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The Experts in Turbomachinery

Case Study

Computational Fluid Dynamics (CFD) Software Used Extensively in First-of-its-kind LNG Cryogenic Power Recovery Turbine

Ebara International used Concepts NREC's Agile Engineering Design System® at customer's request to predict turbine efficiency

The Cryodynamics Division of Ebara International Corporation (Ebara) is the recognized world leader in the engineering and production of specialized cryogenic liquefied gas pumps and turbine expanders. All of the equipment Ebara produces utilizes submerged electric motors or generators, thus eliminating any rotating sealing system. In 1999, the Liquid Natural Gas (LNG) Complex built for the Sultanate of Oman went fully operational after three years in development. It incorporated the first submerged hydraulic turbine generators, which were developed and built by Ebara. These required in-depth analysis in order to minimize risks and comply with strict new development requirements imposed by the end user. Ebara employed Agile Engineering Design System® turbomachinery software from Concepts NREC headquartered in White River Junction, Vt., to perform essential turbine analyses.

"A major requirement of this project was to make it as efficient as possible, increasing productivity of the liquefaction process, while recovering the fluid energy as electrical power" said Hans Kimmel, Executive Director R&D, Ebara International Corporation - Cryodynamics Division. "It was a completely new development with no prior art. We used only Concepts NREC computational fluid dynamics (CFD) software by request of our customer."
Kimmel reiterated that this project required development of a novel hydraulic turbine, the mechanical concept of which was based on submerged liquid pumps in cryogenic service. Many new aspects required in-depth analysis. The best possible thermodynamic efficiencies had to be achieved, satisfying not one but a range of operating conditions. This efficiency had to be confirmed through both theoretical and empirical means. Concepts NREC software was used extensively throughout the design process.

THE CHALLENGE:

Within the past 20 years, as energy costs have increased, several pump manufacturers began systematically investigating the feasibility of using existing centrifugal pumps as turbine generators for energy recovery and technical processes. Plant operators became aware of the possibilities for increased LNG production in cryogenic plants while also recovering energy by replacing Joule-Thomson valves for expansion with turbine expanders. The LNG Complex in Oman demonstrates the feasibility of this concept.

Part of the challenge for engineers was to be able to test efficiency before installation. The design includes a variable speed unit, so the mechanical analysis was required to satisfy rotordynamic aspects, avoid critical frequencies, and comply with electrical requirements, all necessitating close attention. Thorough testing of all units had to be done at Ebara's manufacturing facility in Sparks, Nev.

The initial design was for a multistage radial turbine. Several stages were necessary to expand the working fluid through the required head drop, and a radial turbine offered the advantage of a higher work output per stage than axial turbine stages of comparable dimensions. A single stage was comprised of an inlet nozzle ring, accelerating the fluid into the runner through which it traveled radially inward. The runner was followed by an S-shaped return bend to return the fluid to the correct radius for the following stage. All of this presented a complex flow path, one that was difficult to analyze. Concepts NREC's software made it possible to complete the needed analyses and predict efficiencies.

THE SOLUTION:

The basic design information was used to construct a computer model of the turbine stage for analysis. The tool used for this purpose was the CCAD module of the Agile Engineering Design System. CCAD is an interactive and highly flexible geometry generator based on the Bezier-Bernstein polynomials to represent the hub and shroud lines and the blade angle variation. CCAD also enabled preliminary estimates to be made of blade row performance by means of inviscid, two-dimensional streamline curvature analysis. This feature was used to guide the redesign of the runner. The properties of the working fluid were those of methane, which closely approximates LNG properties. (Note: CCAD is now a part of a broader code named AXCENT, a name taken from Axial and Centrifugal, which retains all of the early CCAD features, plus all axial stages and many new features as well).

CFD analysis enabled a complete assessment to be made of the flow field through each component of the turbine. Additionally, by mass averaging the properties on planes at the inlet and exit of each component, the performance was estimated. The gross work output of the rotor was calculated from the change in the product of radius and tangential component of velocity across the runner, according to the Euler turbomachine equation, as detailed by Dr. David Japikse and Dr. Nick Baines of Concepts NREC in 1994.

"An examination of the CFD results showed that there were several poor features in the flow field. Near the leading edge of the rotor, the flow separated on the outside of the band where the flow suddenly contracted," said Nick Baines, Distinguished Corporate Fellow of Concepts NREC. "There also was evidence in this region of a suction surface separation, presumably the result of incidence. Near the trailing edge, there was evidence of a large separation on the pressure side of the blade where the flow reversed. A very large vortex formed on the return bend."

Based on the results of the CFD analyses, the runner was redesigned in several steps, in order to reduce or eliminate the poorer flow features that were identified. In summary, the changes were to:

- Increase the blade number from six to ten in order to reduce the loading per blade.
- Modify the hub and shroud contours to reduce the curvature and improve the annulus area distribution.
- Modify the blades to increase the turning and reduce the passage area going from the inlet to the exit.
- Eliminate the sudden contraction at inlet to the rotor by changing the radii of the band just upstream in order to blend smoothly with the rotor inlet.

The CFD analysis of the redesigned rotor showed much better results than previously. On a mass average basis, the rotor efficiency on the redesigned unit showed 93.6%, which was an improvement of eight points over the preliminary design. The meridional plane flow was now very smooth and regular. On the blade-to-blade plane, the pressure side of the blade was still not quite optimum, and there was still a small separation bubble. Also, the curvature on the shroud was still somewhat too high near the trailing edge, leading to a small recirculation zone. However, these were relatively small effects, and the changes noted clearly addressed the major shortcomings of the preliminary design.

The return bend also was redesigned, both to match the redesigned runner and to improve its own performance. It was recognized that any significant improvement relied on increasing the axial length of the return bend, and it was agreed that a 10% increase in overall stage length was permissible. This allowed the return bend itself to be increased by approximately 20% in axial length. As with the runner, a series of modifications to the return bend hub and shroud lines were made to provide a smooth increase in passage area in order to diffuse the flow without introducing excessive curvature. CFD analysis of the redesigned return bend showed that

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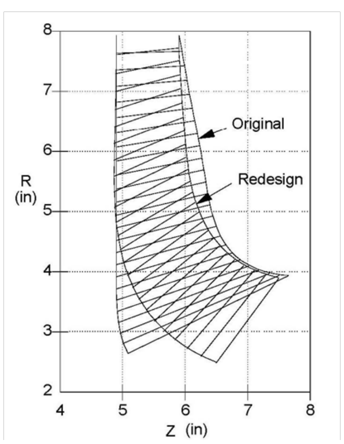
the flow field was considerably improved.

As a result of redesigning the runner and return bend, the stage efficiency was increased by eight points to 89.4%. Most of this improvement was due to modifications to the runner, but the changes to the return bend also made a significant contribution. In total, there were six turbines and critical components developed for the Oman facility. In addition to the above analyses, the Ebara facility performed:

- Mechanical running tests to prove technical integrity and confirm vibration levels.
- Performance tests to confirm and validate the required efficiency.
- Endurance runs to prove technical integrity at runaway conditions.
- Strip down and component inspections of units after completed tests.
- Utilization tests of the system and voltage transformers under full load conditions.
- All tests utilizing liquid LNG, flow, and head values as identical as applicable for the site.

RETURN ON INVESTMENT:

The final stage of the redesign was to validate the analysis by the testing of a prototype turbine. Prototype testing with LNG was not feasible, since no cryogenic torquemeter exists with which to measure shaft torque to assess power and efficiency. Accordingly, a water test was undertaken. Application of scaling rules led to the conclusion that the prototype hydraulic design could be built to fulfill the actual operating conditions with differential pressure, flow rate, and speed being tested at full size in the available facility. It was decided to repeat the CFD analysis at the water test conditions, using the properties of water. This was done in two stages, with CFD analysis repeated using the properties of water at full speed condition and again at the scaled speed condition.



This figure shows a comparison of the orginal and new meridinal profiles. The changes to the rotor imply significant reshaping of the return bend.

The project demonstrated the value of CFD as a tool for both design and performance prediction of cryogenic rotating machines. Using CFD analysis, the nozzle, runner, and return bend were all redesigned to provide a smooth change of annulus area, to minimize streamline curvature, and to correctly match the various components. By this means, the predicted efficiency was increased to 89.4%.

According to Kimmel, the acceptance tests proved to be successful and the required efficiency values were achieved.

Test Results

Tested vs. Predicted Capacity	986.2 m3/h vs. 986.22 m3/h
Tested vs. Predicted Head	899.6 m vs. 898.4 m
Tested vs. Predicted Power	898.5 kW vs. 931.1 kW
Tested vs. Predicted Efficiency	81.6% vs. 79.3 %

Kimmel also added, “Novel and new equipment can only be applied in LNG plants if the design is an extrapolation of existing designs, and novel aspects are carefully reviewed and analyzed. The Concepts NREC software we employed made it possible for us to perform the analysis needed to develop the first-of-its-kind LNG cryogenic power recovery turbine for the LNG Complex in the Sultanate of Oman.”

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