Technical Paper

Prediction of Torque Converter Characteristics by Fluid Flow Simulation

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Torque converter is a hydraulic coupling that gives and receives the angular momentum of a fluid to transmit torque while effectively protecting the prime mover and extending the service life of components. It shows excellence in effectively generating torque under severe working conditions, such as material handling. On the other hand, it has disadvantages in efficiency, etc. So, it is important how to design a high-efficiency torque converter. But, because of complicated blade shapes and large curvature of flow passage, it is not easy to control internal flow. Concerning manufacture, it is difficult to determine the requirements for manufacturing the complicated blades that directly influence performance or to investigate improvements. Therefore, presently they are determined by trial and error based on experience. In these circumstances, we are studying the analysis of torque converter internal fluid flow using computer to see its feasibility as a tool to predict the characteristics and evaluate the performance of torque converter. This report introduces the analysis method, taking the investigation of blade shapes by fluid flow simulation.

Key Words: *Fluid Flow Simulation, Finite Volume Method, CFD(Computational Fluid Dynamics), FLUENT, Torque Converter, Rothalpy, Simulation, CAE, Fluid Flow Analysis*

1. Introduction

Torque converter is a hydraulic coupling of rotating speed difference sensitive type that gives and receives the angular momentum of a fluid to transmit torque, where the torque to transmit is automatically determined according to the difference in rotating speed between input and output shafts. Torque converter absorbs and damps the variation of engine torque or the vibration input from the reduction gear and has a smooth torque transmission characteristic. It provides various advantages, such as making prime mover easily start, protecting prime mover in case of overload, cutting or absorbing the torsional vibration or impact of shaft system to extend the service life of components, and enabling automatic speed change, and shows excellence in protecting prime mover or the output side transmission gear under severe working conditions, such as material handling, or in effectively generating torque during soil scooping work. On the other hand, its maximum efficiency is low, i.e., 80% to 90%, compared with gear transmission. This leads to the problem of fuel consumption especially when operating at low speed, which is often encountered during work. So, it is important how to design an high-efficiency torque converter. For this, it is necessary to grasp the flow in the passage of internal impeller and determine the shape so that desirable flow can be obtained. However, it is not easy to determine the shape that can

effectively control the flow in the complicated passage, where fluid circulates along the blades of pump, turbine and stator in order in the torus and the curvature of passage is large. On the other hand, concerning manufacture, it is necessary to manufacture the complicated blades that directly influence performance. But it is difficult to determine the requirements of manufacture that do not sacrifice peformance or to investigate improvements that prevent performance from dropping. Therefore, presently they are determined by trial and error based on experience. Many methods of experiment using visualization have been performed to clarify the internal flow phenomena of torque converter, but experiment needs to be repeated till desired solution is obtained. Thus it is difficult to apply them as the method for investigating optimum plan. On the other hand, according to the recent remarkable progress of computer technology, the approach to get solution by numerical calculation (CFD: Computational Fluid Dynamics) comes to be applied. In such circumstances, we tried to apply fluid flow simulation (which is regarded as the same as CFD) to the internal fluid flow analysis of torque converter and investigated the method for predicting the torque converter characteristics or evaluating performance based on flow loss as well as its feasibility as a tool for investigating cost improvement plans. Following is the result of our study.

2. Investigation of the Method for Simulating the Internal Fluid Flow of Torque Converter

2.1 Creating analytical model for fluid flow simulation (overall model)

For fluid flow simulation, like other numerical analysis such as structural analysis, it is necessary to create a three-dimensional shape and discretize it to make a model for analysis. For fluid flow simulation, however, unlike structural analysis where the designed shape of product itself becomes the object of analysis, the object is the space that is formed by the structures, i.e., the space through which fluid passes. Therefore,

1) It is necessary to extract a new passage space for fluid flow simulation and create a shape for analysis (duplicated modeling).

2) Because the object of analysis is a passage space, unlike structural analysis, the simplification in the direction of width by making into shell is impossible. Instead, the discretization of three-dimensional space by solid (creation of 3D mesh) is necessary. (Mesh is hard to create. Large memory capacity is necessary for analysis, and it is difficult to save memory.)

3) For fluid flow simulation, convergence properties and the result of analysis (analytical accuracy) are greatly influenced by the shape of created mesh (aspect ratio), compared with other analysis, so that distorted mesh cannot be used. (Mesh is hard to create. Large memory capacity is necessary for analysis, and it is difficult to save memory.)

Therefore, it is generally hard to create a model. We tried to avoid these problems by devising the procedures for creating a model, as follows:

1) Utilizing 3D-CAD model, blade surface contour and the interal surface contour of shell and core were extracted from a torque converter model in a Pro/E assembly model to configure a passage shape. In this way, a passage model that is interrelated with torque converter model was created. (**Fig. 1 (a)**)

2) Mesh was created by extracting the minimum model unit that has periodicity, and then the periodic model was copied to make an overall model. In this way, appropriate mesh was created, minimizing the deviation of mesh shape among the components having the same shape or between symmetric components. (**Fig. 1 (b)**)

3) Concerning the problem that the number of mesh elements of passage space is large, minute surfaces were merged into the passage model extracted in 1) above to prevent the occurrence of fine mesh elements, and mesh size was made as uniform as possible to prevent analytical accuracy from dropping. (**Fig. 1 (c)**)

4) Concerning the blade surface that requires high accuracy, laminar mesh was created along blade shape to control the increase in the number of mesh elements and create appropriate mesh. (**Fig. 1 (d)**)

These measures made it possible to create an analytical model of torque converter with approximately 600 to 900 thousand mesh elements, which otherwise becomes 5 to 7 million mesh elements (in general, 1 to 1.5 million mesh elements are the limit of analytical calculation with one unit of computer). **Fig. 1** shows the modeling procedure.

a) Extract a fluid space model   b) Extract the minimum model unit with periodicity for each of pump, turbine, and stator   c) Merge minute surfaces   d) Create laminar mesh along blade shape   e) Create mesh for passage space   f) Copy the periodic model to create an overall model
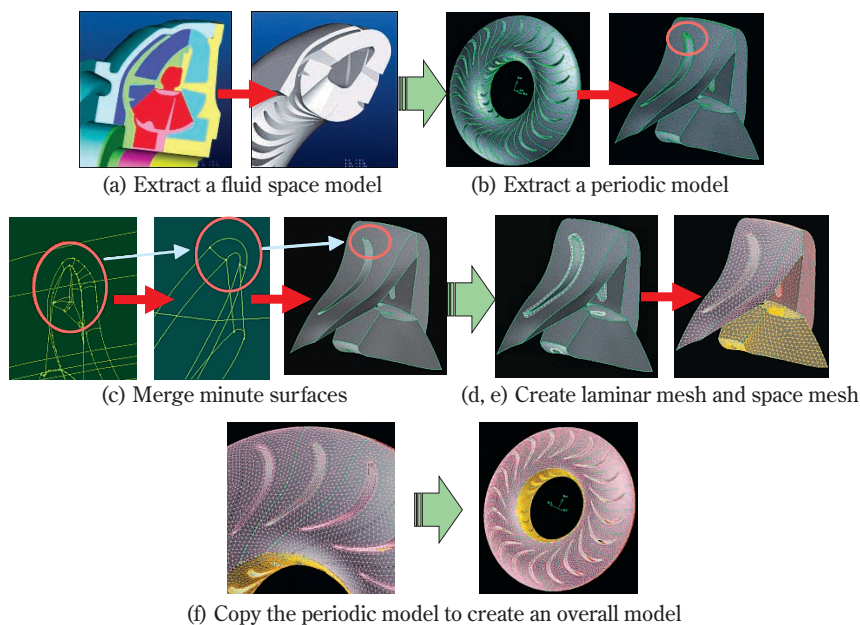

(a) Extract a fluid space model   (b) Extract a periodic model

(c) Merge minute surfaces   (d, e) Create laminar mesh and space mesh

(f) Copy the periodic model to create an overall model

Fig. 1   Procedure for creating an analytical model

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2.2 Creating analytical model for fluid flow simulation (partial model)

When the efficiency and torque ratio of torque converter is obtained by calculating the transmission torque based on the difference of rotating speed between input and output shafts, it is desirable to perform analysis using an overall analytical model that permits phase difference due to the difference in the number of blades. But there is a limit on the number of mesh elements that can be used. For more detailed investigation of specific portion, it is necessary to increase the resolution (the number of mesh elements) of analytical model. A means for this is the "partial model analysis" that cuts out a region in a shape with periodicity and then performs analysis on it. For torque converter, the minimum model unit with periodicity is a combination of the contours of pump, turbine, and stator for each one blade, as shown in **Fig. 1 (b)**. In this case, however, cross sections do not coincide with each other at contact boundary due to the phase difference resulted from different number of blades or the difference in blade shape around contact boundary surface among these elements. As a result, fluid circulation cannot be established at the boundary among pump, turbine, and stator (non-contact surface becomes a barrier: see **Fig. 2 (a)**). Therefore, for partial model analysis, as shown in **Fig. 2 (b)**, we created an analytical model that was cut out in the shape of cheese cake by the greatest common measure of the number of blades of the three elements so that fluid circulation becomes possible while keeping the law of conservation of mass.
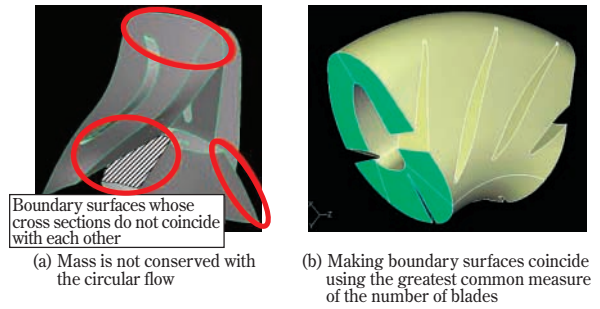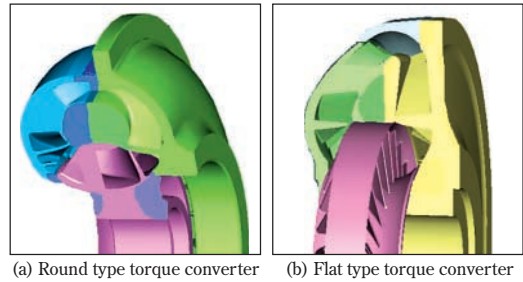
2.3 Verification

Analytical calculation was made for two types of torque converters, which have performance test result, to compare calculation with measurement and thus verify the accuracy of analysis. For flow calculation, general-purpose CFD software FLUENT that uses finite volume method was used. As for various settings necessary for the calculaiton, k-ε turbulence model, Non-Equilibrium wall functions, and 0.012 cm^2/s for the coeffcent of kinematic viscosity of oil at 90°C were used.

Fig. 3 (a) shows the round type torque converter used for the verification analysis; **Fig. 3 (b)** shows the flat type torque converter.

Fig. 4 shows the result of analysis (velocity vector diagram) at a certain point of time for the round type torque converter; **Fig. 5** shows the comparison of analysis and measurement at various speed ratio.

Analytical calculation and measurement show a good coincidence in efficiency, torque ratio, and primary torque coefficient.

Fig. 6 shows the comparison of analytical calculation and measurement at various speed ratio for the flat type torque converter.

Also with the flat type torque converter, like with the round type one, analytical calculation and measurement show a good coincidence in efficiency, torque ratio, and primary torque coefficient.

Thus, it was confirmed that the fluid flow simulation using the analytical model, which is created using the procedures described in 2.1, can favorably predict the performance characteristic of torque converter, such as efficiency, torque ratio, and primary torque coefficient.
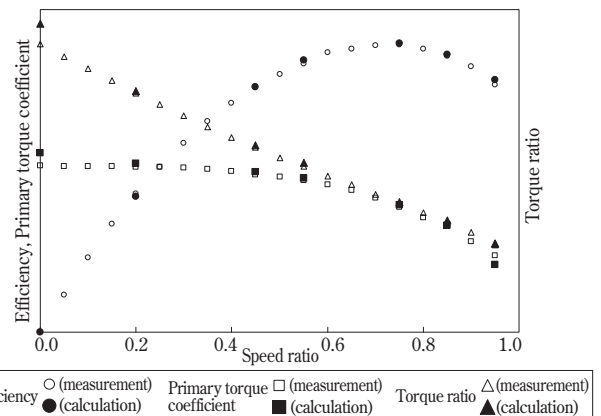

(a) Mass is not conserved with the circular flow

Boundary surfaces whose cross sections do not coincide with each other

(b) Making boundary surfaces coincide using the greatest common measure of the number of blades

Fig. 2 Partial model analysis

(a) Round type torque converter   (b) Flat type torque converter

Fig. 3 Analytical model

Flow occurs with the rotation of pump.

Fig. 4 Result of analytical calculation (velocity vector diagram)

| Efficiency | ○ (measurement) ● (calculation) | Primary torque coefficient | □ (measurement) ■ (calculation) | Torque ratio | △ (measurement) ▲ (calculation) |

Fig. 5 Comparison of performance characteristic between measurement and calculation for round type torque converter

| Efficiency | ○ (measurement) ● (calculation) | Primary torque coefficient | □ (measurement) ■ (calculation) | Torque ratio | △ (measurement) ▲ (calculation) |

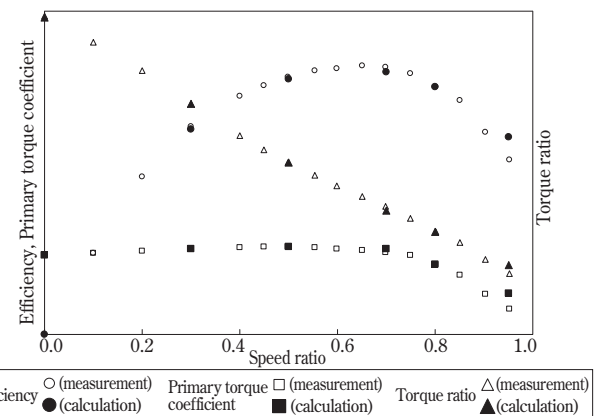**Fig. 6** Comparison of performance characteristic between measurement and calculation for flat type torque converter

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3. Investigation of the Method for Evaluating the Performance of Torque Converter Using Fluid Flow Simulation

For investigation of improving the performance of torque converter, it is important how to reduce the flow loss of the fluid that flows through the passage and make the fluid efficiently circulate through the three elements. For this purpose, we must clarify the internal flow of passage and improve blade shapes (the shape of passage) so that the deviation of flow velocity and the stagnation of flow will be minimized. However, it is difficult to judge whether or not fluid flow condition is good, except when apparantly problematic. Therefore, using the index called rothalpy [1] that enables us to evaluate the flow loss in a passage, we tried to evaluate the flow.

3.1 Loss evaluation formulae

Rothalpy is defined as follows and can be used to evaluate occurred loss.

$$I = P / \rho + 1 / 2\, W^2 - 1 / 2\, U^2 \qquad (1)$$

I: Rothalpy P: Static pressure ρ: Density
W: Relative velocity U: Peripheral velocity

$$\Delta I = I - I_0 \qquad (2)$$

ΔI: Change of rothalpy with respect to element inlet
I_0: Rothalpy at element inlet

$$\eta = 1 + \Delta I / \Delta E \qquad (3)$$

η: Efficiency of element
ΔE: Theoretical energy increase (decrease)

We improved the system by adding formulae (1) through (3) to it so that calculation can be made for individual mesh element of fluid flow simulation, which made the evaluation by rothalpy possible.

3.2 Comparison of analysis result using rothalpy

Using the analysis result of flat type and round type torque converters described in 2, we evaluated the difference of efficiency by the flow loss of passage.

Fig. 7 shows the comparison of efficiency between round type and flat type torque converters; **Fig. 8** shows the comparison of analysis result (velocity vector diagram).
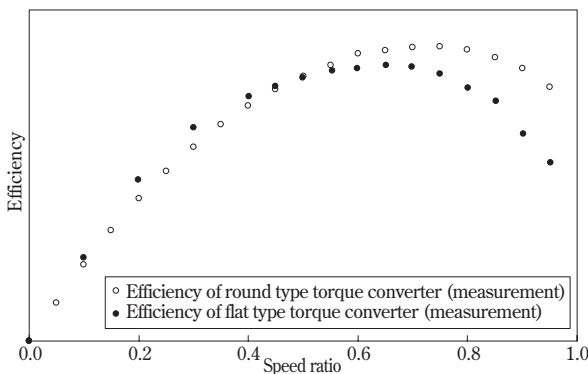

Fig. 7 Comparison of efficiency between round type torque converter and flat type torque converter

(a) Velocity vector diagram for round type torque converter

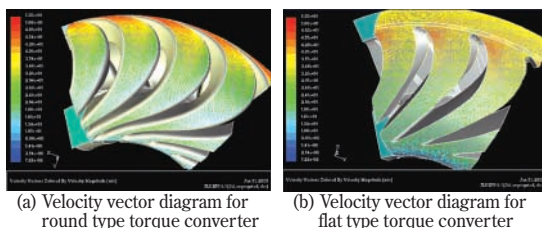(b) Velocity vector diagram for flat type torque converter

Fig. 8 Result of analysis (velocity vector diagram)

From Fig. 7, it is understood that round type torque converter has higher efficiency than flat type torque converter. However, with the velocity vector diagram (**Fig. 8**) that shows the condition of internal flow and the magnitude of flow velocity, it is difficult to analyze the difference. This is because the extent of occurred flow loss is unknown. Therefore, we compared internal flow, using rothalpy. **Fig. 9** shows the comparison of the rothalpy related to pump; **Fig. 10** shows the comparison of the rothalpy related to turbine.
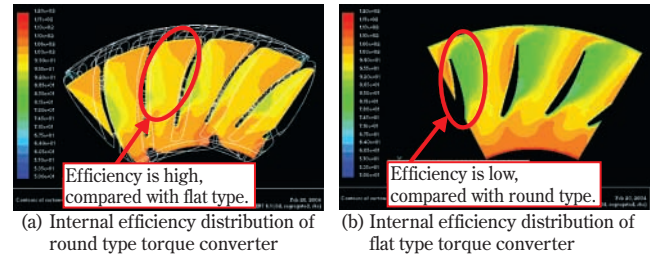

(a) Internal efficiency distribution of round type torque converter

(b) Internal efficiency distribution of flat type torque converter

Fig. 9 Efficiency distribution in passage, evaluated by rothalpy (pump)

(a) Internal efficiency distribution of round type torque converter

(b) Internal efficiency distribution of flat type torque converter
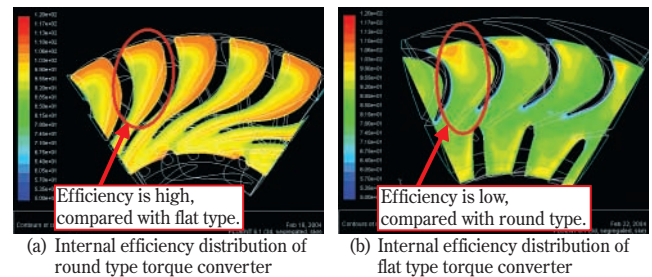
Fig. 10 Efficiency distribution in passage, evaluated by rothalpy (turbine)

From **Figures 9 and 10**, it is undrstood that the area where flow loss (energy loss) is apaprently large is smaller with round type torque converter than with flat type torque converter, for both pump and turbine (flow loss decreases as the color shifts higher on the color index bar at left). As a result, we can evaluate that when this blade shape is used, fluid circulation will be more balanced with round type torque converter than with flat type torque converter and that round type converter is more advantageous in achieving high efficiency.

Thus, it was confirmed that the method using rothalpy is an effictive evaluation tool for investigating blade shapes (the shape of passage).

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4. Investigation of Blade Shapes from the Manufacture Point of View

The torque converters that are used in construction equipment are manufactured by casting, and the difficulty of manufacture depends on their shape that differs with purposes. For example, greater number of cores is required when manufacturing an impeller having the blades with three-dimensional large curvature than when manufacturing an impeller having the blades with two-dimensional curvature (see **Fig. 11**). The former requires additional man-hours in setting cores for the number of blades or removing the burrs that arise in the gap between cores as well as in controlling the gap between cores at proper level, making manufacture highly difficult. For these reasons, in many cases, the torque converters that have the blades with two-dimensional curvature are easier to manufacture and more advantageous costwise when the output is the same.

Therefore, we investigated whether or not the performance characteristic equivalent to that of the round type torque converter having the blades with three-dimensional curvature can be obtained with a flat type torque converter having the blades with two-dimensional curvature by changing blade inlet and output angles. For this investigation, the round type torque converter having the blades with three-dimensional curvature and the flat type torque converter having the blades with two-dimensional curvature, which were described in 2.3 above, were used. **Fig. 12** shows the comparison of performance characteristic between these torque converters.
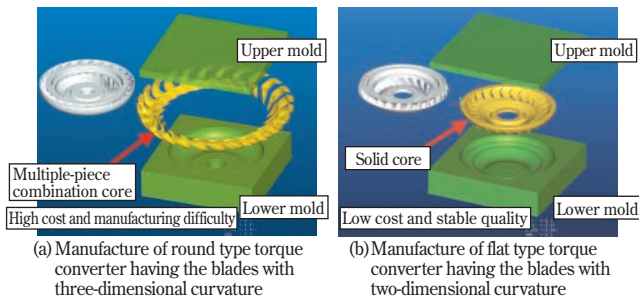

(a) Manufacture of round type torque converter having the blades with three-dimensional curvature
(b) Manufacture of flat type torque converter having the blades with two-dimensional curvature

Fig. 11 Comparison of manufacturing process (molding method)

○ Efficiency of round type (measurement)
● Efficiency of flat type (measurement)
□ Primary torque coefficient of round type (measurement)
■ Primary torque coefficient of flat type (measurement)
△ Torque ratio of round type (measurement)
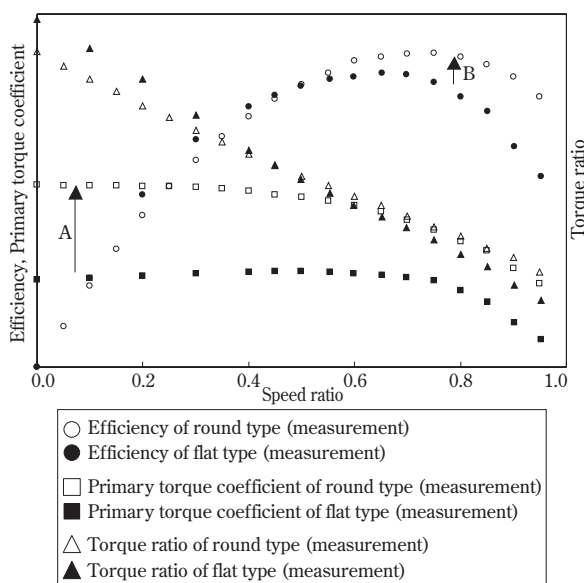▲ Torque ratio of flat type (measurement)

Fig. 12 Comparison of performance characteristic between round type torque converter having the blades with three-dimensional curvature and flat type torque converter having the blades with two-dimensional curvature

4.1 Investigation of primary torque coefficient

According to **Fig. 12**, for matching the performance characteristic, it is necessary to increase the primary torque coefficient of the flat type torque converter during stall (A in **Fig. 12**). However, there is the relation of antinomy between primary torque coefficient and torque ratio. So, torque ratio decreases if primary torque coefficient is increased carelessly. Therefore, according to the result of experiment by Mr. Nunobe [2], we decided to use the method of increasing primary torque coefficient beyond the target value by controlling the outlet angle of pump blades that has a great influence on primary torque coefficient and on torque ratio while compensating for the decrease of torque ratio by changing the inlet angle of pump blades and the inlet and outlet angles of turbine blades that have a great influence on torque ratio but only a small influence on torque coefficient, and tried to adjust the values by repeating fluid flow simulation. **Fig. 13** shows the result of analytical calculation obtained from fluid flow simulation for the improved flat type torque converter as well as the comparison of performance characteristic (primary torque coefficient and torque ratio) with the round type and the conventional flat type torque converters.
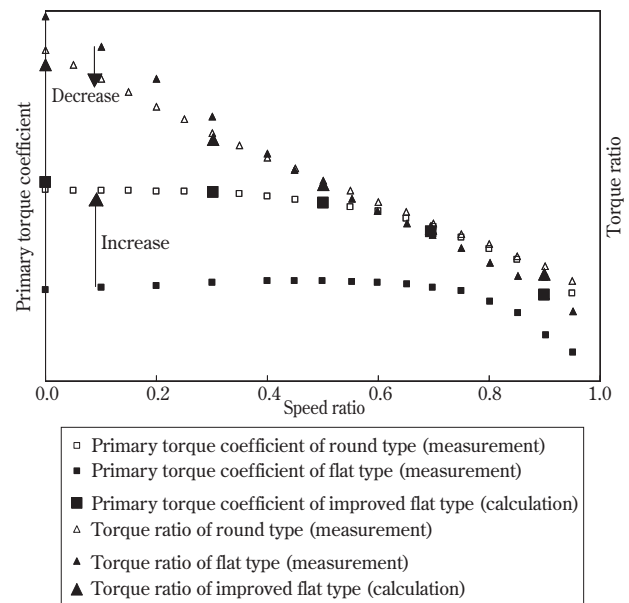

□ Primary torque coefficient of round type (measurement)
■ Primary torque coefficient of flat type (measurement)
■ Primary torque coefficient of improved flat type (calculation)
△ Torque ratio of round type (measurement)
▲ Torque ratio of flat type (measurement)
▲ Torque ratio of improved flat type (calculation)

Fig. 13 Comparison of the calculation result of improved flat type torque converter with the measurement results of round type and flat type torque converters

Fig. 13 indicates that the fluid flow simulation revealed the possibility of increasing the primary torque coefficient during stall by approximately two times, or to almost the same level as round type torque converter, while keeping the decrease of torque ratio as small as possible, by adjusting the blade angles of flat type torque converter having the blades with two-dimensional curvature.

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4.2 Investigation of efficiency

Then, concerning the subject of increasing the efficiently of flat type torque converter in the high speed ratio range (B in **Fig. 12**), we first evaluated the conventional flat type torque converter by rothalpy to pinpoint the portions of low energy efficiency and then adjusted blade length, the position of curvature of blade, ovality, etc., so that the relation between primary torque and torque ratio, which was obtained as described before, will not be lost by repeating fluid flow simulation. **Fig. 14** shows the comparison of rothalpy between conventional flat type torque converter and the improved flat type torque converter.
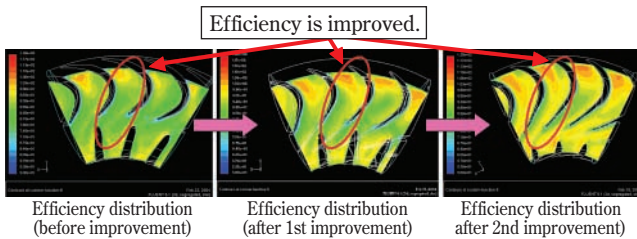
Efficiency is improved.

Efficiency distribution (before improvement)　Efficiency distribution (after 1st improvement)　Efficiency distribution after 2nd improvement

Fig. 14 Improvement of energy efficiency by changing the shape of passage (blade shapes)

From **Fig. 14**, it is understood that the flow loss in passage is improved with the improved flat type torque converter. **Fig. 15** shows the comparison of performance characteristic between the round type torque converter having the blades with three-dimensional curvature and the improved flat type torque converter having the blades with two-dimensional curvature.
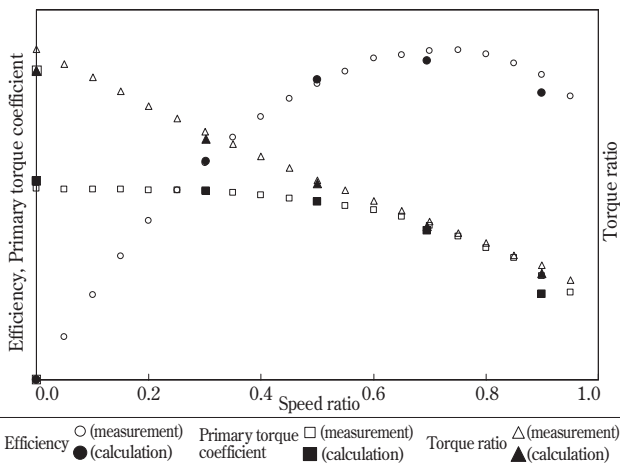
Efficiency, Primary torque coefficient

Torque ratio

Speed ratio

Efficiency ○ (measurement) ● (calculation)　Primary torque coefficient □ (measurement) ■ (calculation)　Torque ratio △ (measurement) ▲ (calculation)

Fig. 15 Comparison of the calculation result of improved flat type torque converter with the measurement result of round type torque converter

This figure reveals that it is possible to investigate the improvement of efficiency in the medium to high speed ratio range without greatly reducing the values of primary torque coefficient and torque ratio by evaluating the shape of passage by rothalpy. Our improvement, however, still results in several percents below the target, requiring further investigation.

5. Conclusion

It was confirmed that many level experiments, which have been difficult to perform, can be done on a desk by applying fluid flow simulation and that such method can effectively be applied to advance investigation of new design or improvements for cost cut. In order to fully utilize the advantage of simulation, or the visualization of the phenomena that are hard to measure, we would like to further investigate the performance evaluation when equipment is used in such a way as is hard to experiment, for example, during rapid acceleration, and the evaluation of structure including peripheral components.

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Introduction of the writers

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[A few words from the writers]

Recently computer technology and numerical analysis technology have shown a remarkable progress. A short time ago we often encountered a limit when analyzing the flow around only a single blade, but now it is possible to predict the flow, taking the movement of pump and turbine into consideration. CAE, which used to be only a stimulus to our brain, has become able to do many things with considerable perfection. We would like to make further effort to use the CAE's capability of visualizing unseen phenomena more effectively.