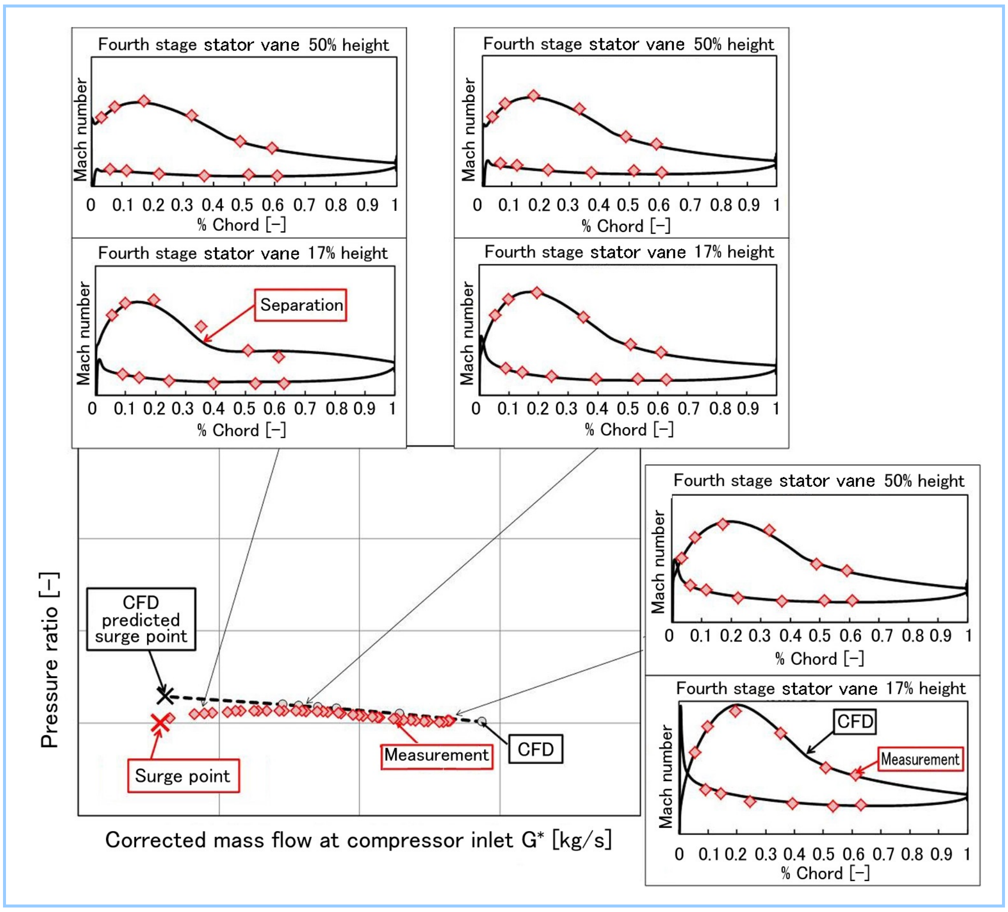

Figure 7 Compressor map and fourth stator surface static pressure at surge test

3. Conclusion

We developed an eight-stage test facility and executed an actual machine verification test. In addition, we applied a 3D printer to make a measuring blade for obtaining detailed internal flow data. The obtained data will be reflected on design of next-generation compressors. The description in this paper is part of the development of compressors for 1700°C-class gas turbines. In addition, technologies for improved performance aiming at practical application are being developed, and verification tests will be implemented continuously using the eight-stage axial flow compressor test equipment. The obtained results will be reflected in the design of 1700°C-class gas turbines for application to an actual machine. We are committed to contributing to the resolution of energy problems and global environmental problems through the diffusion of the latest gas turbine combined cycle power generation technologies.

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