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A Comparison of Manufacturing Methods, Accuracy, Quality Control and Testing Methods as they relate to High Head Low Flow Impeller Efficiency and Overall Compressor Performance

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ABSTRACT

This paper presents a detailed analysis and evaluation of impeller efficiency and overall compressor performance as they relate to specific impeller manufacturing methods, manufacturing tolerances, and quality control. The manufacturing process used in the construction of an impeller has a direct influence on the impeller's performance The authors explain and compare different manufacturing methods and introduce the Taguchi Method Application as an available tool for statistical evaluation of key manufacturing parameters influence on impeller performance.

As a best practice, manufacturing techniques for one piece impeller production are presented. In the case of high pressure centrifugal compressor applications with very narrow tip width impellers, and corrosive gas applications requiring special materials, EDM (Electrical Discharge Machining) and ECM (Electrolytic Machining) can be applied as a manufacturing process to improve quality control over conventional manufacturing methods.

In response to a compressor performance discrepancy encountered during OEM FAT, a review was initiated into improving quality control and performance prediction based on enhanced impeller manufacturing processes for narrow tip width impellers.

In this analysis, two compressor rotors are evaluated and compared; the first using traditional, two piece welded impellers and the second with one piece impellers machined via EDM and ECM. The resulting data from both series of tests suggests a significant improvement in individual impeller performance, as well as overall compressor performance for the single piece impeller compared to the two piece impeller.

INTRODUCTION

For gas injection applications, the discharge pressure required by users has increased to over 12000 psi as shown in Figure 1. Impellers designed for low flow coefficients and narrow flow passages are necessary to meet these increasing demands.

During this decade, the capacity of ethylene plants has tended to increase continuously as shown in Figure 2. The market demand for larger compressors has required development of large impellers and longer bearing span rotors. Compressor trains with over 1.5MMTPY capacity are already designed, manufactured and successfully in operation such as those shown in the photographs of Figure 3 and Figure 4. The same trend can be observed in LNG plants, which are approaching capacities of 7.8 MMTPY.

To accommodate these demanding services, compressor stability and impeller efficiency are two key design areas. Notable characteristics of high pressure compressor design include higher excitation forces at higher densites, narrow impeller passages, and higher rotating speeds.

In addition to implementing an effective compressor design, it is necessary to be able to accurately predict the compressor performance, apply the most cost effective manufacturing method that will meet performance and quality expectations, and verify that the compressor performance meets the user's required operating condition.

Although performance prediction methods have improved, differences between measured and predicted performance are still recurrent throughout the compressor industry. Delay in equipment delivery whilst performance issues are resolved can results in significant costs to both the OEM and customer. Understanding the sensitivity of impeller parameters to impeller performance is important for setting manufacturing tolerances that are reflective of each parameters sensitivity. This will result in improved performance prediction whilst not over specifying parameters that have only a minor impact on the performance.

Since the manufacturing process used in the construction of an impeller has a direct influence on the impeller’s performance, the authors explain and compare different manufacturing methods, and introduce the Taguchi Method Application as an available tool for statistical evaluation of key manufacturing parameters influence on impeller performance.

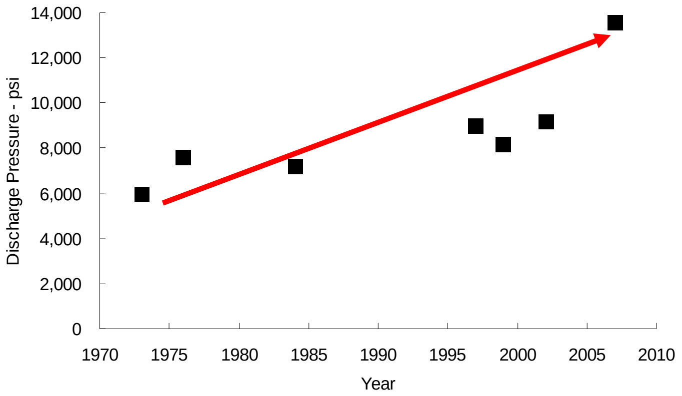


Figure 1. World wide Centrifugal High Pressure Compressor

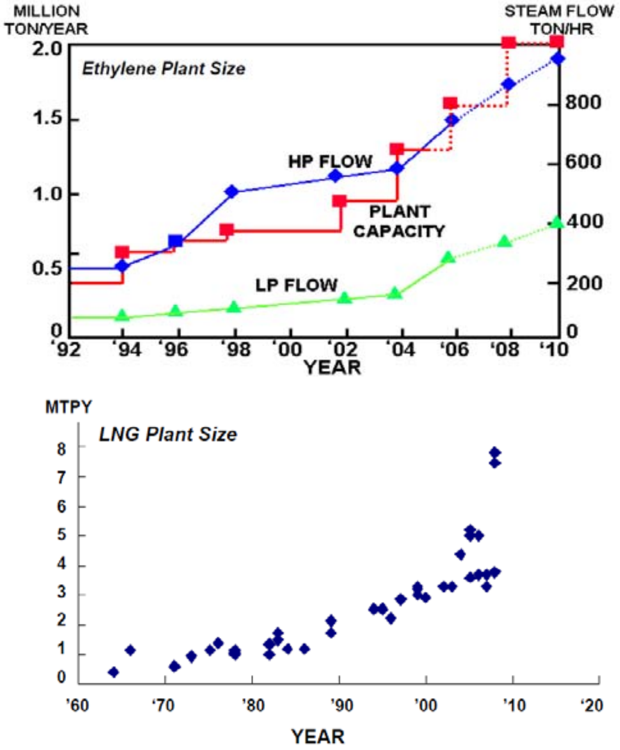


Figure 2. Ethylene and LNG Plant Size–Past & Future Trends

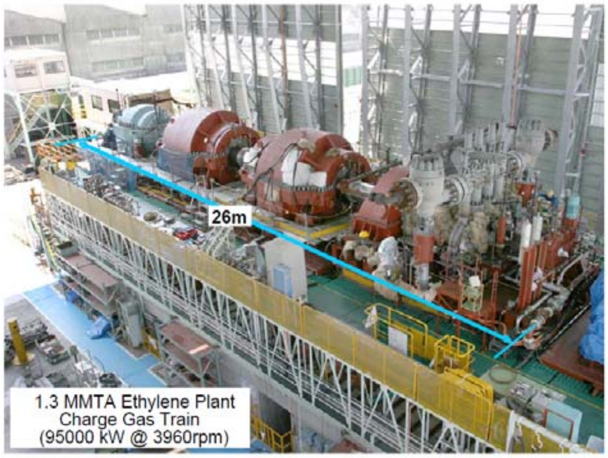


Figure 3. Typical Mega Ethylene CGC Trains Shop Test

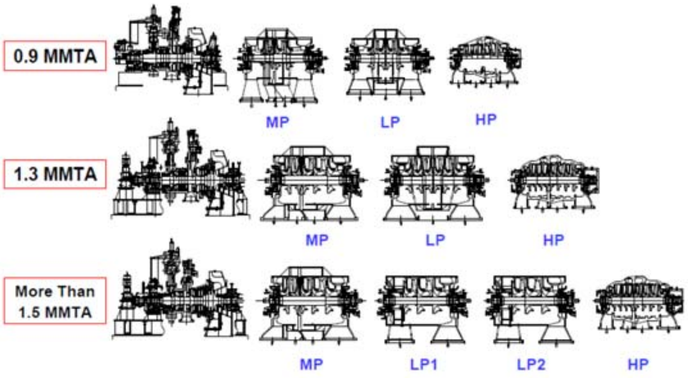


Figure 4. Typical Mega Ethylene CGC Trains

Application of Scaling Principle in the Design of Impeller Flow Path

Over several decades the basic design process has evolved from using only empirical knowledge based, numerical logical single-objective optimization to the latest tools in multi-objective optimization (see Figure 5). Depending on these processes, the simulation technologies have been improved from simple in-viscid Q3D, 1D performance prediction expanding to 3D NS steady blade passages, full model and unsteady interaction. In parallel with changes in simulation technologies, the procedure has also changed from systematic experiments, design considering interactions between multi-components, and manual operation of performance, to multi-objective (e.g. polytropic head, efficiency and operating range) optimization of performance curve and recently multi-objective & multi-disciplinary (fluid dynamics, coupled with acoustic and structural vibration in high dense phase gases), value supply optimization.

As a result of improvements in simulation technologies, impeller profiles had been optimized to achieve efficiencies of over 90% polytrophic efficiency. This equates to a 10% increase from the conventional type 30 years ago as shown in Figure 6.

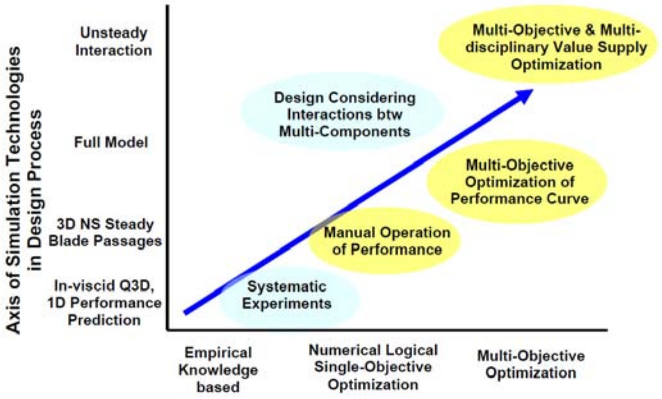


Figure 5. Axes of Design Simulation Technologies

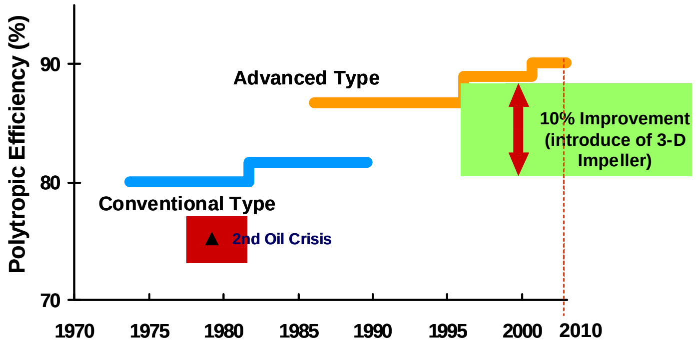
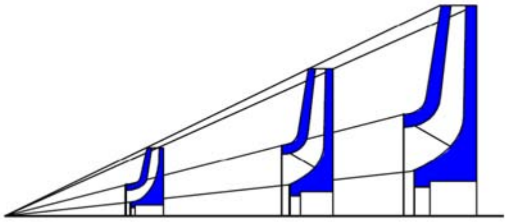


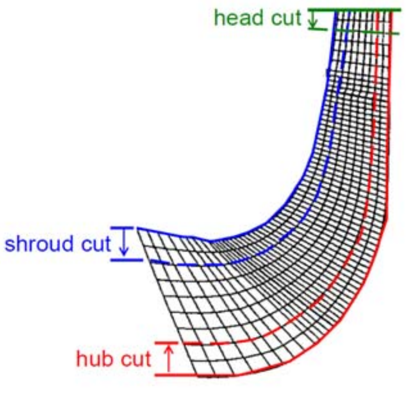
Figure 6. Trend of Compressor Efficiency

The standard impeller performances, which become impeller family data, are measured by using standard stages manufactured to the design based on CFD analysis. The impeller flow path for a specific application is designed by scaling the standard stages based on the scaling principle (see Figure 7a). For a specific application, the tip diameter and flow passage along the streamline are adjusted by head cut, shroud cut, and hub cut to optimize impeller for operating conditions (see Figure 7b).

Since the manufacturing process used in the construction of an impeller has a direct influence on the impeller's performance (due to the impeller shape difference from the standard impeller and deviation from the similarity principle in the range of tolerances), it is important for the compressor designers to have an understanding of how these variables influence the impeller performance.



a) Scaling Principle



b) Head Cut, Shroud Cut and Hub Cut

Figure 7. Stage Design Procedures
Technical approach, Design Philosophy

Evaluation Study based on Statistical Method (Taguchi Method Application) for Impeller Manufacturing Accuracy and Influence for Performance

It is important to understand how configuration differences of impeller gas flow passage will affect its performance and the sensitivities of configuration selection.

In order to evaluate these characteristics, the Taguchi-method, an experimental / simulated design methodology used to investigate the sensitivity of performance characteristics (head and efficiency), to parameter variation through experimentation, can be useful for quality control engineering. The Taguchi- Method can be useful for identify which parameters to focus on and establishing tolerance requirements for each parameter to minimize deviation from target performance.

The authors classify several basic patterns in terms of impeller figure, dimensions and flow path surface roughness difference as shown in Figure 8.

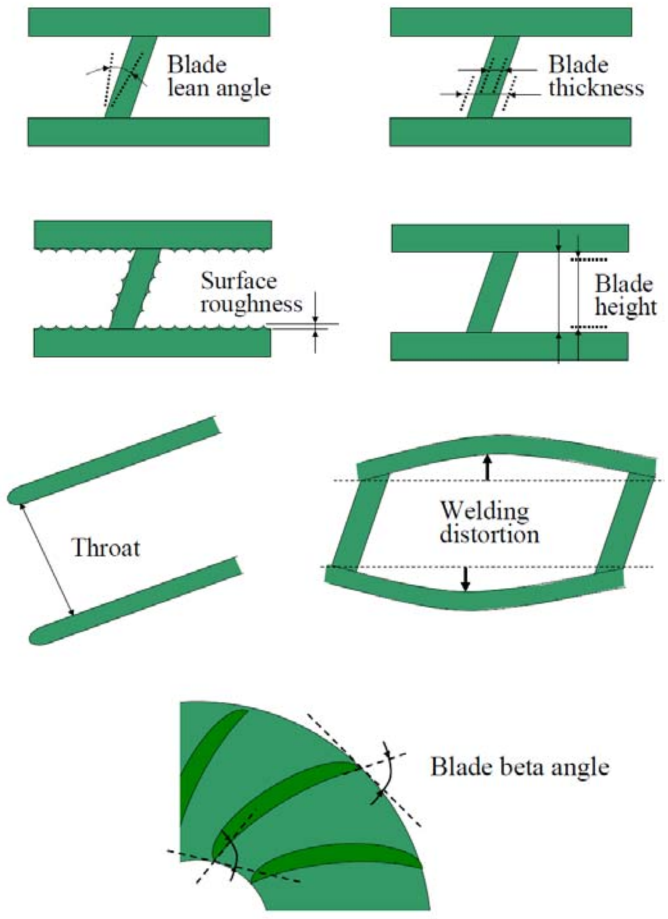


Figure 8. Configuration pattern parameters for impeller Performance Statistical Analysis

The control factors for the parameters of; blade lean angle at both inlet and outlet, blade height at both inlet and outlet, welding distortion and blade thickness are defined. The throat area is dependent on blade height, blade thickness and welding distortion, therefore, variation of throat area can be simulated by changing these parameters. The angle between vane camber-line and meridional coordinate 'blade beta angle' although an important parameter on the impeller performance, was not included in this study as the manufacturing data was not available. The typical theoretical analysis results of the head coefficient and stage efficiency in terms of beta angle for outlet side is shown in Figure 9 to understand their sensitivity independently. The normalized head coefficient is affected.

The outlet blade angle variation of +/- 3 degrees results in a pressure coefficient variation of +6/-8% relatively, thus beta angle is a key manufacturing parameter that must be tightly controlled to avoid performance discrepancies.

It is also difficult to incorporate surface roughness into CFD modeling because its scale is much smaller than other components such as blade height, blade thickness, therefore, surface roughness is modeled as a constant factor in this study, however, it is important to note that surface roughness is still an important parameter affecting performance.

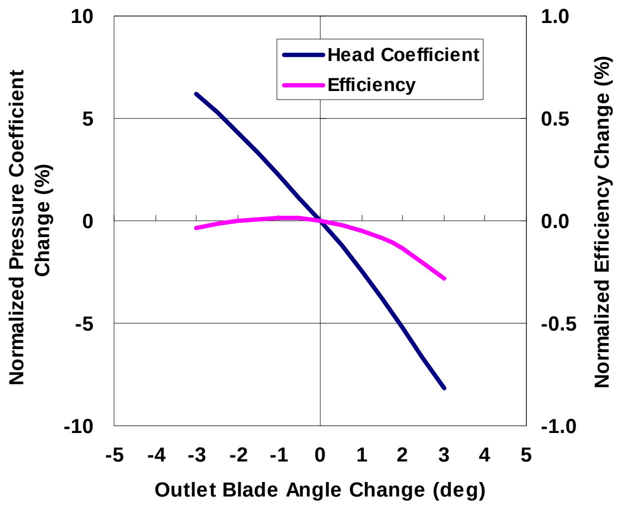


Figure 9. Typical Impeller Performance Sensitivity of Blade Profile Angle in case of Low Flow Coefficient

By changing the control factors within the measured variation bounds (based on the actual machined work inspection results), the performance is calculated by CFD, and the polytropic efficiency and pressure coefficient change are compared to the measured sensitivity for each factor. Typical statistical analysis results for low coefficient impellers are shown in Figure 10, and summary of performance statistical analysis results in Table 1.

Pressure coefficient and polytropic efficiency have high sensitivity to blade height at outlet (tip width) and blade height at inlet. Welding distortion affects both pressure coefficient and polytropic efficiency with moderate sensitivity. As described above, these parameters are representative of the throat area and also flow area of the impeller passage. The stage performance of low flow coefficient impellers is thus adversely affected and sensitive to throat area and flow area reduction. In the case of two piece welded impellers, the welding penetration will reduce the flow area. Therefore excessive welding penetration leads to a reduction in the pressure coefficient from design.

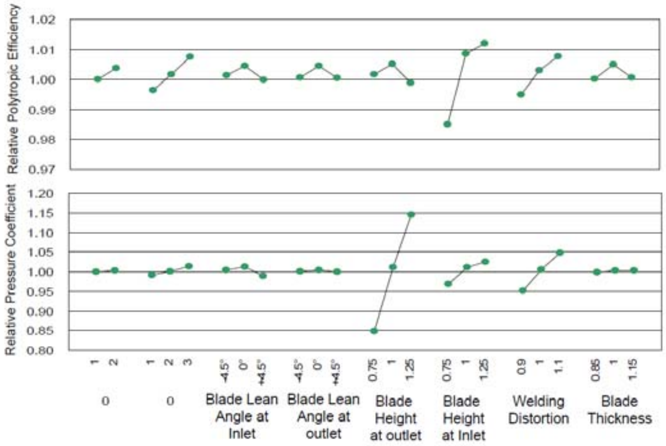


Figure 10. Impeller Performance Statistical Analysis Results

Table 1. Summary of Performance Statistical Analysis Results

Control Factor	Polytropic Efficiency	Pressure coefficient
Blade Lean Angle @ inlet	L	L
Blade Lean Angle @ outlet	L	L
Blade Height @ outlet (Tip Width)	L	H
Blade Height @ inlet	H	M
Welding Distortion	M	M
Blade Thickness	L	L

H : High Sensitivity
M : Moderate Sensitivity
L : Low Sensitivity

Type of Impeller Manufacturing Methods

The range of impeller manufacturing methods includes; classical riveted type, three piece welded type; two piece welded type, two piece brazed, and one piece weld-less type. Any manufacturing deviations from design dimensions affect impeller performance, and cause the performance to deviate from the expected performance. Welded impellers have a performance and strength disadvantage over the one piece impellers, due to manufacturing issues such as; strength at the weld heat affected zone, distortion during the welding process, and challenge welding each piece at precise locations and angles. As a best practice, manufacturing techniques for one piece impeller production are presented.

In this paper, the one piece weld-less type impeller is focused on as one of the most accurate manufacturing methods.

In the case of high pressure centrifugal compressor applications with very narrow tip width impellers and corrosive gas applications requiring special materials, EDM (Electric Discharge Machining) and ECM (Electrolytic Machining) can be applied to improve quality control where a 5 axis mill machine cannot be used due to the practical limitations of machine tool head accessibility. The dimensional accuracy of EDM and ECM process is the same as conventional 5-axis mill machining

Typical Manufacturing Method for One Piece Impeller

The typical manufacturing process plan for one piece impellers is shown in Figure 11.

The raw material is a forged disk, solution treated, water quenched and stress relieved. This disk is roughly machined and is inspected by NDT for defects. Impeller gas passages are then formed using EDM and polished using ECM process. Final machining and balancing are then conducted.

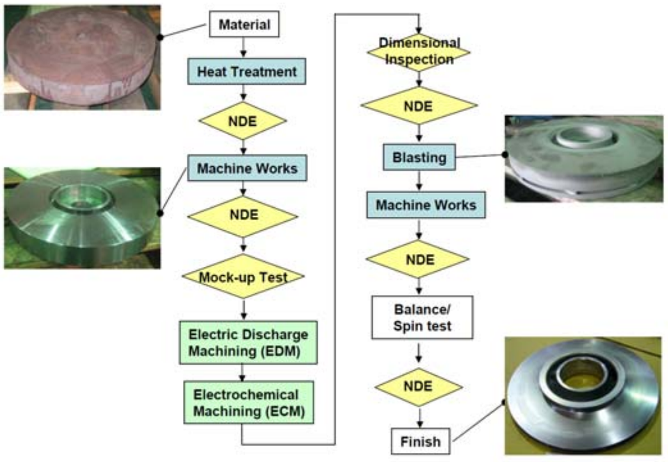


Figure 11. Typical Manufacturing Process for One Piece Impellers

Due to its unique properties, duplex stainless steel can be difficult to weld and can also experience large deformations after machining / stress relieving. To address these challenges, EDM and ECM are applied.

The EDM process melts the material at the surface. A thin layer of the molten material re-solidifies. This thin layer on the surface is referred to as the recast layer. A Heat Affected Zone (HAZ) also forms below the recast layer as a result of the high temperatures associated with the EDM process. These surface conditions affect impeller efficiency and strength under corrosive conditions. To remove the recast and HAZ, and improve the surface finish, polishing has to be considered such as: Electrolytic Machining (ECM).

Electrical Discharge Machining (EDM) Process

The gas passages in the impeller are machined by using a series of carbon electrodes shaped to form the gas passage (see Figure 13. A set of approximately ten (depending on impeller configurations) different shaped electrodes are required to form the gas passage. The impeller and electrode are immersed in a dielectric fluid and a DC current is applied. The current is cycled on and off. When the dielectric strength of the fluid is achieved, plasma forms, which allows a spark between the electrode and the impeller. The spark melts and vaporizes the impeller material, and over time forms the shape of the impeller's gas passage. The dielectric solution cools the impeller and electrode, and carries the debris away where it is filtered from the fluid (see Figure 14).

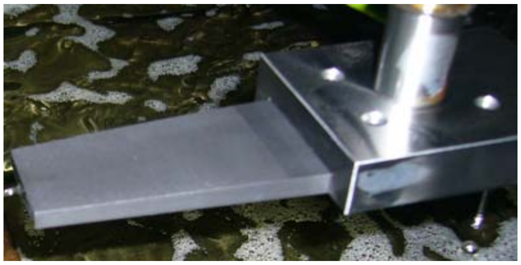


Figure 13. Sample of Electrode

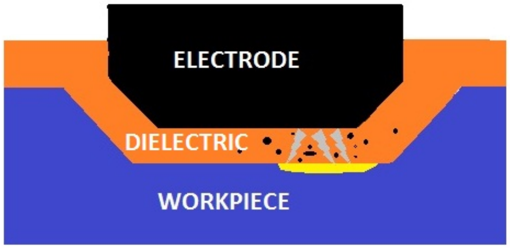


Figure 14. EDM Process

Electrolytic Machining (ECM) Process

ECM uses Faradays principle (electrolysis), to remove material from the impeller. The process is the reverse of electro plating. The impeller (Anode) and electrode (cathode), are immersed in a electrolyte solution (see Figure 15).

ECM in this application is considered a polishing process, which removes a small (50 micron) layer from the impeller surface. This removes the recast layer and HAZ, and improves the surface finish. Typical surface finish from ECM is finer than Ra = 6 microns.

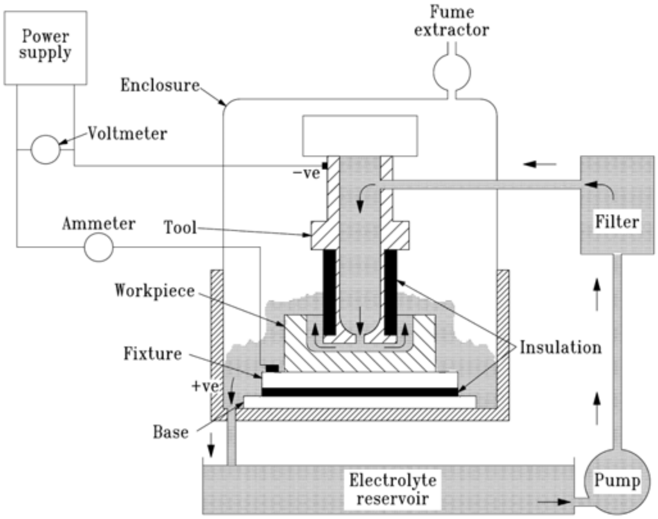


Figure 15. ECM Process

How to Evaluate Quality Control Process of EDM (Electrical Discharge Machining) Including special materials for high corrosive gas application

When utilizing enhanced design and manufacturing processes such as EDM and ECM, risk assessment and quality control are necessary to ensure quality of the final product.

As a risk control measure, a mock up (sacrificial) test of the impeller was conducted to verify dimensions after EDM. The mock up testing is used to prove the EDM process prior to manufacturing the production impellers. The blade profile, throat area, flow passage area profile along radial flow, surface roughness and hardness, and any deformation are measured on test impellers as shown in Figure 16.

Testing results showed that all of the critical dimensions and surface conditions, including material properties, were within design specifications.

Figure 16 .Trial Manufacturing (Mock up Test) for EDM

When considering applications with corrosive conditions, it is necessary to focus on the sensitivity of surface condition and residual stress affecting rupture time, and to evaluate the surface condition before/after machining, EDM, and polishing via ECM. In this regards, Duplex stainless steel should be considered as a commonly used material for corrosive services (shown in Figure 17).

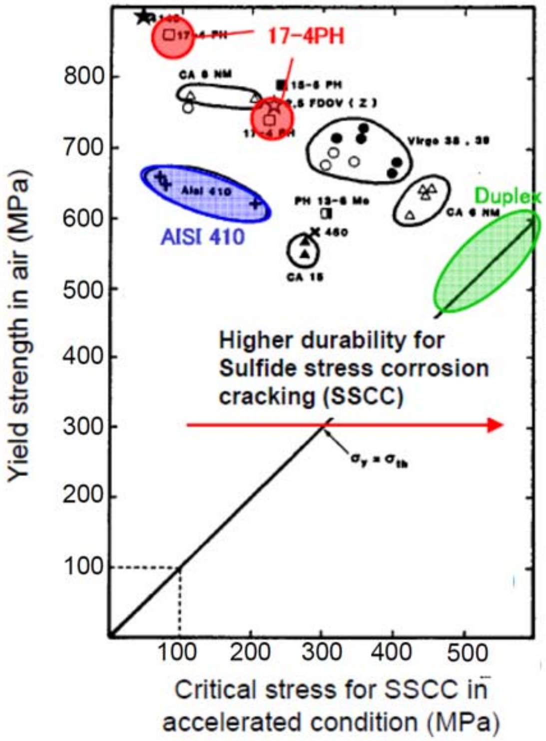


Figure 17. SSCC durability of AISI410 and 17-4PH for Cl+H2S environment (NACE test in accelerated condition)

Figure 18 shows cross-sectional photographs, after EDM and ECM, of duplex stainless steel (SUS329J4L) specimens. The ECM process has removed the recast layer which was created by the EDM process; the material properties at the surface are returned to the base material's properties.

In addition, a proof ring test according to NACE standard TM-0177 is conducted at the following conditions:

- 1 atm H2S
- Room temperature
- pH2.7
- Cl: 30,000ppm / 50,000ppm
- Applied stress: 95% of yield strength

Test results are shown in Figure 19. The EDMed specimens were ruptured within 240 hours;, in contrast, ECMed specimens exhibited similar results as the machined specimens, which achieved at least 720 hours without rupturing.

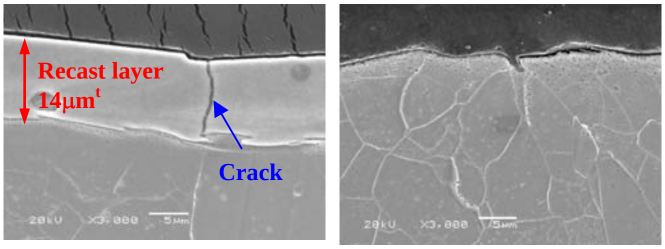


Figure 18. Section of Specimens after EDM and ECM

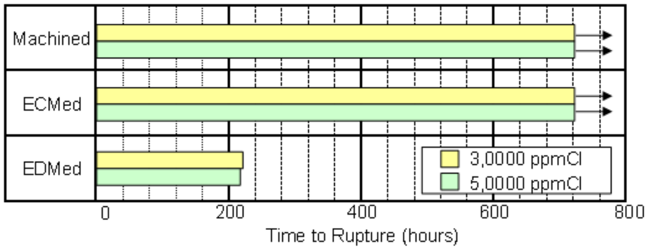


Figure19. Proof Ring Test Result

Performance Evaluation of Conventional Two Piece Impeller

The arrangement of the high pressure compressor train is shown in Figure 20 and basic specifications are summarized below:

Compressor Model: 3V-7
Service: Gas Lift
Driver: Fixed Speed Induction Motor and Gearbox
Suction Pressure: 83 kgf/cm2a
Discharge Pressure: 179 kgf/cm2a
Suction Flow: 75,370 kg/h
Suction Temperature: 33 deg.C
Maximum Continuous Rotational Speed: 12,815 rpm
Shaft Power: 2,993 kW

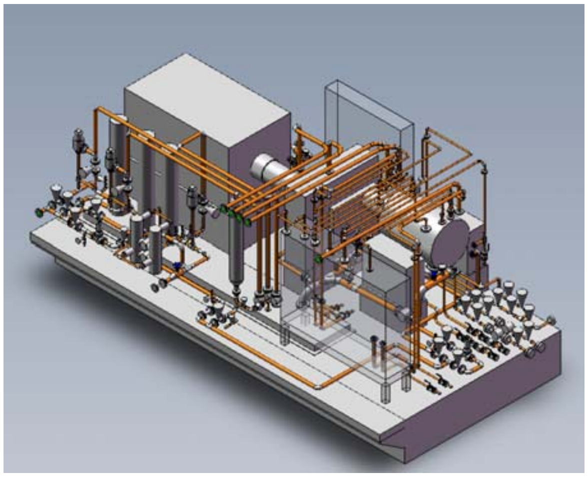


Figure 20. High Pressure Compressor Train

Table 2. Impeller Basic Dimensions

Stage	Model	Tip Diameter (mm)	Tip width (mm)	Material
1	B2	300	9.0	JIS G4053 SNCM431 (AISI 4330 equivalent)
2	B2	300	7.9	Ditto
3	B2	300	6.9	Ditto
4	B2	300	6.1	Ditto
5	B2	280	6.2	Ditto
6	B2	280	5.7	Ditto
7	B2	280	5.6	Ditto

Table 2 shows the compressor impellers' basic dimensions. The minimum tip width is 5.6mm, and the nominal flow coefficient of impeller is 0.02 for all stages.

Initially, the compressor utilized conventional two piece welded impellers as shown in Figure 21, with welding. performed from the disc side (groove welding). An ASME PTC-10 Type-2 test was carried out to check performance.

A comparison of the measured and predicted results for overall efficiency and pressure coefficient are shown in Figure 22. The measured efficiency was higher than predicted, however the measured pressure coefficient was lower than predicted. To investigate this phenomenon, a root cause analysis was conducted.

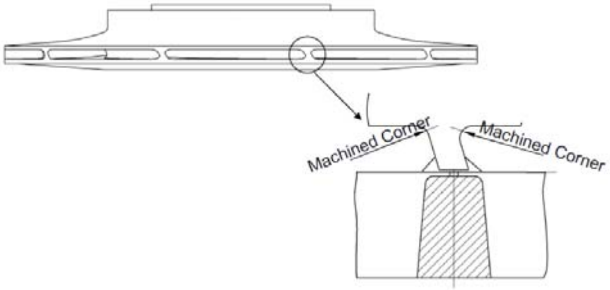


Figure 21. Two Piece Welded Impeller

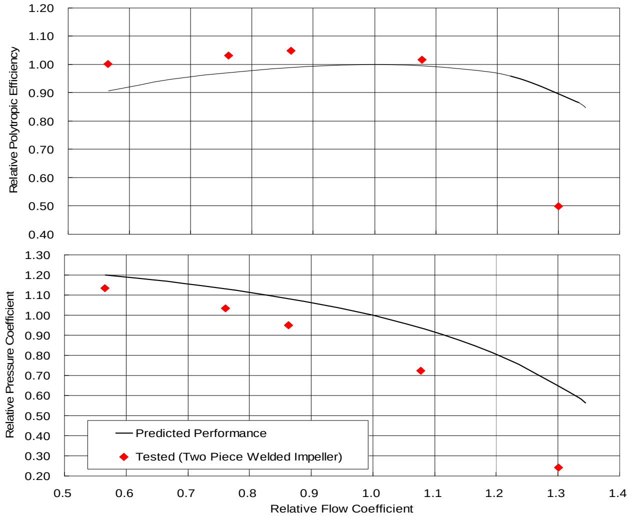


Figure 22. Type-2 Performance Test Result in case of Tow Piece Impeller

Root Cause Analysis (RCA) for Compressor Performance Deviation

The elements involved in the RCA included: performance prediction, fabrication drawings, manufacturing records, assembly conditions, and performance measurements (e.g. instruments' correlation, test loop conditions, test gas properties). The RCA results indicated that the impeller flow passage area is the most likely cause of the performance discrepancy. To check this, the outlet flow area of each impeller was measured and compared against the design value. The area reduction ratio from design, for each stage is shown in Figure 23.

Stage	1st	2nd	3rd	4th	5th	6th	7th
Outlet Area Ratio (Actual/Design)	0.88	0.89	0.93	0.93	0.95	0.97	0.93

Figurer 23. Shape of Impellerand Area Reduction Ratio

The flow area of the impellers was restricted by excessive welding-penetration, and the blade thickness at the impeller inlet and outlet were larger than those of the scaled B2 standard impeller, due to fabrication reasons. The deviation from scale model impeller's principle of scaling, and the restriction of impeller flow area, affected the performance test result.

The authors simulated the compressor performance, adjusting the performance model to account for the restricted flow passages. Figure 24 shows the simulated pressure coefficient, and the prediction with restricted impellers matches well with measurements. If the impeller was manufactured with no deviations, it would match the scaled standard impeller according to the principle of scaling, and the compressor would have matched the predicted performance.

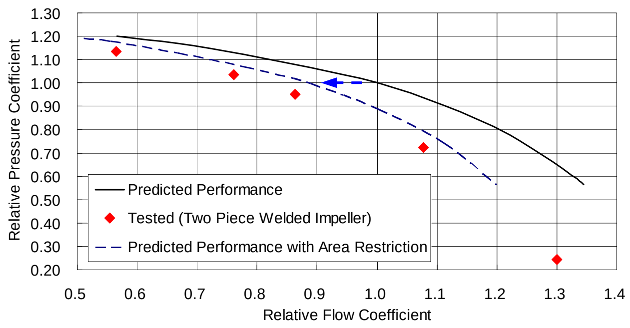


Figure 24. Performance Prediction with restricted Impellers

One of the options available to the authors for addressing the restricted flow passages, the application of weld-less one piece impellers was chosen as the optimum resolution based on the narrow gas passages. This was substantiated by reviewing the quality control and manufacturing process control of the EDM and ECM method mentioned previously, as well as a technical audit at OEM and technical and quality audit at EDM manufacturer's shop.

After this review process, the one piece impeller rotors were manufactured with a very short lead time to meet the project required schedule. This was achieved despite the catastrophic earthquake disaster occurring in Tohoku Japan by the collaboration of our team.

The actual one piece impeller rotor is shown in Figure 25.

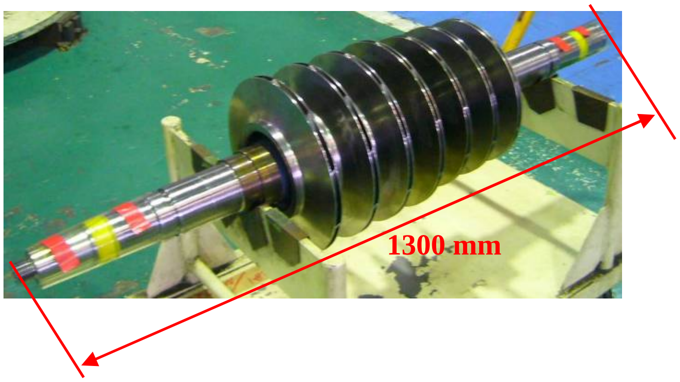


Figure 25. One Piece Impeller Rotor Photograph

Performance Evaluation of Conventional One Piece Impeller

The one piece impeller rotor was installed in the high pressure compressor casing and an ASME PTC-10 Type-2 performance test was conducted. The measured results with one piece impellers are compared to the measured results for the original two piece impeller rotor in Figure 26. At the guarantee point, the one piece impeller has a 20 % improvement in the pressure coefficient and a 2.5 % improvement in polytrophic efficiency. This result is consistent with the result of statistical analysis shown in Figure 8, in other words, improved tolerance control and no welding distortion due to the use of enhanced single piece manufacturing process, accounts for this improvement in both pressure coefficient and efficiency. Figure 27 shows the actual dimensions of tip width for both one piece impeller and two piece impeller in comparison with design values.

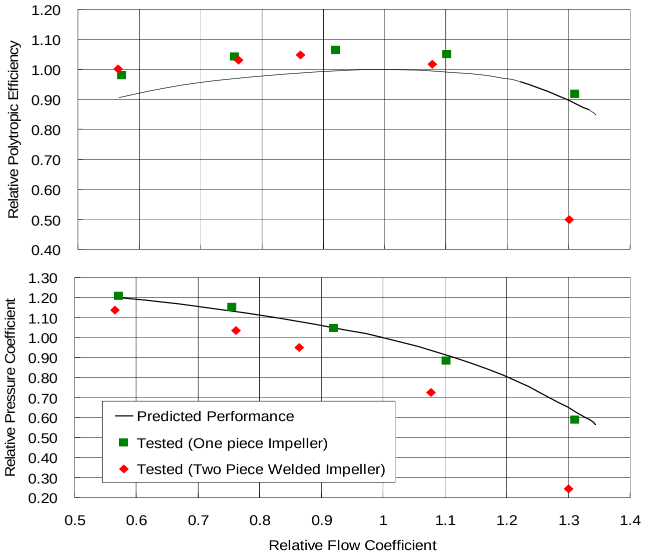


Figure 26. Performance Improvement by One Piece impeller Type-2 Test Comparison with Two Piece Impeller

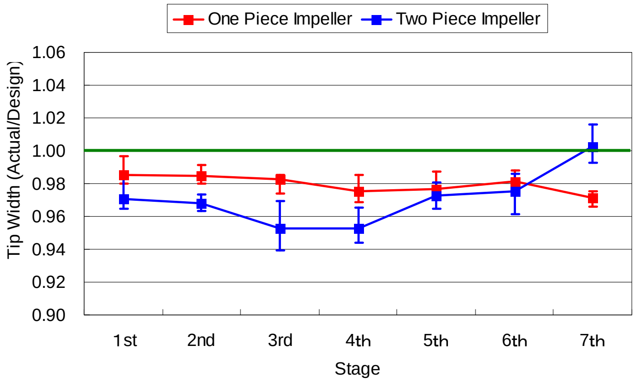


Figure 27. Tip Width Ratio (Design/Actual) for One Piece Impeller and Tow Piece Impeller

In evaluating the compressor performance, the predicted polytropic head is adjusted by a correction factor depending on the type of impeller manufacturing process, impeller diameter size, area and type of mother impeller. The one piece impeller has the same configuration as the standard impeller, therefore it is not necessary to apply a correction factor to the predicted performance which will be based on the standard impeller performance test data.

Originally, the OEM offered the compressor performance with a margin in consideration of deviations from fabrications as described above and shown in Figure 28, thus, the actual polytropic head with one piece impellers was higher than contract value. The OEM and end user evaluated the higher head capability of the compressor with respect to the motor rating, available power, and facility and process requirements. The project reviewed the process system downstream of the compressor to ensure there were no issues with the higher head capability of the compressor. The compressor was accepted based on there being no requirement to modify the facility design and the upside potential to utilize the additional capacity of the compressor for gas lift.

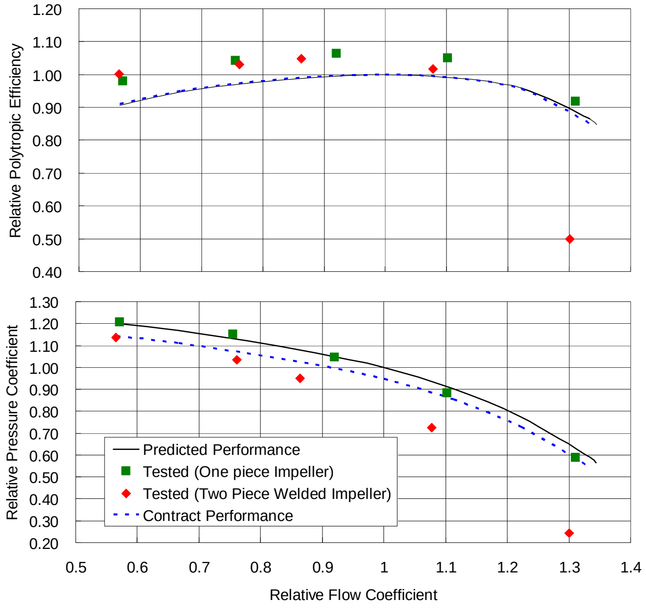


Figure 28. Predicted Performance with Safety Margin

Based on the above test results for two piece impeller and one piece impellers, the OEM has improved the design procedure for the application of one piece impellers and performance correction factors for the two piece welded impellers when in applications with narrow tip widths.

The OEM is seeking to apply the one piece impellers on future projects where the higher cost of one piece impeller manufacturing, is justified. In the future, the OEM will apply the one piece impeller for all projects with narrow flow pass impellers, instead of conventional two piece impellers.

CONCLUSIONS

The dominant parameters which influence the impeller performance were evaluated by statistical method (Taguchi Method) and confirmed;

- Blade height (tip width) at outlet and inlet, welding distortion (including weld affects) were defined as control factors with high to moderate sensitivity for smaller narrow impellers.
- According to independent theoretical analysis for typical low flow coefficient case, the normalized pressure coefficient is affected by blade beta angle. thus beta angle is a key manufacturing parameter that must be tightly controlled to avoid performance discrepancies.

- Impeller performance was analyzed by CFD for several cases based on Taguchi statistical method.
- For low flow coefficient impellers blade height at the outlet (tip width) had the highest sensitivity to the pressure coefficient. Welding distortion and blade height at inlet had moderate sensitivity to pressure coefficient and efficiency.
- Blade height, welding distortion, and blade thickness affected only the pressure coefficient.
- Some factors were in a tradeoff between polytropic efficiency and pressure coefficient.

Authors established manufacturing method of one piece impellers for narrow gas flow passage and corrosive gas application for high pressure centrifugal compressor;

- EDM (Electrical Discharge Machining), instead of 5-axis mill machining, is applied to make gas passage for narrow tip width impellers.
- OEM experience is that minimum tip width of EDM is approximately 4.0 mm.
- ECM (Electrolytic Machining) is applied to remove the re-cast layer and HAZ which are formed during the EDM process.
- It was confirmed that ECM was effective in returning surface properties back to the base material properties by testing to NACE TM – 0177.
- EDM is effective for difficult material applications such as duplex stainless steel, which is difficult to weld and subject to distortion.

The actual compressor performance with both two piece impellers and one piece impellers were compared in OEM's ASME PTC-10 Type-2 shop performance tests;

- Measured performance with two piece impellers was much lower than predicted because of flow pass restriction cased by excessive welding penetration.
- To eliminate the risk of the welding penetration, weld-less one piece impellers were manufactured in accordance with established manufacturing methods.
- Performance test result with one piece impellers showed good improvement as expected by statistical analysis, and matched well with prediction.
- OEM's design process for narrow tip width impellers has been improved based on the test results with two piece impellers and one piece impellers. New applications will consider
  a) The application of one piece impeller for narrow tip widths.
  b) Performance correction factors into performance prediction for two piece impellers.
- In the future, OEM will apply one piece method for all upcoming projects, which contain narrow flow pass impellers, instead of conventional two piece method

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