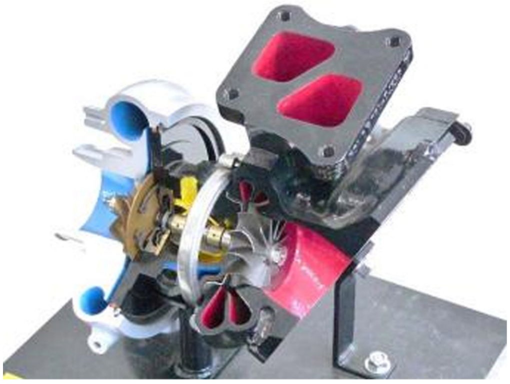
# Development of Twinscroll Turbine for Automotive Turbochargers using Unsteady Numerical Simulation



KATSUYUKI OSAKO*1 TAKAO YOKOYAMA*2

TOYOTAKA YOSHIDA*3 TORU HOSHI*4

MOTOKI EBISU*5 TAKASHI SHIRAISHI*6

*In recent years, in response to growing interest in environmental issues, many automotive technologies for fuel efficient vehicles and countermeasures for emission control have been developed. Among such technologies, turbochargers have been increasingly used for the downsizing of engines. It is necessary for the further enhancement of fuel efficiency to improve the efficiency of turbochargers. However, the radial turbines used for turbochargers operate under conditions of pulsing exhaust. Because large pulsation makes the flow unsteady, it has been difficult to understand flow phenomena and improve efficiency. MHI uses unsteady computational simulation to understand complex flow phenomena. Based on this, MHI has refined a twin scroll to improve flow in the scroll and rotor blade, and then developed a more efficient twin scroll turbine.*

## 1. Introduction

Along with growing interest in global environmental issues, regulations regarding the gas emissions and fuel economy of automobiles have been tightening every year. An engine with a turbocharger, which feeds compressed air into the engine, can use a smaller displacement than normal aspiration engines. Therefore turbochargers can reduce the weight and friction loss of engines, resulting in the improvement of fuel efficiency and a reduction of $CO_2$. In particular, European automotive manufacturers have been increasingly employing smaller engines for the improvement of fuel efficiency. Therefore the use of turbochargers has been growing, which results in growth of the turbocharger market.

An automotive turbocharger uses exhaust gas to rotate the turbine, and then the compressor blade wheel, the shaft of which is connected directly with the shaft of the turbine, is driven. A standard turbocharger uses a single scroll turbine. However, at lower engine speeds during acceleration, it cannot compress the air supply sufficiently because the exhaust gas flow is small and the boost pressure is low. To increase the boost pressure, a twin scroll turbine is effective.[1]

The fuel economy displayed in automobile brochures is measured according to a certain driving pattern (test cycle)[2] designated in the country or local region. In Europe, NEDC (New European Driving Cycle)[3] has been used since its introduction in 2000. Now Europe is planning test cycles where the fuel economy and gas emissions of vehicles are measured under conditions simulating actual driving conditions as closely as possible. They are considering the use of CADC (Common Artemis Driving Cycle)[4], etc., in the future. In such future test cycles, it is predicted that a driving mode with repeating acceleration from lower engine speeds and deceleration will be added in consideration of driving in urban areas. Therefore it will be increasingly necessary to comply with such regulations to improve fuel efficiency at lower engine speeds.

*1 Chief Staff Manager, Yokohama Resarch & Development Center, Technology & Innovation Headquarters
*2 Deputy Manager, Nagasaki Research & Development Center, Technology & Innovation Headquarters
*3 Nagasaki Research & Development Center, Technology & Innovation Headquarters
*4 Yokohama Resarch & Development Center, Technology & Innovation Headquarters
*5 Chief Staff Manager, Turbocharger Engineering Department, Turbocharger Division, General Machinery & Special Vehicles
*6 Deputy Manager, Turbocharger Engineering Department, Turbocharger Division, General Machinery & Special Vehicles

The improvement of fuel efficiency at lower engine speeds requires the enhancement of turbocharger efficiency. However, because the internal flow of a twin scroll turbine is made unsteady by the largely pulsing flow, the internal flow is difficult to analyze and its details have not been well understood. This document presents work on the improvement of twin scroll turbine efficiency through the use of unsteady computational simulation.

## 2. Mechanism and performance of twin scroll turbine

**Figure 1** (i) illustrates the structure of a standard single scroll turbine combined with a four-cylinder engine. Exhaust gas flows through the exhaust manifold that gathers upstream of the inlet of turbine. At lower engine speeds, the flow rate of exhaust gas is low, and therefore the exhaust pressure at the gathering point of the exhaust manifold that rotates the turbine is low, resulting in a low boost pressure. On the other hand, Figure 1 (ii) shows the structure of a twin scroll turbine combined with a four-cylinder engine. The induction flow path from the turbine inlet to the leading edge of the rotor blades is divided into the front and rear sides. Based on the explosion order, a twin scroll turbine combined with a four-cylinder engine inducts exhaust gas into the rear scroll to which the exhaust pipes No. 1 and No. 4 cylinders are connected and the front scroll to which the exhaust pipes No. 2 and No. 3 cylinders are connected. While the crankshaft is rotating two turns, exhaust gas is inducted into the front and rear scrolls alternatively and intermittently, and thus the dynamic pressure of the exhaust pulsation of the engine is used effectively. Due to the division of the flow path, a twin scroll turbine can have higher pressure and then use the dynamic pressure of the exhaust pulsation of the engine effectively. As a result, even at lower engine speeds, it can increase the boost pressure higher than that of a single scroll turbine, which leads to the enhancement of engine torque and the improvement of fuel efficiency.

**Figure 2** compares turbine performance under conditions with exhaust pulsation. Figure 2 (i) illustrates the turbine pressure ratios using the same engine. A twin scroll turbine has a higher pressure ratio and a larger pressure fluctuation, and as a consequence the greater turbine output power shown in Figure 2 (ii) compared with a single scroll turbine. When the generated engine power is identical, a twin scroll turbine, which can effectively convert the dynamic pressure of exhaust pulsation to power output, can achieve higher efficiency than that of a single scroll turbine.

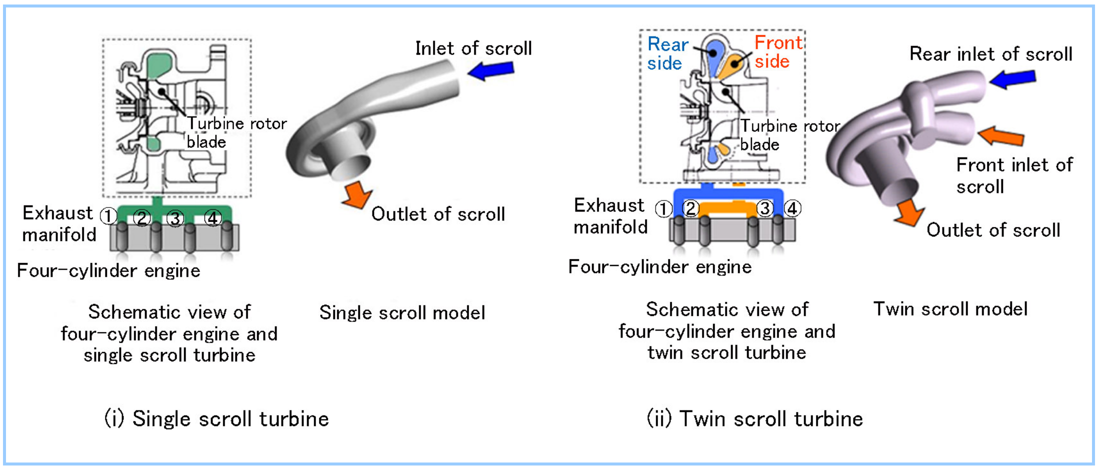



**Figure 1 Shapes of turbine scroll**

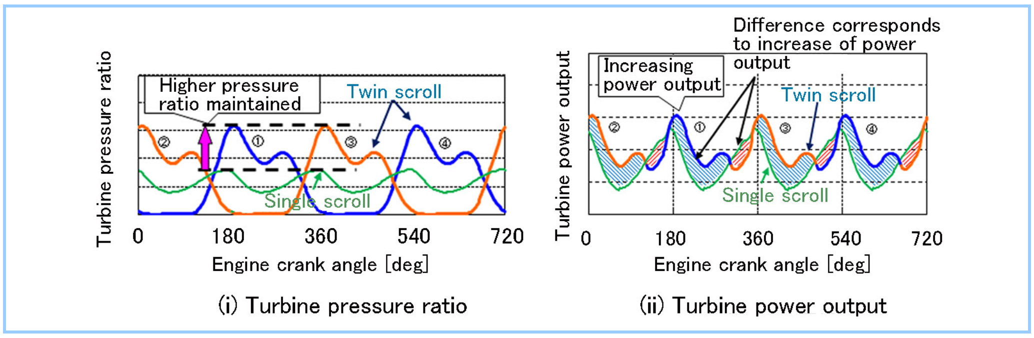



**Figure 2 Comparison of turbine performance under conditions with exhaust pulsation**

## 3. Understanding and improving flow phenomena inside turbines under conditions of exhaust pulsation

In the past, twin scroll turbines were analyzed under steady operating conditions as shown in **Figure 3** (i). **Figure 9** (i) illustrates the internal flow results of conventional steady analysis at a constant pressure. Because such conventional analysis used a constant pressure that represented the mean exhaust pulsation condition, the unsteadiness of the internal flow that actually occurred as a result of exhaust pulsation flowing into the two scrolls alternatively and intermittently was unknown. MHI, which is a manufacturer of both engines and turbochargers, has used this advantage to perform unsteady analysis that simulates exhaust pulsation as shown in Figure 3 (ii).

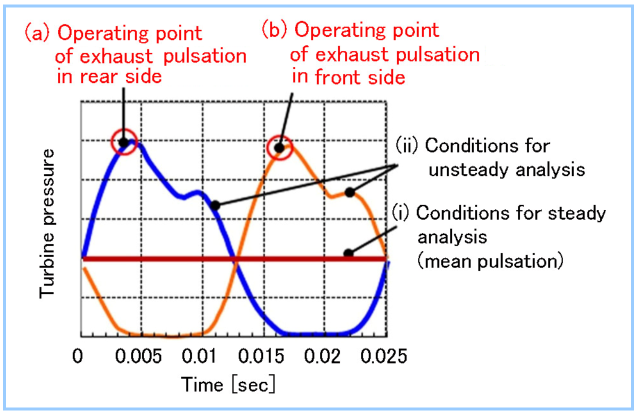



**Figure 3 Turbine pressure used for flow analysis**

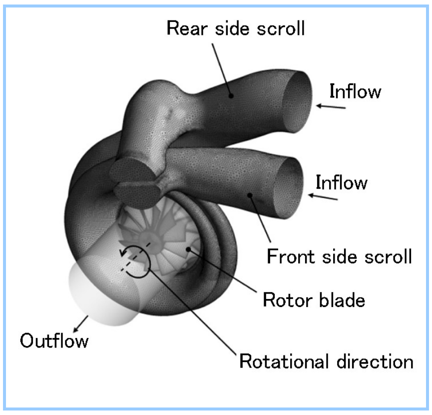



**Figure 4 Grid for analysis**

### 3.1 Numerical analysis method and analysis conditions

To understand unsteady phenomena under conditions of exhaust pulsation, MHI performed flow analysis using CFD (Computational Fluid Dynamics). The object of analysis was the entire turbine, including the scroll and the turbine rotor blade. As shown in **Figure 4**, the computational grid used contained 2.07 million cells on the turbine rotor blade and 1.44 million cells on the scroll, or 3.51 million cells in total. The numerical flow analysis used ANSYS CFX general-purpose 3D viscous flow simulation code. The turbulent model used was the k-ε model. This analysis was performed at the lower engine speed of 2400 rpm (turbocharger speed of 125700 rpm).

### 3.2 Analysis of turbine operation under conditions of exhaust pulsation

No exhaust pulsation interference results from a two- or one-cylinder engine, very little from a three-cylinder, and it is intense from a four-cylinder. It is assumed that the exhaust efficiency of a single scroll combined with a four-cylinder engine is reduced by this interference. On the other hand, no exhaust interference occurs with a twin scroll, where each scroll corresponds to a scroll connected to a two-cylinder engine. **Figure 5** illustrates exhaust pulsation in a twin scroll combined with a four-cylinder engine. An analysis of the operation of a twin scroll shows that partial inflow from one side occurs in almost all ranges of crank angle and perfect full inflow from both sides occurs only at points where pulsation switches. Therefore the most important factor for the performance evaluation of a twin scroll is when inflow from one side occurs.

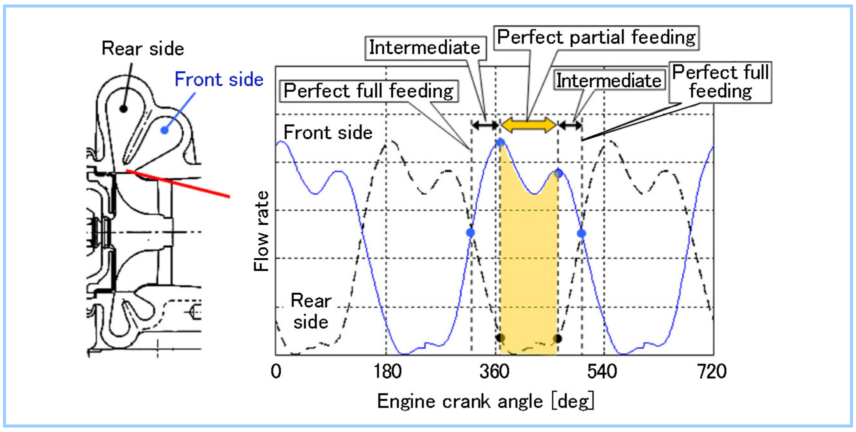



**Figure 5 Exhaust pulsation in twin scroll (combined with four-cylinder engine)**

### 3.3 Understanding of internal flow phenomena of turbines under conditions of exhaust pulsation

For a conventional shape, it was found that the mean in-cycle turbine efficiency during inflow from the rear side was lower than that during inflow from the front side. To understand the cause of this lowering of turbine efficiency during inflow from the rear side, MHI focused its attention on the formation of internal flow loss during inflow from the rear side.

**Figure 6** illustrates the distribution of the loss inside a turbine during the inflow of exhaust gas from the rear side. Loss is generated in the scroll over time. The generated loss flows down in the circumferential direction of the scroll, and propagates through the rotor blade to the outlet. As time passes, the loss in the front side scroll, which is not fed, becomes larger.

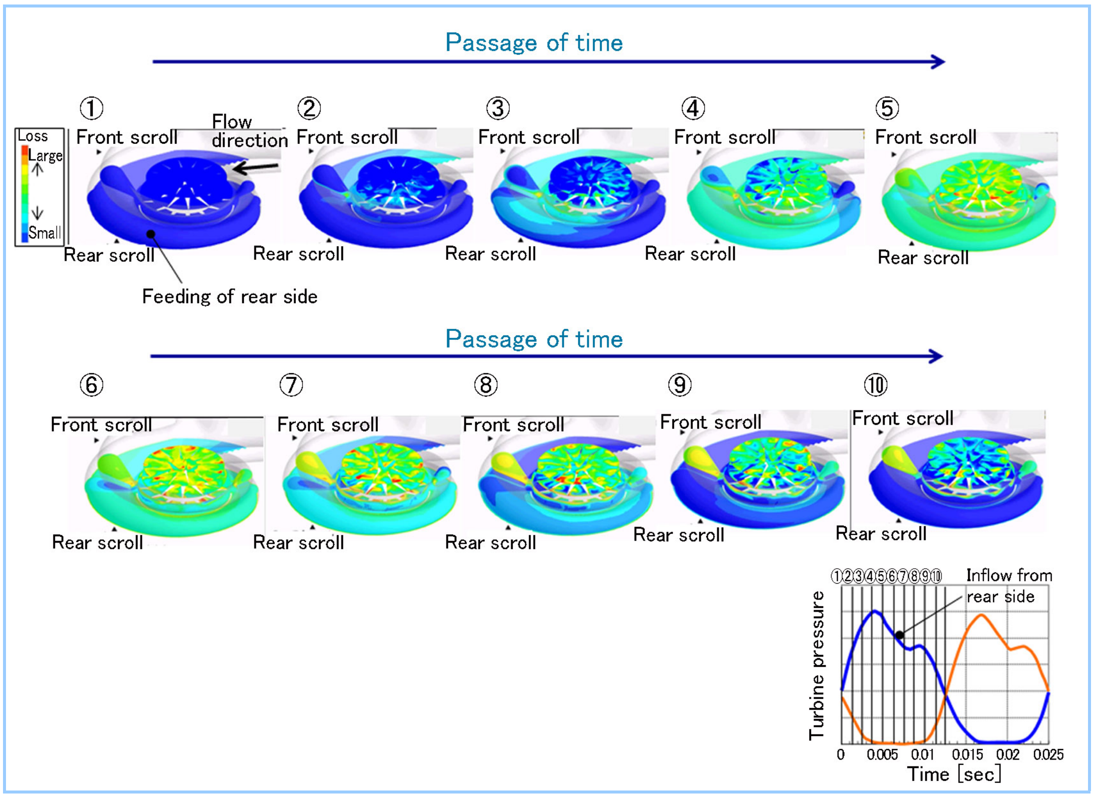



**Figure 6 Internal flow of turbine during inflow from rear side (a)**

To understand the cause of the increase of the loss in the front side scroll not being fed during inflow from the rear side, MHI checked the internal flow on the rear and front cross sections. **Figure 7** shows the loss distribution and flow distribution on cross sections of the rear side where the main stream is being fed and the front side where no stream is being fed during inflow from the rear side (Figure 3 (ii) (a)).

It is found that there is leakage in the non-fed side, which results in a large loss. It is assumed that because a twin scroll, where exhaust pulsation flows into the front and rear scrolls intermittently, generates a pressure difference between each scroll, in-leakage to the lower pressure scroll occurs. The in-leakage flow into the lower pressure side flows in the scroll for a while, and then enters into the rotor blade, resulting in the loss and lower efficiency.

**Figure 8** shows the loss distribution inside the turbine rotor blade during inflow of exhaust gas from the rear side (Figure 3 (ii) (a)). In this figure, the horizontal axis represents the passage of time and the vertical axis represents the height directional position of the cross section. Each increment of time corresponds to two pitches (60 degrees rotation). On cross section α, the most upstream part of the rotor blade, a loss is formed at the position 60 degrees from the tongue area of the scroll. The loss propagates over time. On cross section ε, a large loss exists at the position -60 degrees from the tongue area. This loss is caused by flow distortion at the tongue area of the scroll, and a similar loss also occurs in a single scroll. In addition, it is found that a loss on the side of the rotor blade hub is generated on cross section α, which was not experienced for a conventional single scroll.

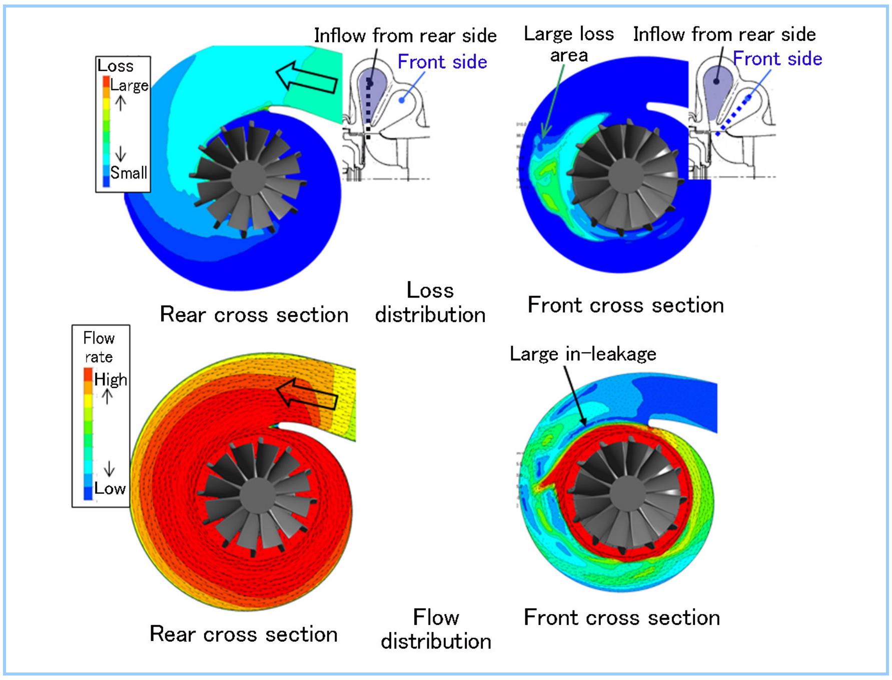



**Figure 7 Internal flow of turbine scroll during inflow from rear side (a)**

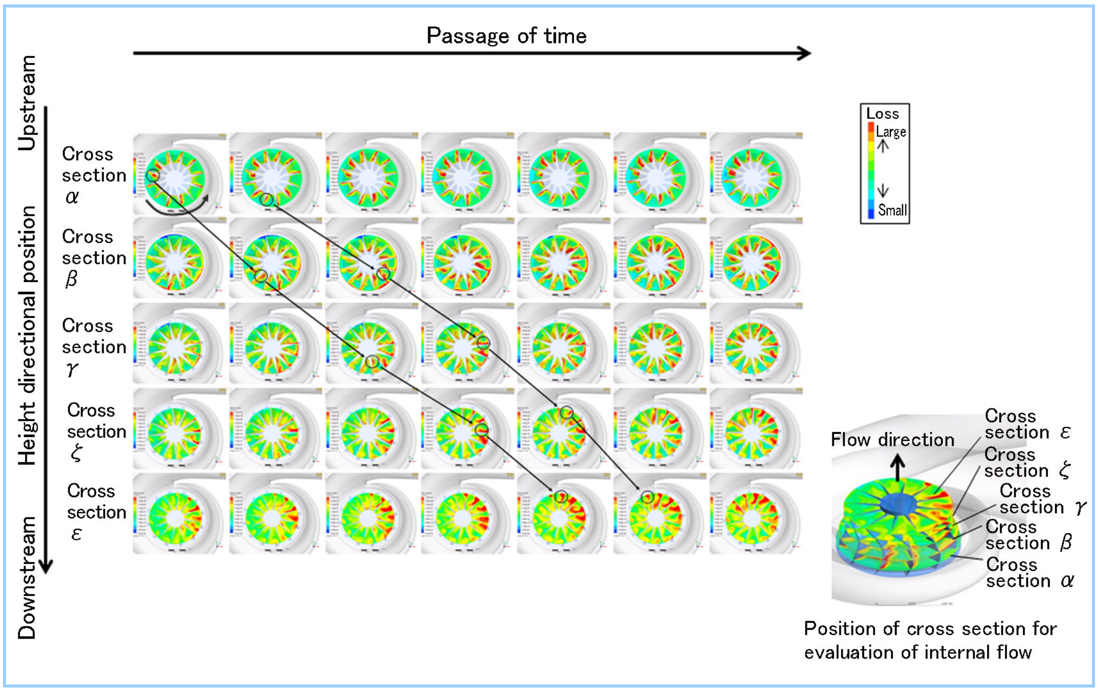



**Figure 8 Internal flow of turbine rotor blade during inflow from rear side (a)**

To understand the cause of the loss generated on the hub side in the rotor blade during the inflow from the rear side, MHI checked the internal flow of the turbine rotor blade on a cross section at a constant position in the circumferential direction. **Figure 9** (ii) (a) shows the internal flow of the turbine on a cross section at a constant position in the circumferential direction during inflow from the rear side (Figure 3 (ii) (a)). It is found that leakage flow from the throat of the rear side scroll flows to the shroud side of the rotor blade, and then flow separation occurs on the hub side inside the rotor blade. On the other hand, Figure 9 (ii) (b) shows the internal flow of the turbine on a cross section at a constant position in the circumferential direction during inflow from the front side (Figure 3 (ii) (b)).

Unlike inflow from the rear side, no flow separation is found on the hub side inside the rotor blade during inflow from the front side. Leakage flow from the throat of the front side scroll flows to the hub side of the rotor blade, and then flow separation occurs on the shroud side inside the rotor blade. However, the flow separation this time is smaller than that during the inflow from the rear side. Conventional analysis under inflow from both sides at a constant mean pressure of exhaust pulsation could not determine the internal flow loss, but it was determined through unsteady analysis that exhaust pulsation flowing into the front and rear scrolls alternatively and intermittently causes flow separation loss in the rotor blade and this loss leads to lower efficiency as transferred to the rotor blade outlet.

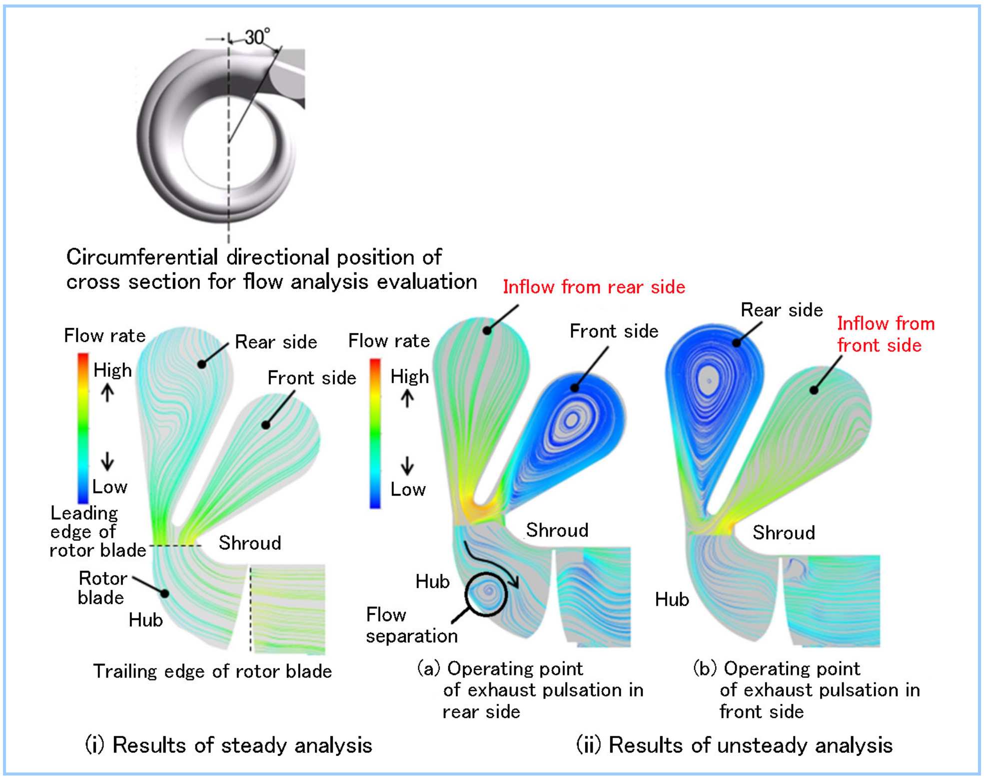



**Figure 9 Internal flow of turbine on cross section at constant position in circumferential direction**

### 3.4 Improvement focusing attention on flow separation inside rotor blade and leakage flow in scroll

Among the internal flow phenomena described above, MHI has focused attention on flow separation inside the rotor blade and leakage flow to the non-fed side in the scroll to make improvements for a new twin scroll turbine. **Figure 10** compares the leakage flow in the non-fed side during inflow from the rear side (Figure 3 (ii) (a)). The conventional twin scroll turbine had leakage flow at the position around 90 degrees in the circumferential direction, but the new twin scroll can achieve a reduction together with the improvement of flow phenomena.

Next, **Figure 11** compares the internal flow of the turbine rotor blade between conventional and new twin scrolls during inflow from the rear side (Figure 3 (ii) (a)). As shown in Figure 11 (i), the flow distribution of the new twin scroll has a smaller low flow rate area in the hub side than that of the conventional twin scroll, which results in the suppression of flow separation during inflow from the rear side. As shown in Figure 11 (ii), the loss distribution on the 90% span cross section of the new twin scroll has a smaller loss at the trailing edge of the shroud than that of the conventional twin scroll. Loss at the trailing edge of the shroud originates in loss generated in the rotor blade hub side. Therefore this reduction of loss means the improvement of the internal separation flow of the rotor blade.

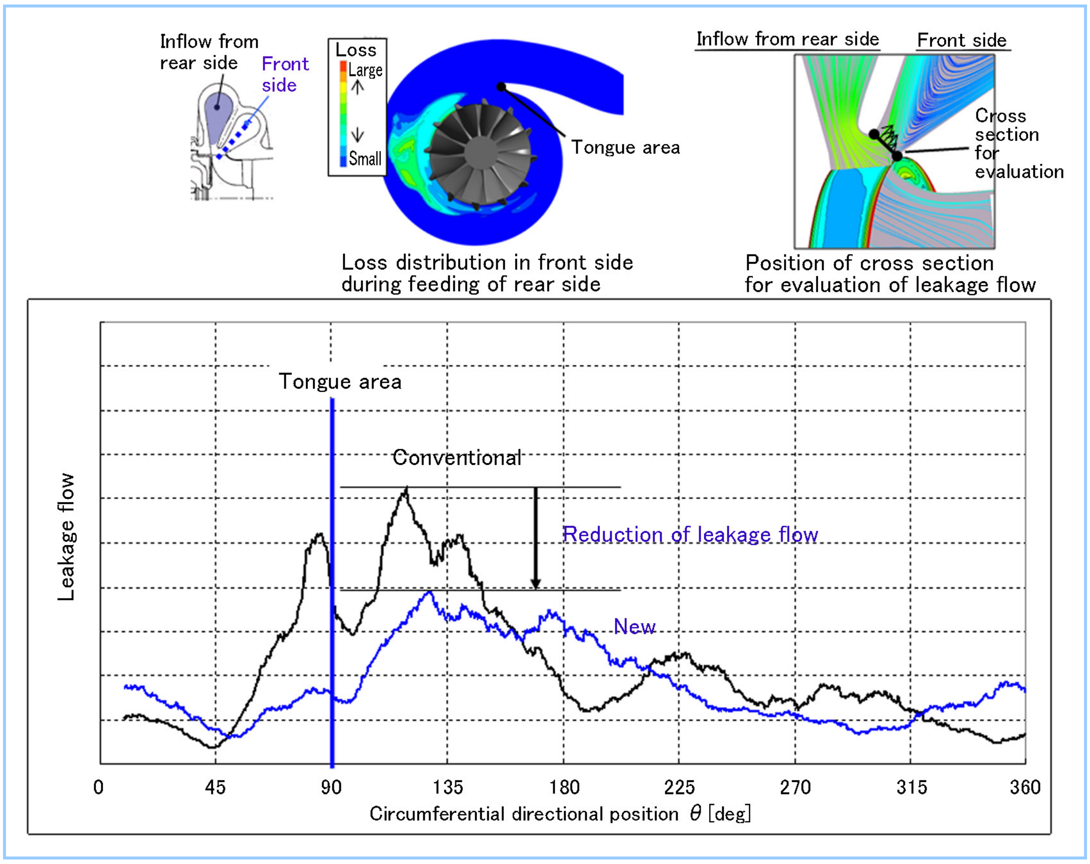



**Figure 10 Comparison of leakage flow on cross section in front side between conventional and new twin scrolls during inflow from rear side (a)**

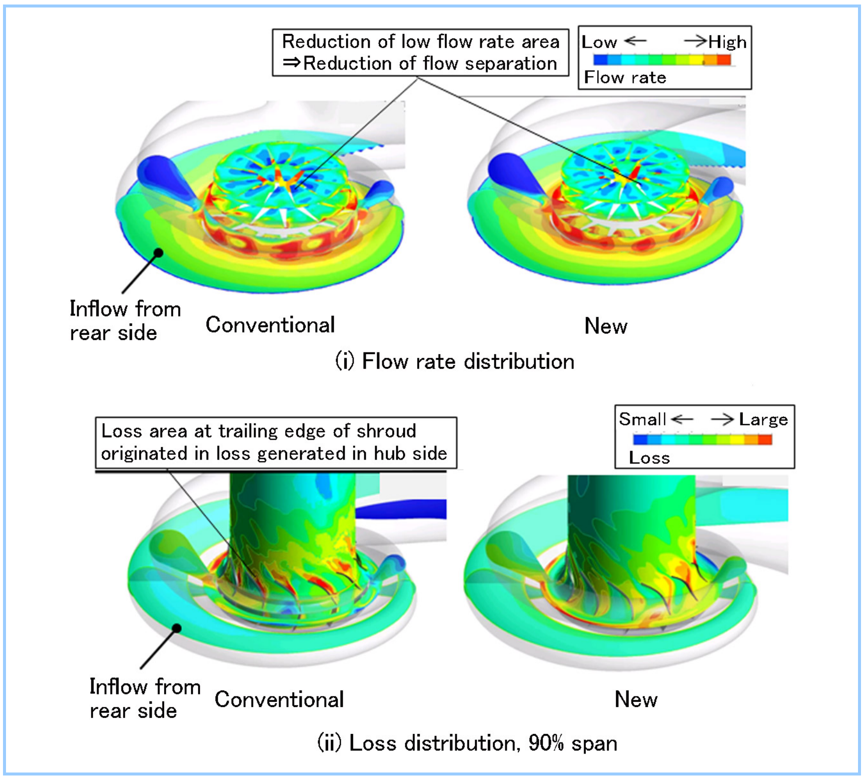



**Figure 11 Comparison of internal flow of turbine rotor blade between conventional and new twin scrolls during inflow from rear side (a)**

**Figure 12** compares turbine efficiency. As shown in this comparison, the new twin scroll has achieved a 1.9% enhancement of mean in-cycle turbine efficiency mainly due to the improvement of efficiency during inflow from the rear side.

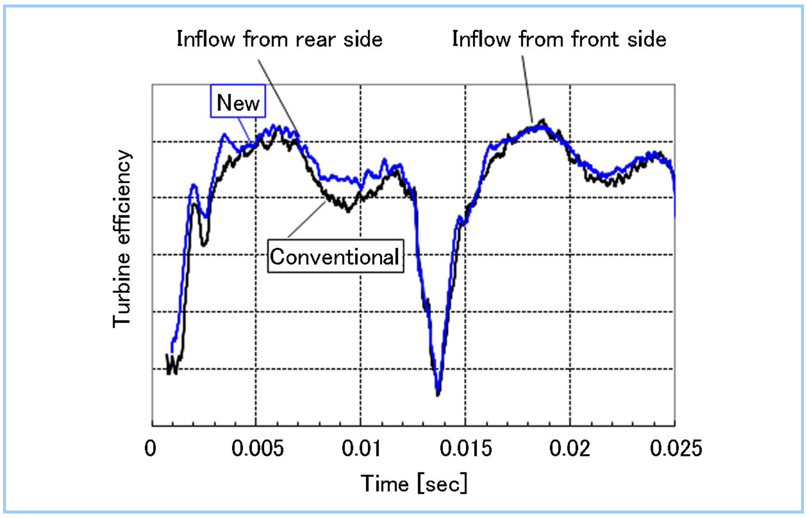



**Figure 12 Comparison of turbine performance between conventional and new twin scrolls**

## 4. Future issues and outlook

MHI has obtained prospects of improving efficiency of twin scroll turbines through restraining internal flow loss of the turbine under conditions of exhaust pulsation. In the future, MHI will conduct performance tests on an engine test bench to verify the effect. Because the internal flow of the turbine under conditions of exhaust pulsation is highly complicated, it is necessary to improve the accuracy of unsteady computational simulation by verification, as well as through an unsteady experiment and the experimental data obtained. MHI will also promote the optimization of the shape of a twin scroll turbine for use with small engines, taking into account its productivity.

## 5. Conclusion

Responding to the tightening of regulations regarding the gas emissions and fuel economy of automobiles, MHI has developed a high-efficiency twin scroll turbine using unsteady computational simulation for the enhancement of the efficiency of turbochargers. This twin scroll turbine can increase the boost pressure even at lower engine speeds during acceleration and increase engine torque, and therefore improve fuel efficiency. It is predicted that the tightening of regulations regarding the gas emissions and fuel economy of engines will continue in the future, and demand for turbochargers with higher efficiency seems to be endless. MHI is willing to develop higher-efficiency turbochargers for the improvement of environmental and driving performance in the future.

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