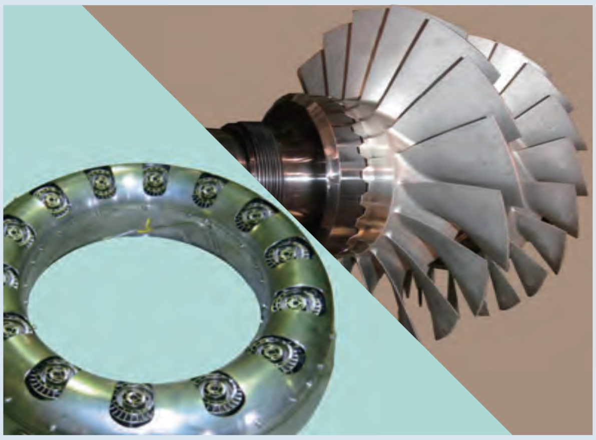
Technology Development of Compressor and Combustor for Performance Improvement of Aircraft Engine



Civil aircraft engines are expected to have excellent economic and environmental friendliness to address the rapid increase in air transportation and global warming due to global economic growth. We are developing technologies for future aero-engine components.

We have developed design methodology for high efficiency compressor for better fuel consumption, and lean staged combustor for NOx reduction. We are continuously working on improving the component testing and the numerical analysis for further development.

Introduction

To address the rapid increase in air transportation due to global economic growth and global warming, there is increasing demand for economical engines which can be met by measures such as lowering fuel consumption and for environmental friendliness by measures such as reducing NOx in the exhaust gas.

Under such a situation, the demand for better performance aircraft engines is high and the market is expected to expand in the near future.

1 Background

We are currently involved in the business of aircraft engines by participating in international joint-development programs and conducting research and development to enhance our market share. Specifically, we are working to improve proprietary technologies for compressors and combustors.

2 Technical Challenges in Developing Aircraft Engines

Figure 1 shows the basic components of a typical aircraft engine such as a compressor that compresses air, a combustor that burns the fuel, and a turbine that extracts power from the high-temperature, high-pressure combusted air.

In the development of each component, a phased performance evaluation is required before incorporating it into an engine. **Fig. 2** shows the technology readiness level (TRL) of component development for combustor. Our research and development activities are aimed at acquiring level-5 technologies of TRL definition that can help reduce fuel consumption and NOx emissions.

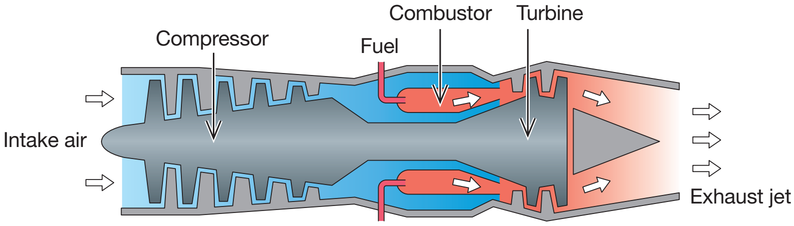


Fig. 1 Schematic of an aircraft engine

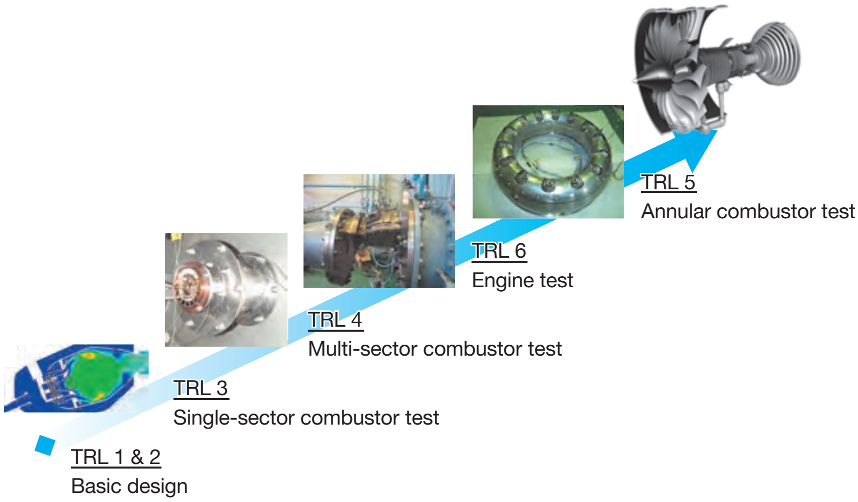


Fig. 2 Technology readiness level (TRL) of combustor

(1) Technical Challenges in Reducing Fuel Consumption

To reduce fuel consumption, each engine component needs to become lighter and more efficient. A compressor comprises multiple stages of rotating blades that rotate at high speed and of stationary vanes. For higher efficiency, we need to design an airfoil shape with lower losses. However, the load on airfoil tends to increase by reducing the number of stages for a lighter engine.

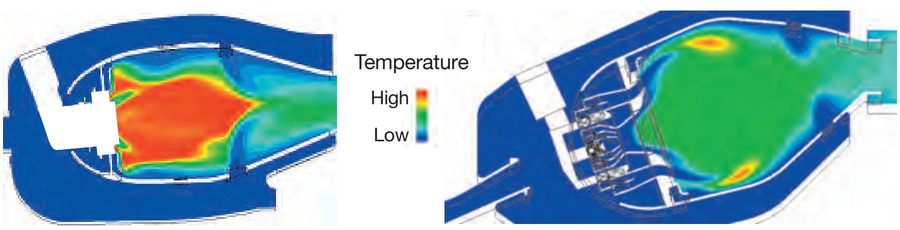
On the other hand, for safe engine operation, the compressor needs to have a sufficient operating range to avoid unstable compressor operations such as surge or stall.

In developing a compressor, the major challenge is realizing a design to maintain balance between weight, efficiency and operating range.

(2) Technical Challenges in Reducing NOx

Aircraft engines produce NOx in the combustors, where the air temperature is the highest in the engines. NOx emissions increase exponentially with combustion temperature; therefore, reducing the combustion temperature is important for NOx reduction.

In response to this issue, we are developing a lean staged combustor[1)] as a combustor that could operate at lower combustion temperature, compared with a conventional one by lowering the ratio of fuel to air as shown in **Fig. 3**. In addition, the combustor is expected as a next-generation combustor since it can significantly reduce particle matters as well as NOx. On the other hand, there are still many technical issues surrounding its implementation such as stability, combustion efficiency and possible damage to the combustor caused by auto-ignition, flashback or combustion oscillation.



(a) Conventional combustor　　(b) Lean staged combustor

Fig. 3 Temperature distribution of combustor

The first step toward reducing NOx, the important issue in developing a lean staged combustor, is forming a uniform premixed fuel-air mixture.

3 Approaches to Reducing Fuel Consumption and NOx

(1) Reducing Fuel Consumption

As an approach to reducing fuel consumption, we have developed an airfoil design system and demonstrated its effectiveness in compressor testing. In addition, we are working on enhancing our numerical analysis technologies to simulate the experimental results more accurately.

(i) Airfoil Design System

In designing airfoils these days, it is common practice that design is performed in parallel with checking various performance characteristics of the airfoil using computational fluid dynamics (CFD). However, a lot of trial and error is needed to select an optimal set of parameters from a broad range of design parameters. To perform such tasks efficiently and accurately, we have built a system that can automatically select a most suitable set of design parameters by using a genetic algorithm as shown in **Fig. 4**. The optimization of aerodynamics and that of vibration and stress were separately conducted in the past, but this system allows them to be performed simultaneously. **Figure 5** shows a comparison of pressure loss distribution in the radial direction for a new type of airfoil designed by this system and a conventional airfoil. This process makes it possible to design efficient airfoils with lower total pressure loss compared with conventional airfoils.

(ii) Compressor Testing

The newly designed airfoils are verified through compressor testing. The testing was performed on a two-stage axial-flow compressor, the equipment for which is shown in **Fig. 6**. Compressor testing enabled us to assess aerodynamic characteristics such as pressure ratio and efficiency as well as vibration characteristics to confirm mechanical integrity. In addition, the stall or surge

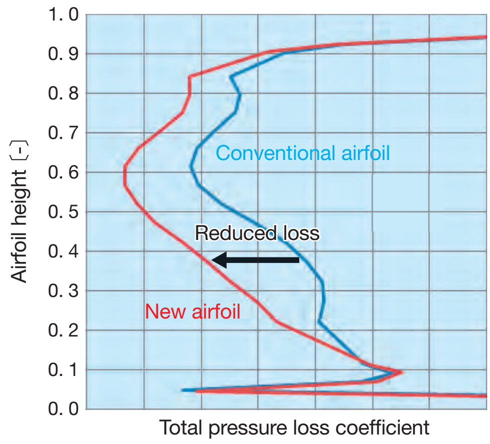


Fig. 5 Distribution of total pressure loss

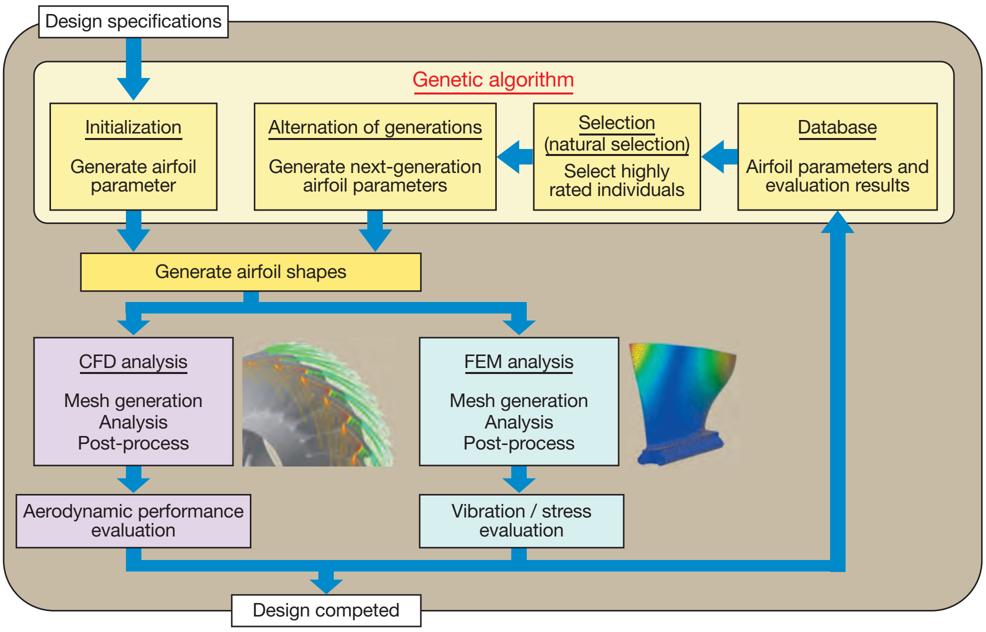


Fig. 4 Airfoil design optimization system

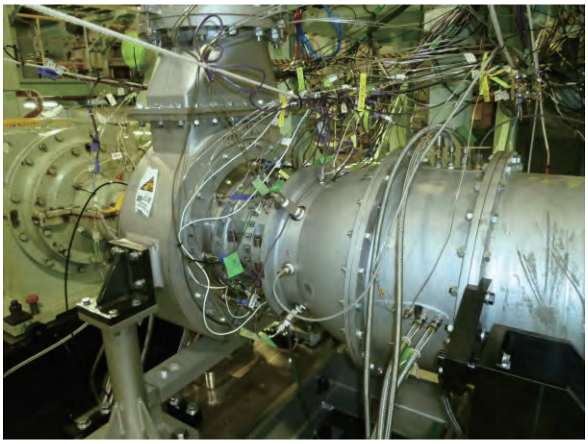


Fig. 6 Compressor test rig

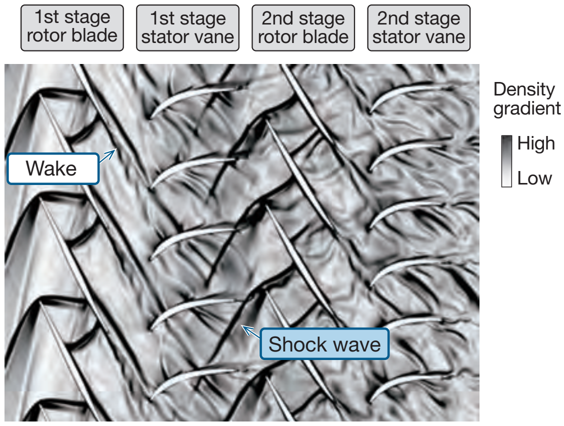


Fig. 7 Density gradient distribution in blade-to-blade plane

conditions were also verified, which are difficult to predict in the design phase.

(iii) Numerical Analysis

In designing airfoils, steady computation with time-average of the flow field is generally used due to the time constraints for analysis. However, as steady computation cannot precisely capture the rotor-stator interactions in a multi-stage compressor, the instability phenomenon such as surge cannot be predicted accurately. Consequently, we are conducting research on unsteady computations with higher time accuracy.

Since unsteady computation is a larger-scale analysis compared to steady computation, we are conducting a collaborative research with Kyushu University using the supercomputer “K computer”[2)]. The research is being carried out on the two-stage compressor for which the compressor testing was conducted. The density-gradient distribution near the airfoil tip is shown in **Fig. 7**. Similarly, a complex flow can be captured in which wakes and shock waves from airfoils interfere with adjacent airfoils.

(2) Reducing NOx

Many combustors for aircraft engines are of the annular type in which the fuel injected from circumferentially placed burners is burned in the annular combustion chamber located downstream, as shown in the representative figure.

In a lean staged combustor, the fuel and air are premixed in the burner before being burned in the combustion chamber. It is important to improve the burner performance because the more uniform the premixed fuel-air mixture is, the less NOx produced.

In developing the burner, we are conducting joint research and development with the Japan Aerospace Exploration Agency (JAXA) to address issues such as creating uniform premixed fuel-air mixture flames, visualizing the air-flow field, fuel distribution and combustion by using numerical analysis and optical measurements to gather data for combustor design. For the combustor designed, we evaluate its performance through high-temperature, high-pressure combustion testing. There are few places in the world where annular combustion testing for engines with increasingly higher compression ratios can be performed under conditions close to the actual temperature and actual pressure. However, as shown in **Fig. 8**, we have access to JAXA's large-scale, high-temperature and high-pressure combustor test rig to conduct performance evaluations under conditions as close to the actual temperature and

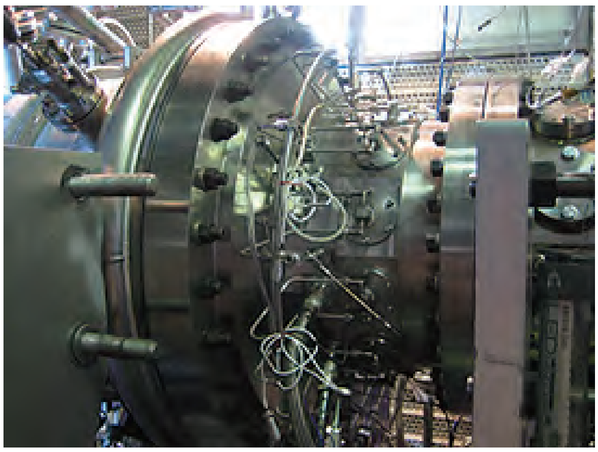


Fig. 8 High temperature and high-pressure combustor test rig

actual pressure as possible, enabling us to evaluate the performance more accurately.

(i) Premixed Fuel-Air Mixture Flames

Figure 9 shows flames from the burner for different premixture levels during the combustion testing. The red circular region is an area where the cylindrical facility is red-heated, the blue region is flames, and the horizontal bar in the center is a probe for measuring exhaust gases.

Figure 9 (a) shows the case where the premix is not uniform and the flames form streaks in the circumferential direction, while **Fig.9 (b)** shows the case where the premix is uniform, and the flames form evenly in the circumferential direction. Furthermore, NOx emissions are significantly reduced when the premix is uniform[3]. To make the premix uniform, we need to accurately determine the air-flow field and fuel distribution.

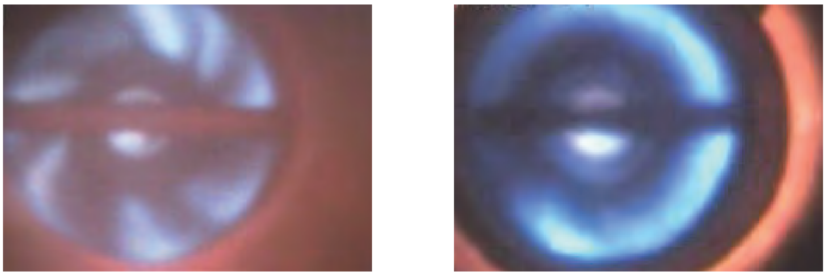
(ii) Numerical Analysis

We use numerical analysis for capturing the air-flow field. Numerical analysis is effective for understanding the premix, large air-flow field in the combustor that affects ignition and stability performance as well as outlet temperature distribution, the air-flow separation and velocity distribution in the burner involving risks of auto-ignition and flashback (**Fig. 10**). Particularly for the latter, a more detailed and a larger-scale analysis is needed to precisely reproduce the shape of the computed object, and the analysis is being performed at JAXA by using the non-combustion analysis code UPACS (Unified Platform for Aerospace Computational Simulation) and a supercomputer.

(iii) Optical Measurement

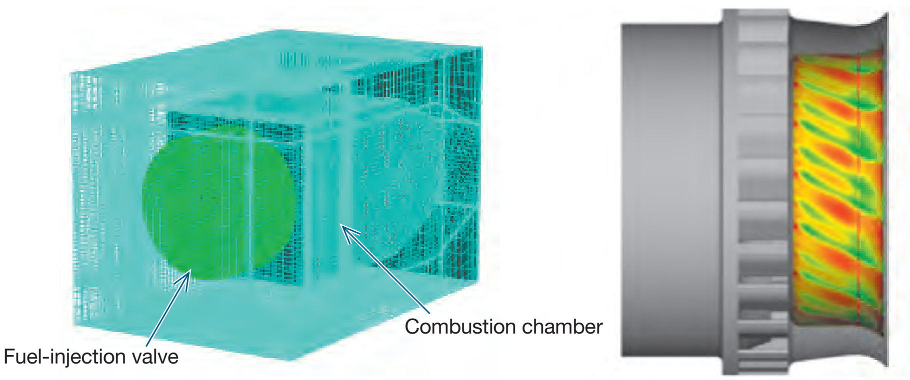
Figure 11 (a) shows a visualization test of fuel spray distribution within a burner in a high-pressure condition. By making the outermost part of the burner transparent, we can visualize the fuel spray distribution in a burner. In addition, using a laser technique makes it possible to obtain more detailed information such as fuel-droplet size and velocity of the visualized burner.

Figure 11 (b) shows flames during combustion testing of a burner. Using a glass-walled combustion chamber for



(a) Flames when premix is not uniform **(b) Flames when premix is uniform**

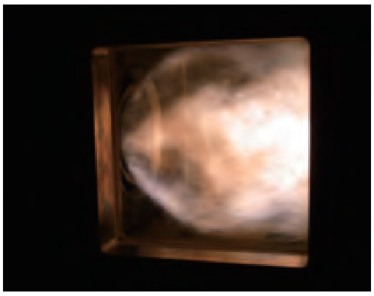
Fig. 9 Premixed flame



(a) Model external view **(b) Velocity distribution in the fuel-injection valve**

Fig. 10 CFD in the burner

(a) Visualization of fuel spraying



(b) Visualization of combustion

Fig. 11 Visualization of the interior of combustor

the test makes it possible to view the combustion status. With optical devices such as a laser, together with visualization, information such as fuel spray distribution, vapor fuel distribution, and combustion can be obtained more in detail.

Conclusion

We are working on improving the technologies for compressors and combustors towards implementing these technologies in future civil aircraft engine business. We will continue developing technologies and proposing activities to engine developers (OEM) henceforth.

Part of this research is the result of our joint study with Kyushu University and JAXA, including an adopted subject for the use of the Research Organization for Information Science & Technology's HPCI system. We express our gratitude to the people involved in this research.

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