IS YOUR RADIAL TURBOMACHINERY OPERATING AT OPTIMUM?

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ABSTRACT

Bryan Research and Engineering, Inc. (BRE) has developed an online, equipment performance monitoring application for radial turbo-machinery in cryogenic gas plants. The application works by capturing process measurement data in real-time and placing it in the ProMax® simulator for analysis. The modeling capabilities of ProMax are then leveraged against a new, empirical representation of momentum transport to deliver actual versus target performance indicators, such as efficiency, head, and power at off-design conditions. The results of the performance indicators are then returned to a data historian and a customizable display is used to monitor the performance of the turbo-machinery from anywhere on the network. As a result, engineers and operators now have the ability to make informed process decisions based on equipment performance adjusted for off design conditions. This paper highlights the application and its benefits using a case study with real-time data from a cryogenic gas train.

1. Introduction

Bryan Research & Engineering, Inc. (BRE) is a widely recognized provider of software and engineering solutions to the gas processing, refining and chemical industries. Since the company's inception in 1974, BRE has combined research and development in process simulation, equipment rating, and state-of-the-art computerized engineering technology to provide our satisfied clients with flexible, accurate, efficient, and dependable tools that ultimately improve their bottom line. Built on the foundation of its renowned predecessors, TSWEET® and PROSIM®, BR&E's ProMax® process simulation package provides design solutions using equipment ratings, state-of-the-art thermodynamic property packages, a large chemical species database, oil characterizations, solvers, and OLE automation tie-ins.

Utilizing the design capabilities of ProMax in a service role for online performance monitoring and optimization represents a significant opportunity for gas processors. Benefits include determining the properties, compositions, and phase behavior of all streams in the process including solid formation temperatures and cricondentherm and cricondenbar limits in real-time. Additionally, performance measures for equipment can be monitored, including column capacity and flooding, heat exchanger fouling, equilibrium approaches to absorbers in amine plants, and radial turbomachinery performance metrics.

The performance of radial turbomachinery is typically described by equipment performance curves or, in some cases, limited empirical models provided by the equipment manufacturer. The curves can be used to determine the optimum flow rate or shaft speeds needed to maximize the efficiency or power of the equipment. However, as the inlet gas conditions move off the design point, the design curves no longer represent the equipment's performance. This limitation can hinder prospective optimization schemes, resulting in significant plant-model mismatch and a diminished capability of gas processors to maximize the performance of their assets in real-time.

In addition, mechanical deterioration that alters the machine's geometry, such as fouling or vane deformation, can also reduce the equipment's performance at off-design conditions. Fouling is typically addressed with a series of scheduled maintenance shutdowns that can quickly become expensive. Continuous monitoring of turbomachinery performance allows engineers to detect events which cause deteriorating performance. This could lead to guidelines for avoiding certain situations. Also, maintenance shutdowns could be scheduled on performance criteria rather than with a fixed schedule.

To help our customers address these performance monitoring limitations, Bryan Research & Engineering, Inc. (BRE) has developed (1) a real-time performance monitoring application that communicates with our ProMax® simulator and OSIsoft's Plant Information (PI) system and (2) a set of radial turbomachinery performance metrics to describe off-design conditions. Communication with other process data historians will be developed on an as-needed basis. This paper reviews the monitoring application, the performance metrics, and highlights a case study using real-time gas plant data.

2. Monitoring Application

BRE created a PI application that communicates with OSIsoft's Plant Information (PI) system for the purpose of utilizing ProMax in a service role. As shown in Fig. 1, the application: (1) pulls PI-tag information from an XML configuration file, (2) uses that information to call the PI-Server and take snapshots of PI-data, (3) loads the information into a ProMax project and solves it, (4) if selected, performs analysis calculations, and (5) returns the results to the PI system where they are (6) accessed by anyone connected to the PI-Server network. The XML file contains each analysis's tag names and equipment specifications inherent to the equipment being modeled in ProMax. All of the equipment specific to a single plant train are located in a single project. The analysis tool is capable of being instantiated multiple times on the client PC and works exclusively with ProMax.

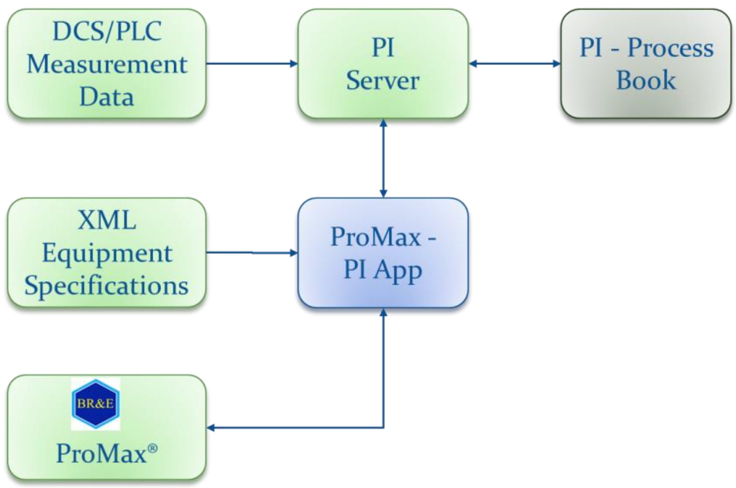

Figure 1: Information Flow for BRE ProMax - PI Application

3. Performance Metrics

ProMax currently calculates turbo-machinery metrics using thermodynamic models and mass and energy balances. The metrics include the actual adiabatic efficiency and power for a radial turbine, the actual polytropic head, polytropic efficiency, and power for a centrifugal compressor, and all of the above plus bearing losses for turboexpanders. To evaluate the off-design performance of the equipment, BRE developed new, empirical representations of angular momentum transport using the Buckingham PI-theorem (BPT). An empirical representation of the angular momentum balance (aMoB) was chosen for this application in order to ensure algorithm convergence when operating in an online capacity. Parameters for the new empirical models are determined by fitting reconfigured turbo-machinery design expressions against a combined momentum, mass, and energy balance at off-design conditions.

3.1. Radial Turbine Models

According to Whitfield and Baines [1], the basic parameters that influence the performance of a turbine are wheel tip diameter, shaft speed, mass flow rate, molecular weight, heat capacity ratio, viscosity, and the pressures and temperatures of the streams entering and exiting the turbo-machinery. These 10 terms can be reduced to 6 non-dimensional variables using the Buckingham π theorem. For a fixed diameter radial expander typically used in cryogenic NGL recovery processes, these variables can be further reduced to pressure ratio (P_R), adiabatic efficiency (η), flow coefficient ($\dot{Q}/N$), speed ratio (U/C_0), and constrained heat capacity ratio (γ_C).

$$f\left(\eta, \frac{\dot{Q}}{N}, \frac{U}{C_0}, P_R, \gamma_C\right) = 0 \tag{3.1}$$

The flow coefficient and speed ratio help to describe the flow regime of the fluid in the expander, while the pressure ratio helps to describe the mechanical geometry. Each of the terms can be parameterized separately. The flow coefficient and speed ratio can be parameterized using the design curves provided by the manufacturer. The pressure ratio, however, requires additional data at off-design conditions which must first be created using the extra degree of freedom gained by utilizing the momentum balance. In most cases, the momentum balance reduces to Euler's turbo-machinery balance with the assumption of negligible or slightly negative axial rotation ($\geq -30°$) entering the rotor and negligible radial rotation exiting the rotor [1]. In some cases, especially near the boundaries of the operating envelope, these assumptions require revision, either by adding geometric complexity, or by correcting the expression using loss mechanism empirical models. Common loss mechanisms include leakage, friction, passage, and incidence losses, among others [2].

Finally, the constrained heat capacity ratio can be utilized to describe compositional changes in the gas stream. Unlike most applications, however, cryogenic gas streams typically phase separate in expanders, significantly changing the composition of the vapor phase, and altering its performance. This dynamic behavior is limited by constraining the heat capacity ratio and off-design performance to an operating region exhibiting similar phase separation characteristics.

3.2. Centrifugal Compressor Models

An alternative representation of the BPT expression can be ascertained for a compressor [3]. Unlike the expander, the compressor has a fixed geometry which results in an expression with only 4 parameters: polytropic efficiency (η), polytropic head coefficient (ψ_p), power coefficient, also known as the work or blade loading coefficient (Ψ), and constrained heat capacity ratio (γ_C).

$$f(\eta, \psi_p, \Psi,\ \gamma_C) = 0 \tag{3.2}$$

The power coefficient helps to describe the flow regime of the fluid in the compressor, while the polytropic head coefficient helps to describe the mechanical geometry. The constrained heat capacity ratio works in the same manner as for an expander, except that it does not encounter multi-phase flow. As before, the expression in Eq. 3.2 is rearranged, non-dimensionalized, and fitted at off-design conditions using the combined mass, energy, and momentum balances. For a centrifugal compressor, the momentum balance can be reduced to Euler's turbo-machinery balance with the assumption of negligible pre-whirl and the addition of a slip factor that describes secondary passage flow mixing with the main stream [1].

3.3. Performance Analyses

The performance of radial turbo-machinery is evaluated by comparing the efficiency calculated by ProMax (designated as the actual efficiency) versus the efficiency as calculated by Eq. 3.1 and 3.2 (designated as the target efficiency). The procedure can also be applied to both head and power calculations. As shown in Fig. 2, four conditions could be evaluated: (A) the design point condition, (B) the operating condition, (C) the design condition with the operating pressure ratio, and (D) the operating condition with the design composition. Comparison A reveals the error generated from converting curves into experimental data points using digitizing algorithms. Comparison B demonstrates the off-design performance of the asset and is often the most important to gas processors.

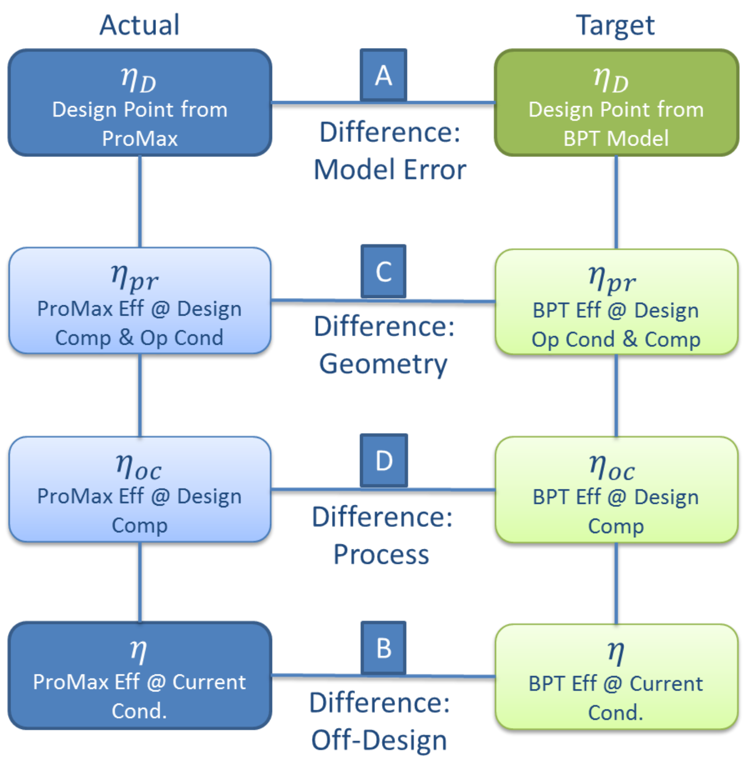

Figure 2: Performance analysis comparisons of efficiency

The remaining two comparisons may require a search of the PI Historian for recent operating conditions matching the specified criteria in order to specify the actual efficiencies. Comparison C reveals the pressure drop/rise through the equipment, which is indicative of changes in geometry. In contrast, process opportunities are identified by contrasting the results of comparison D with comparison C, using either (1) a state function analysis or (2) a composition corrected empirical model. It should be noted that because there is a slight difference in the end states between the target and actual models, the individual comparisons will ultimately not sum to the difference between the target and actual efficiencies.

3.4. Required Data

The following operating and equipment specifications are required to determine the parameters and coefficients in Eq. 3.1 and 3.2:

1. Expander and/or compressor efficiency, head, and power curves.
2. Train design process flow diagram (PFD) showing flows, compositions, and thermodynamic properties of the streams entering and exiting the radial turbo-machinery.
3. Equation of State used to create the design curves
4. Expander:
   a. Stator vane angle control scheme
   b. Stator vane angle at full open
   c. Stator vane angle at 50% open
   d. Stator vane area at full open
   e. Number of stator vanes
   f. Rotor blade angle at the hub and shroud
   g. Diameters at the wheel tip, hub, and shroud.
5. Compressor:
   a. Diffuser blade angle
   b. Number of impeller blades
   c. Impeller pre-whirl angle
   d. Impeller blade angle at the wheel tip
   e. Backward swept blade angle
   f. Diameters at the wheel tip, eye, and eye tip

4. Cryogenic Gas Plant Case Study

To demonstrate the application's capabilities, Williams Midstream (WM) provided real-time access to operating data, process flow diagrams, and equipment performance specifications of a cryogenic gas plant train. This information was used to create a turbo-machinery momentum balance on a turboexpander, which was then approximated using the new, BRE developed empirical BPT model. To begin this process, BRE digitized the expander performance curves provided by the equipment manufacturer, Mafi-Trench, and the fit them to Eq. 3.1 at the design composition and pressure ratio, resulting in predictive expressions for the flow coefficient ($\dot{Q}/N$) and speed ratio (U/C_0).

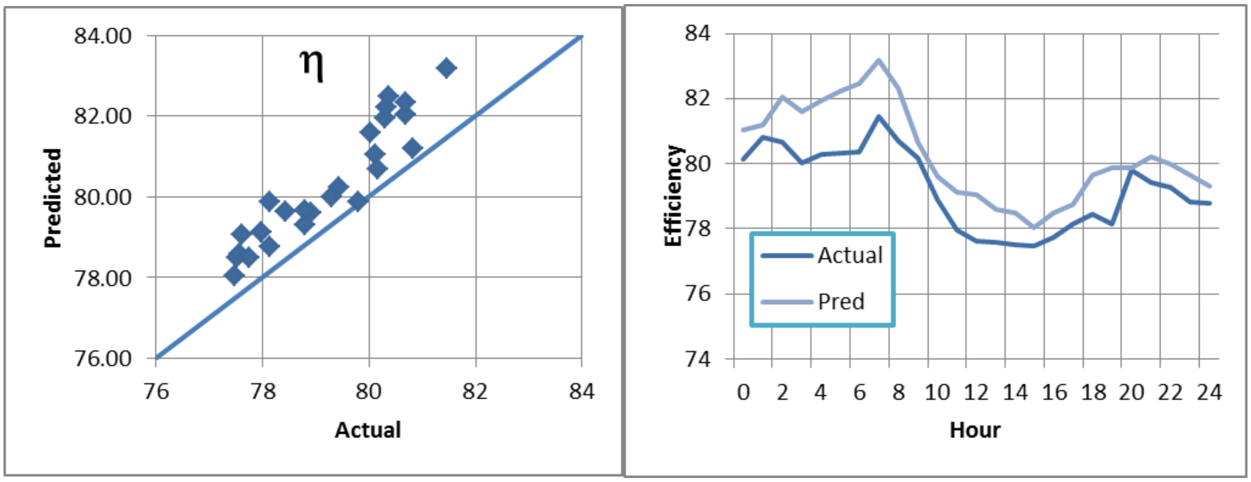

Figure 3: Turbo-machinery momentum model (Predicted) vs. gas train data from the PI Historian (Actual)

Next the turbo-machinery momentum model was constructed using equipment specifications and tested against the predicted efficiency of Eq. 3.1 at the design composition and pressure ratio in order to develop a vane angle response model. The resulting model was incorporated into the turbo-machinery momentum model. Finally, the turbo-machinery momentum model was tested at off-design conditions against real-time data from the PI-Historian. The mean hourly conditions for Jan 19, 2013 are shown in Fig. 3. The model slightly over-predicted the efficiency, indicating that additional loss models were warranted.

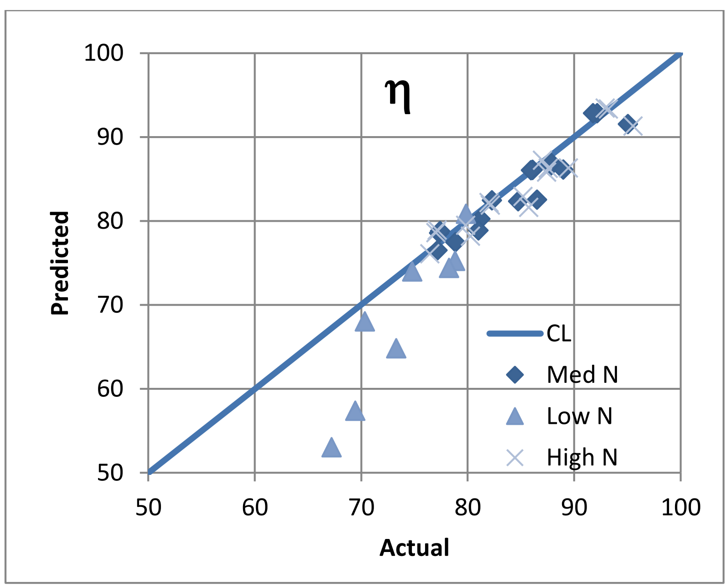

Figure 4: Empirical BPT model (Predicted) vs. the turbo-machinery momentum model (Actual)

Both the pressure ratio (P_R) and constrained heat capacity (γ_C) predictive expressions were then developed running scenarios against the turbo-machinery momentum model. Using the concept of a face-centered factorial design, the empirical BPT model of Eq. 3.1 was tested against the turbo-machinery model at high and low off-design conditions of incoming pressure, mass flow rate, composition, and pressure ratio resulting in Fig. 4. The analysis test shows good agreement, with the two exceptions: (1) a region where the two-phase flow enters the rotor and (2) a region of operation where the fluid exits the rotor at an angle and violates one of the assumptions made in the application of turbo-machinery momentum balance. The first exception occurs because the operating composition has again significantly deviated from the design composition. A warning was built into the tool to alarm when this situation occurs and the model was constrained.

The second exception occurs under low shaft speed, low pressure ratio, and/or high mass flow rate. Under these conditions the kinetic energy of the entering fluid is not completely converted into shaft work and the fluid exits the rotor at an angle, creating rotational flow at the exit. Additional loss mechanisms such as leakage and friction are also more prevalent under these conditions, leading to an underestimation of the efficiency of the system by the turbo-machinery balance. A warning was built into the tool to alarm when this situation occurs and the model was constrained.

The procedure was repeated for the compressor side of the turboexpander. BRE again digitized the compressor performance curves and the fit them to Eq. 3.2 at the design, resulting in predictive expressions for the polytropic head coefficient (ψ_p) and blade loading coefficient (Ψ). Next the turbo-machinery momentum model was tested at off-design conditions against real-time data from the PI-Historian, resulting in good agreement near the design point and off-design conditions. Using the a face-centered factorial design again, the fully parameterized empirical BPT model of Eq. 3.2 was tested against the turbo-machinery model at high and low off-design conditions of incoming pressure, mass flow rate, and composition resulting in good agreement over the range of conditions explored.

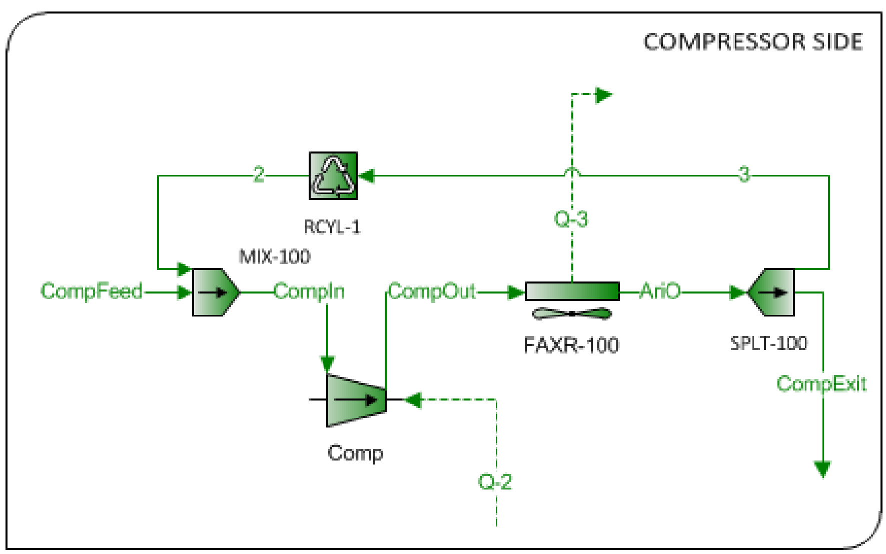

Figure 5: Compressor-side flow sheet of the modeled turboexpander

Next, the empirical BPT models were placed in an online service capacity using a ProMax project file, a XML file, and the ProMax - PI Application. First, ProMax was installed on a WM client PC. Then a ProMax project file was created and a flow sheet was designed to utilize the locations of known, reliable process measurements. The ProMax flow sheet representation of the modeled turbo-machinery is shown in Fig. 5 and Fig. 6.

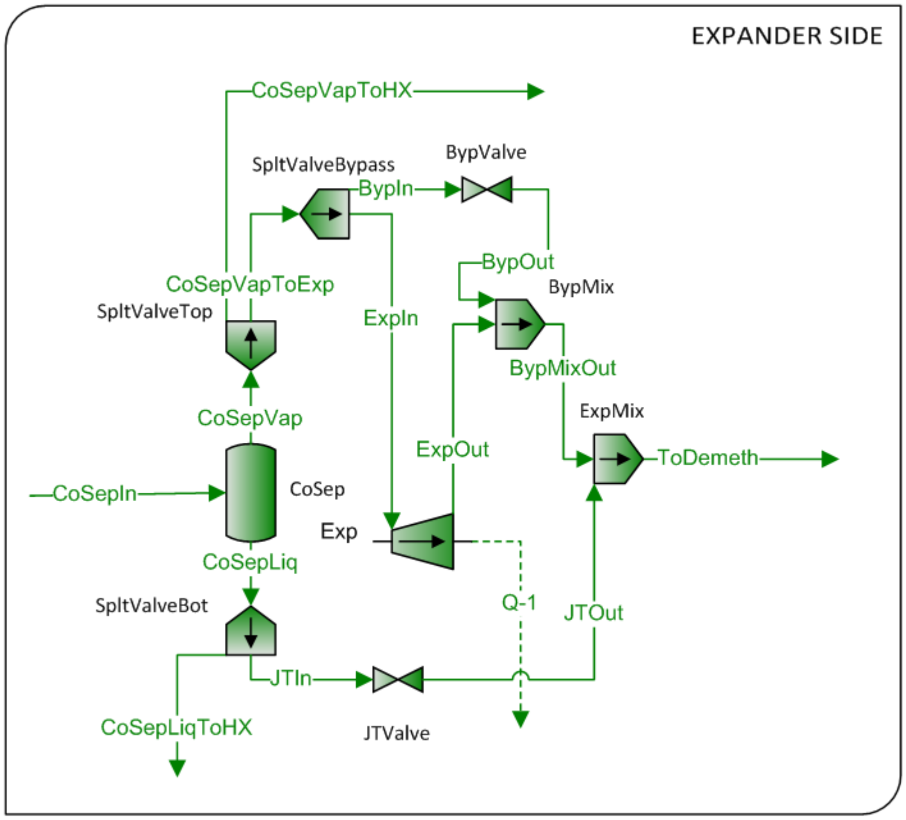

Figure 6: Expander-side flow sheet of the modeled turboexpander

Parameters from the empirical BPT models were then placed in the XML file (shown in Fig. 7) along with equipment specifications, property conditions at the design point, property monikers, and PI tag locations.


```
  <?xml version="1.0" encoding="UTF-8"?>
- <Catalog>
  - <Location PrjPath="C:\Documents and Settings\svc_OPGData\Desktop\BRE\PMX\XXXX.pmx" LocType="XXXXXXX">
    - <Analysis flowsheet="Turboexpander">
      + <Keys blkName="Exp" infoType="PITagInputs">
      + <Keys blkName="Exp" infoType="SpecificationInputs">
      + <Keys blkName="Exp" infoType="PITagOutputs" calcType="Design Conditions">
      + <Keys blkName="Exp" infoType="PITagOutputs" calcType="Operating Conditions">
      + <Keys blkName="Exp" infoType="PITagOutputs" calcType="Operating Conditions with Design Compositions">
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      + <Keys blkName="Comp" infoType="PITagOutputs" calcType="Operating Conditions">
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      + <Keys blkName="Comp" infoType="PITagOutputs" calcType="Design Conditions with Operating Pressure Ratio">
      </Analysis>
    </Location>
  </Catalog>
```


Figure 7: Truncated view of the XML file for the modeled turboexpander

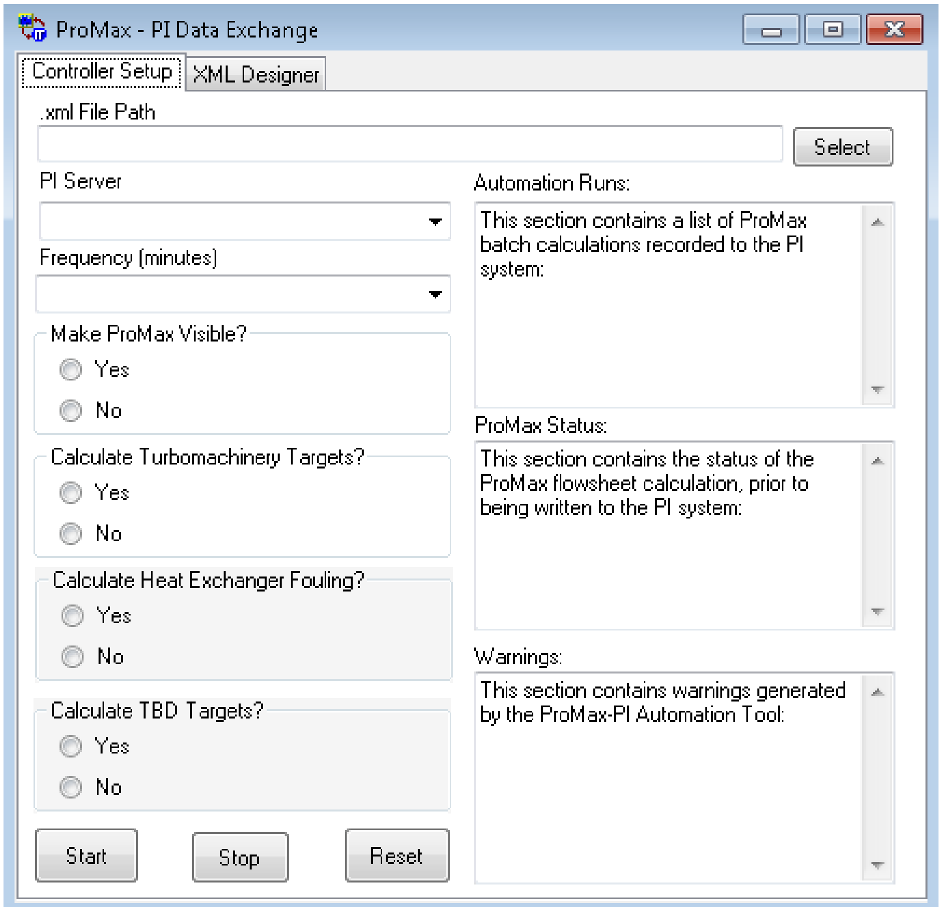

Figure 8: ProMax – PI Application GUI (v. 1.1.2.3)

Finally, the ProMax – PI Application (shown in Fig. 8) was installed on the WM client PC and populated with the XML file path, the server name, and the frequency of execution. To visualize the performance of the equipment, BRE constructed a PI-ProcessBook display on the WM client PC. The display consisted of actual and target efficiencies and losses in trend and graphical formats. Figure 9 shows the target and actual operating efficiencies of the expander-side of the turboexpander plotted on the original manufacturer design curves at shaft speeds 14000, 18000, 21000, 25200, and 28500 rpm against mass flow rates in lb/h. The efficiencies shown were calculated every minute on the 19th of January. Similar figures for the compressor were also constructed.

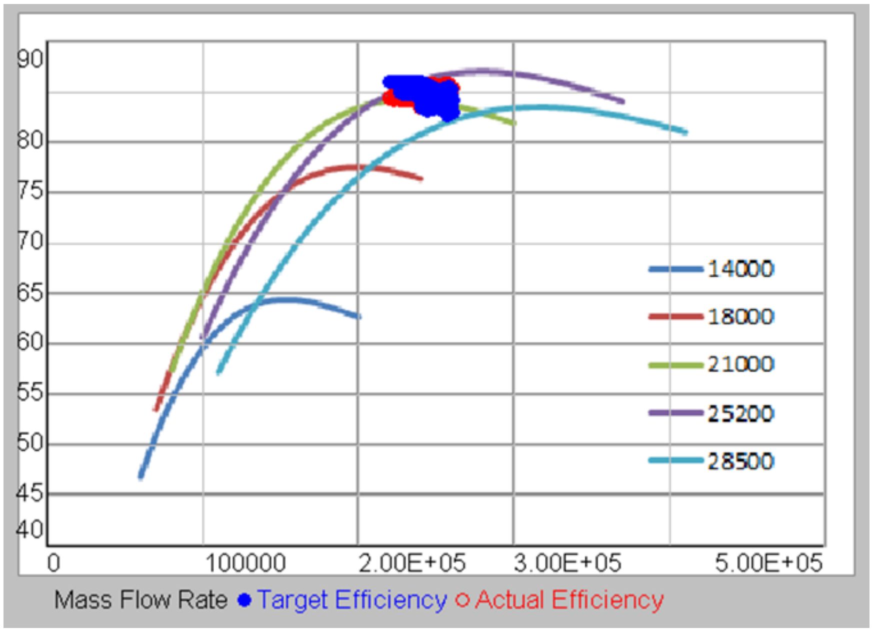

Figure 9: Real-time PI – Processbook display of the expander performance

On January 22, 2013 the cryogenic gas plant being monitored experienced a slight upset in the stream temperatures around the turboexpander and returned to normal. However, pressure began to increase in the demethanizer.

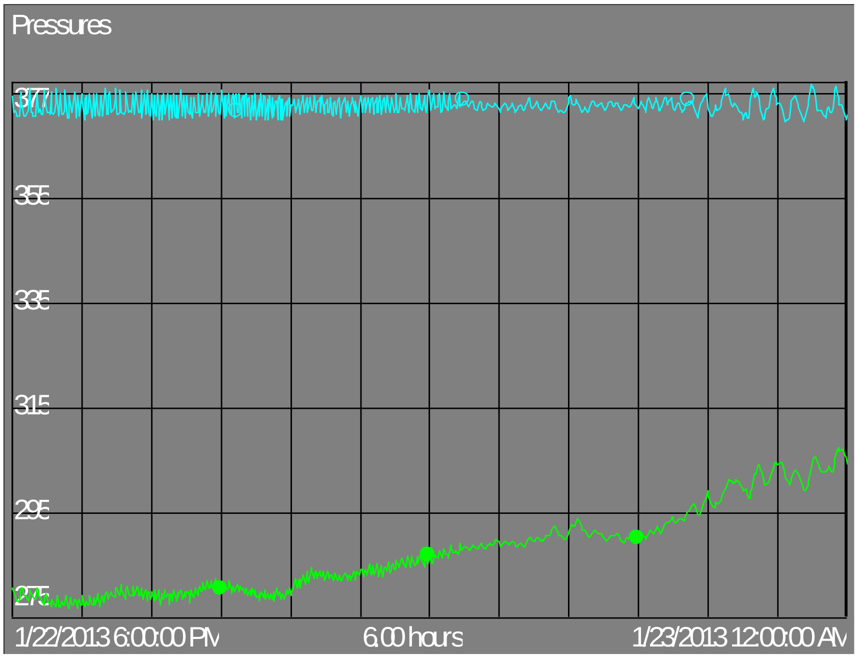

Figure 10: Pressure measurements from inlet (blue) and outlet (green) of compressor at the onset of an upset

As the pressure increased, the compressor reduced demand for head and stayed on its target throughout the process (see Fig.11).

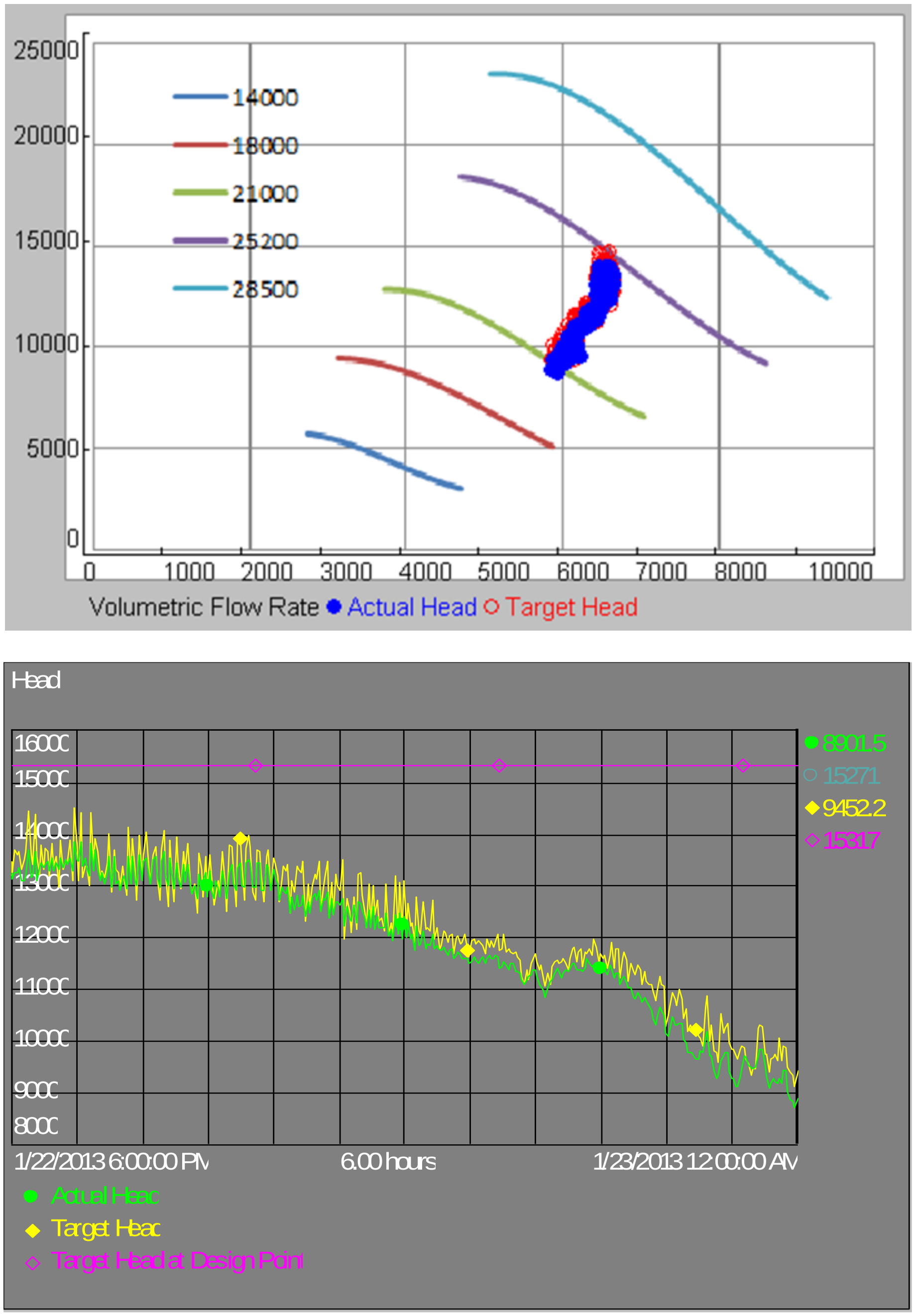

Figure 11: Compressor head response during the response

The reduced need to generate head was achieved by slowing the turboexpander shaft speed, by adjusting the guide vanes on the expander side of the turboexpander. No changes to the volumetric flow were made in the process (see Fig. 12).

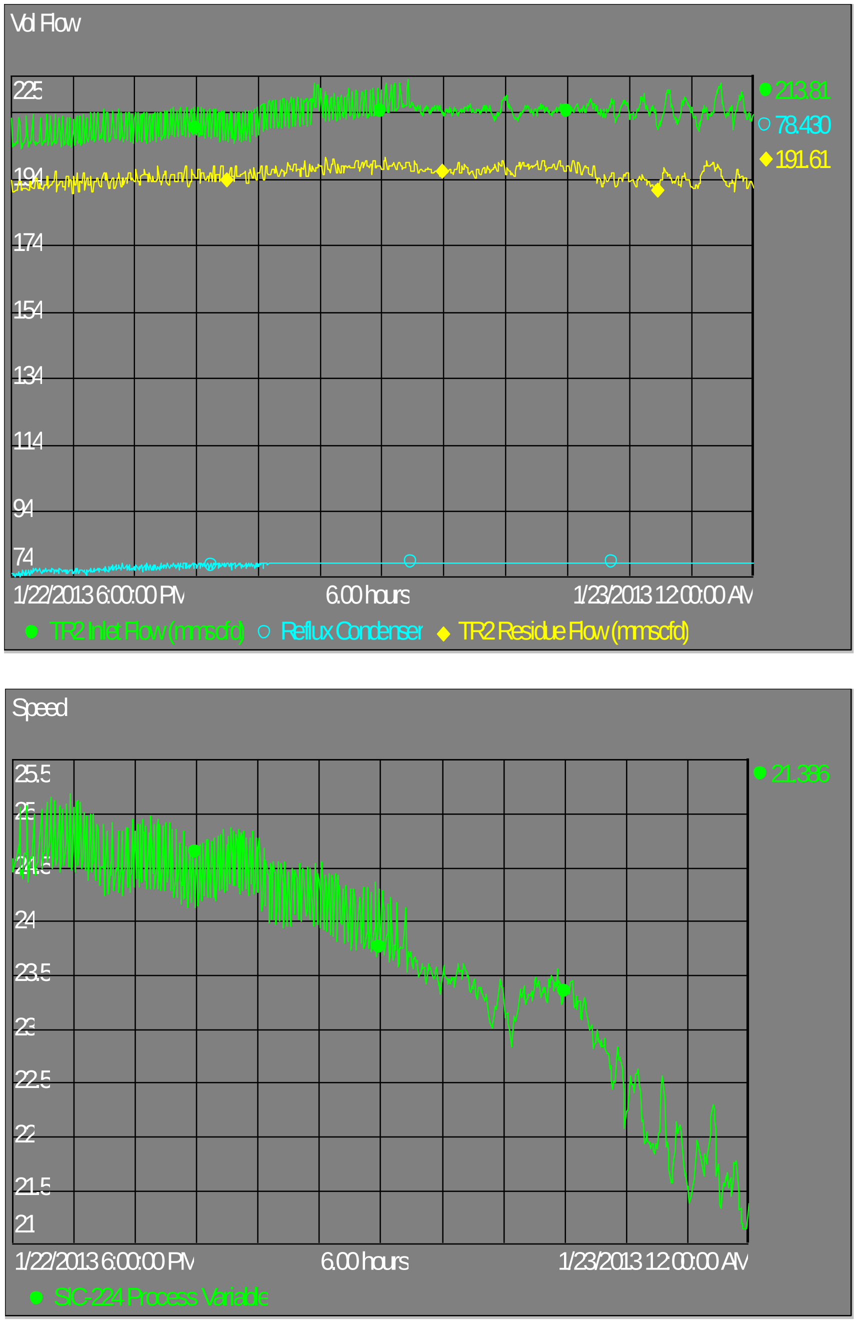

Figure 12: Volumetric flow and shaft speed responses to the upset

As a result of the compressor "braking" the expander, the target expander efficiency falls dramatically, but the expander continued to operate above the target setpoint, meaning a significant amount of energy was lost in the braking of the expander (see Fig. 13). An operator seeing trended results from this monitoring application could respond by diverting LTS overhead vapors away from the expander. That would better balance the expander and compressor and more promptly minimize bearing losses caused by compressor "braking".

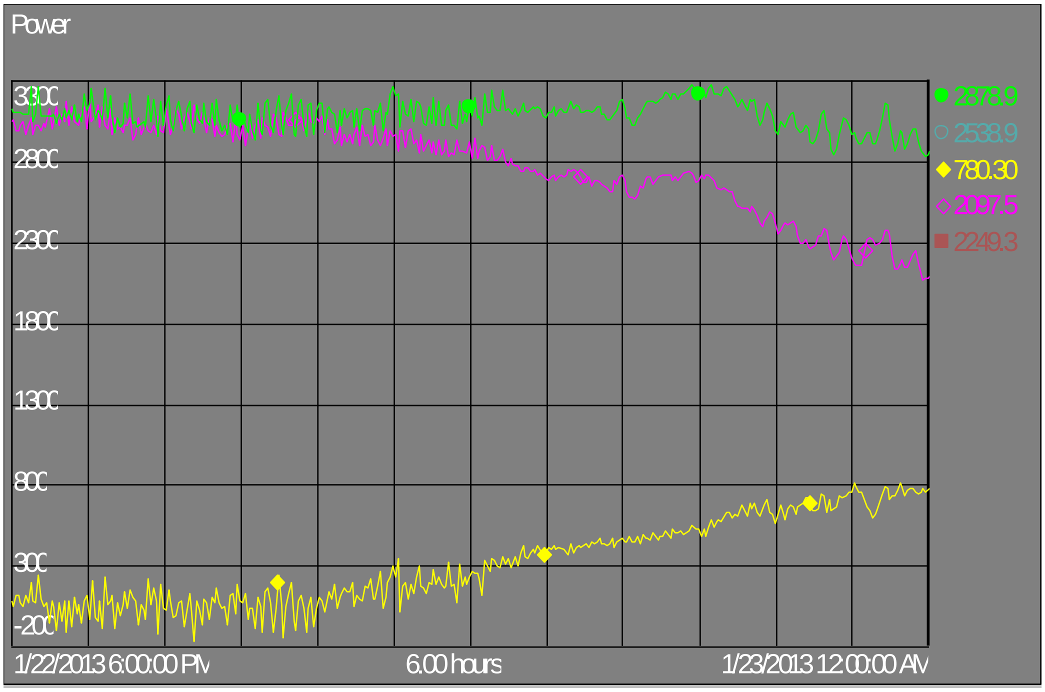

Figure 13: Bearing loss during the onset of the upset

Ultimately, the upset led to the bypass JT-valve being opened and the turboexpander going briefly off-line before returning to service. Potential causes of the "braking" included compositional changes, column flooding, and control valve failure. Resolving this issue carries an economic impact in operational savings in addition to the limiting of upset conditions via reliability improvements. For instance, improving the efficiency of turboexpander by 1% would save approximately $75,000/yr/1000 hp operating in ethane recovery mode, or about $6,000/yr/1000 hp operating in ethane rejection mode.

5. Conclusions and Further Information

In conclusion, BRE has developed a set of performance metrics to evaluate radial turbomachinery equipment performance and an application that allows ProMax to operate in a service role with the PI historian. Now, as inlet gas conditions move off the design point, gas processors will have the ability to monitor performance and differentiate between mechanical related opportunities and process related opportunities. The opportunities can be leveraged in real-time economic optimization and scheduled maintenance planning in order to maximize uptime and profit. BRE is currently developing future endeavors including real-time heat exchanger fouling estimates, process parameter setpoint control, and economic optimization for future releases.

6. Acknowledgements

Bryan Research & Engineering, Inc. would like to thank Williams Midstream for providing equipment specifications, operating data, and other resources used in the development of this application.

7. References

[1] Whitfield and N.C. Baines (1990). *Design of Radial Turbomachines*. Longman Scientific & Technical, Essex, England.

[2] R.S. Benson (1970). A Review of Methods for Assessing Loss Coefficients in Radial Gas Turbines. *International Journal of Mechanical Sciences*, 12, pp. 905-932.

[3] R. McIntire (1982). Increased Productivity of Turboexpanders. *Oil & Gas Journal*, 80(27), pp. 95-102.