HYDROCARBON
PROCESSING

Improve performance monitoring of your turbomachinery

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Performance measurements of critical turbomachinery are very important to ensure reliable plant operations. Downtime related to unavailable critical equipment can cost the facility millions of dollars in lost production and maintenance.

Steam turbines are one group of the most important prime turbomachines used commonly within hydrocarbon processing facilities. Overhauling of steam turbines is normally done during major planned outages and generally warrants including the original equipment manufacturer's (OEM's) expertise. Accordingly, online performance monitoring and establishing performance indices (PIs) for steam turbines are crucial when optimizing equipment reliability and plant availability.

Performance of a steam turbine deteriorates due to various reasons such as deposition on steam-path components, erosion and damage to blades, leakage, etc. The American Society of Mechanical Engineers (ASME) performance test code (PTC 6) stipulates detail procedures when testing steam turbines. However, PTC 6 is not a cost-effective method for continuous monitoring. Online-monitoring systems can be an efficient and cost-effective way to evaluate machinery performance. A PI process book capability to create data sets (DSs) and a built-in steam function library can provide an economical tool when implementing complex thermodynamic calculations and defining additional performance variables for continuous monitoring.

This case study documents the performance variables to consider and apply when monitoring and tracking the efficiency deterioration for a steam turbine using DSs in a PI process book. The PI process book is a powerful online process application tool used widely in many industries to gather and analyze static and dynamic plant process data.

GENERAL TURBINE DATA

In this case history, the equipment focus is a 2,000-kW back-pressure steam turbine. It drives a barrel-type centrifugal compressor at 10,000 rpm. This turbine is a multistage unit with an inlet steam pressure of approximately 4,248 KPa at a temperature of 355°C and an outlet pressure of 365 KPa and a temperature of 155°C.

Thermodynamic and performance indicators

From the first law of thermodynamics and steady flow energy equation:

$$U_1 + P_1V_1 + \frac{v_1^2}{2g} + Z_1 + Q = U_2 + P_2V_2 + \frac{v_2^2}{2g} + Z_2 + Ws$$
$$H_1 + \frac{v_1^2}{2g} + Z_1 + Q = H_2 + \frac{v_2^2}{2g} + Z_2 + Ws \quad (1)$$

Where enthalpy (*H*), velocity (*v*) and head (*Z*) are used.

For the steam nozzle $Q = Ws = 0$

$$Z_1 \approx Z_2$$
$$H_1 - H_2 = \frac{1}{2g}\left(v_2^2 - v_1^2\right) \quad (2)$$
$$\Delta H = \frac{1}{2g}\left(v_2^2 - v_1^2\right)$$

In the case of the nozzle fouling, the enthalpy drop, D*H*, decreases and reduces the nozzle exit velocity, v_2. **Result:** The turbine slows down. The turbine responds to this condition by increasing the steam flowrate to keep the speed isochronous.

For the turbine (Q = 0). Since the turbine casing is insulated, the flow process can be assumed adiabatic (Q = 0)

(Q ˘ 0)
Z_1 ¯ Z_2
v_1 ¯ v_2
$H_1 - H_2 = Ws$
D$H = Ws$

Turbine performance indices

Some critical parameters can be monitored when the turbine is online. These parameters can provide an accurate picture of the state of the running machine:

Isentropic efficiency. The internal efficiency of a turbine is a key indicator of turbine performance and is termed as an enthalpy drop in the PTC code 6. This is the simplest and the most accurate test. The requirements are stipulated in the code.

Isentropic efficiency =

$$\eta = \frac{H1_{(P1,T1)} - H2_{(P2,T2)}}{H1_{(P1,T1)} - HS_{(P2s-T2s)}} \quad (3)$$

Steam mass flowrate. The mass flowrate is inversely proportional to the internal efficiency of the turbine.

Exhaust temperature. The loss in efficiency increases entropy and, also, higher exhaust temperature occurs.

Turbine shaft position. Fouling increases the wheel chamber pressure, and it subsequently develops an axial thrust on the rotor.

Turbine active thrust bearing temperature. The thrust bearing temperature shows an increasing trend when the wheel chamber pressure increases.

PROBLEM CASE AND SOLUTION

Canadian Natural Resources Ltd. (CNRL) plant operations expressed concerns regarding the efficiency of the steam turbine over issues related to poor steam quality. The solution entailed either to have the turbine vendor present onsite and use dedicated instruments to measure and record steam turbine performance, or to address the issue in-house with locally available software. CNRL plant reliability engineering was assigned the task of monitoring and tracking turbine efficiency and the subsequent evaluation of machinery performance.

The enthalpy drop method from PTC code section 6 was used to calculate the efficiency drop across the turbine. This involved determining the isentropic enthalpy drop and the actual enthalpy drop, and then using their ratio to determine the stage group (operating) efficiency of the turbine.

Manual method

Manual calculations, as summarized in **Table 1,** were initially done using the steam table, as shown in **Fig. 1,** to determine the operating overall turbine efficiency. Gauge readings from the PI online system (**Fig. 2**) were taken for the inlet and outlet conditions. The pressures were converted to absolute for the case history calculations. The stage group efficiency, approximated as per the calculations, was determined to be around 70%.

TABLE 1. Calculations to approximate turbine efficiency in the running condition

Location		Pressure, kPa	Temperature, °C	Enthalpy, kJ/kg	Entropy, kJ/kg K
Turbine inlet	(Point A)	4246.40	352.12	3,175	6.67
Turbine exhaust	(Point B)	486.99	163.42	2,800	7.35
	(Point C)	486.99		2,645	6.67
Isentropic enthalpy drop		530			
Actual enthalpy drop		375			
Approximate stage group efficiency, %		**70.75**			

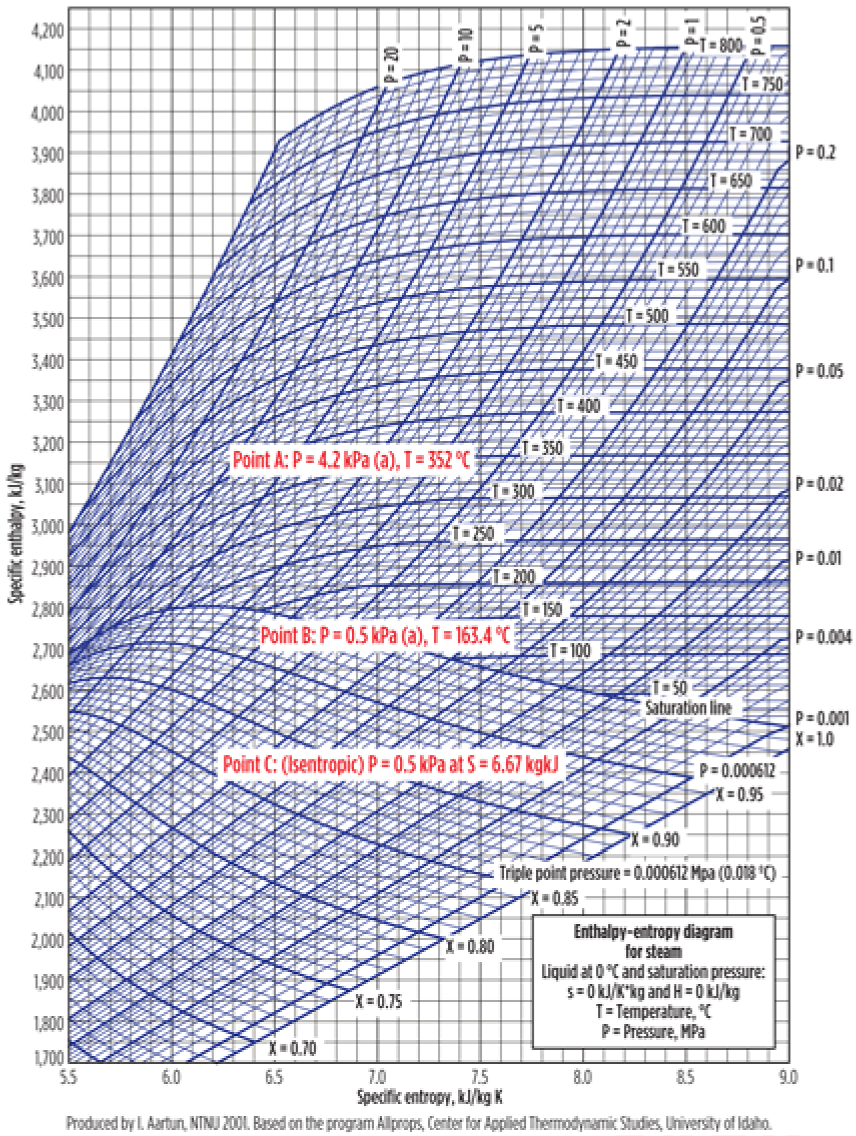

Fig. 1. Enthalpy/entropy (H-s) steam table showing the three points of P, T, H and s.

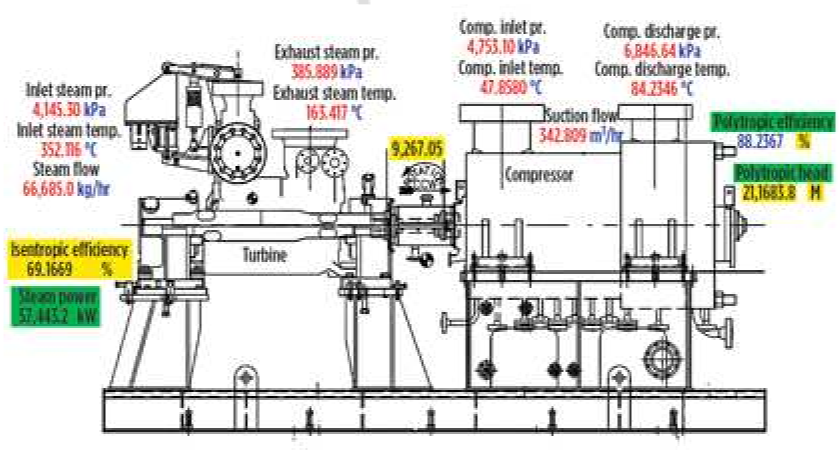

Fig. 2. PI screen shot of various “s” parameters for the entire compressor/turbine system.

PI data set

The PI was used to model and track the turbine efficiency in accordance with the PTC procedures. This information was then used to trend and monitor the efficiency of the turbine on a real-time basis within the PI process book. *The PI has a builtin steam table that can be called out functionally by the use of PI data sets*. This provides a powerful and excellent feature to track and monitor efficiency trends over long periods without using sophisticated software. The DS provided a valuable tool in programming equations and other logic to monitor key machinery parameters. Various other process parameters such as turbine inlet and outlet pressure conditions, temperatures, flowrates, etc., can also be simultaneously plotted along with the efficiency to form an inclusive view of the turbine.

Performance measurement and analysis can provide valuable insight into the health status of a given machine. It is important to ensure data reliability and accuracy prior to performing any analysis to prevent incorrect conclusions and misguided decisions.

The steam flow, turbine efficiency and steam-outlet temperature were trended from the process book. It is evident from the enthalpy drop (Eq. 3) that an increase in the steam-outlet temperature, T_2, will cause an increase in the outlet enthalpy of the steam, consequently dropping the efficiency. This efficiency drop only holds true when the inlet temperature, T_1, and pressure, P_1, are held constant. The constant inlet pressure and temperature conditions are required for most operating steam turbines to ensure reliable process and machinery operation.

Pressure drop (over design specifications) will occur across the nozzle (for impulse type) or across the turbine blades (for reaction type) due to steam path fouling issues such as deposit build up across the nozzles or turbine blades (**Figs. 3** and **4**). This condition must be compensated by an increasing steam flow, which is achieved by an increased opening of the governor valve to maintain constant turbine speed. In this case, it was observed that the steam-flow input to the turbine had increased over time to maintain constant speed and that a gradual decrease of efficiency was observed due to steam-path fouling issues. After the governor valve opens to 100%, a fully open condition, then the speed of the turbine begins to decrease. **Result:** The turbine is unable to meet the required compressor demand. Eq. 4 shows the general flow–pressure relationship for all turbine stages:

$$w = (3{,}600)(C_q)(A_n) \times \sqrt{(2 \times g)\left(\frac{\gamma}{\gamma - 1}\right)\left(\frac{P_1}{v_1}\right)\left[\left(\frac{P_2}{P_1}\right)^{\frac{2}{\gamma}} - \left(\frac{P_2}{P_1}\right)^{\frac{\gamma+1}{\gamma}}\right]} \quad (4)$$

Where:

w = Flowrate, lb_m/hr

C_q = Flow coefficient

A_n = Nozzle flow area, ft^2 (stationary–blade flow area)

γ = Ratio of specific heats

P_1 = Stage inlet pressure, psia

P_2 = Pressure between rotating and stationary blade rows, psia

g = Acceleration due to gravity, ft/sec^2

v_1 = Specific volume at stage inlet, ft^3/lb_m.

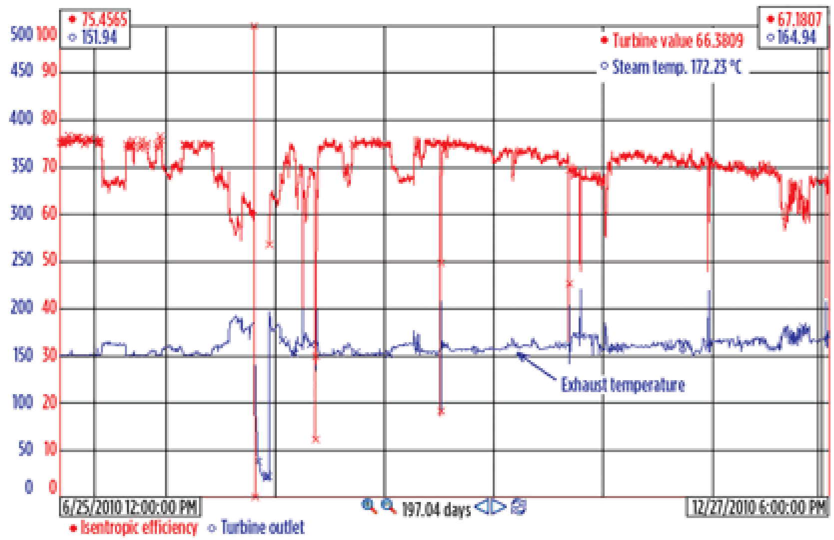

Fig. 3. A decrease in the isentropic efficiency causes an increase in the exhaust temperature (entropy).

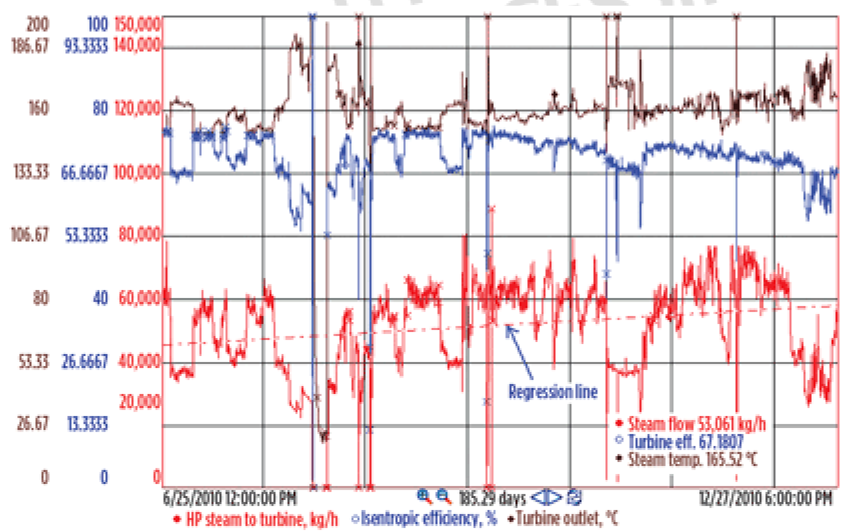

Fig. 4. An increase in the steam mass flowrate is followed by a decrease in the turbine isentropic efficiency.

As per Eq. 4, most stages, including the first and last stage, operate with a constant pressure ratio under the changing governor valve setting, throttle flow, throttle steam conditions and condenser pressure (for condensing type turbines). However, when the governor is fully open (w at its maximum), there is a reduction in the nozzle area, A_n, as a result of steam fouling. The pressure ratio, P_2/P_1, begins to change, and this is indicative of a loss of turbine power to maintain the required load demand. Trending the pressure ratios of the input and output steam could also provide valuable information on the turbine status.

Evaluation results

It was determined, based on the data and analysis mentioned previously, that the steam turbine was experiencing fouling due to steam quality issues. These results initiated a follow-up investigation on steam quality and, subsequently, control.

The online performance analysis coupled with trending of the governor position, provided a good measure of the turbine's health. Reasonable predictions were possible on the reliability of the turbine. It is important to ensure that proper instrumentation signaling is maintained into the distributed control system to acquire reliable data for such analysis and subsequent decision making. Plant reliability personnel can use similar strategies coupled with the functionality of their online monitoring system to determine the condition of critical turbomachines during plant operation. Accurate data monitoring, understanding and avoiding complacency during the decision-making process can help save the plant millions of dollars and affect the bottom line in a positive manner. **HP**

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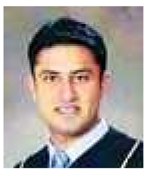

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