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**Bill Kubik, Graham Corp., USA,** explains why turbine operating costs depend on condenser and ejector performance.

aving energy and thus reducing a plant's carbon footprint is vitally important in today's world. One of a plant's greatest energy users can be its steam-driven turbines. Steam turbines have excellent reliability and durability and are used to drive pumps, compressors, generators, and other rotating mechanical equipment throughout the refining, chemical, and petrochemical industries for processes that produce petroleum products, chemicals, fertilizers, electric power, and other products that are used every day by people around the world.

Turbines utilise the potential energy contained in pressurised steam, converting it into kinetic energy to power a rotating shaft. Optimising turbine operation, which can often be accomplished by correcting issues in the auxiliary equipment that supports the turbine, will result in reduced energy use.

This article will focus on condensing turbines that discharge into a steam surface condenser which operates under vacuum. It will describe how the operation of the steam surface condenser and venting ejector package can greatly affect the amount of steam needed to produce the desired power output. Reducing a plant's energy needs can depend on optimising the operation of these components, yet it is common for plants to neglect the condensers and ejectors, not realising the important role this equipment plays in influencing a plant's steam use.

In an ideal world, steam turbines are isentropic machines, where the entropy of the steam leaving the turbine is equal to the entropy entering. Many improvements have been made to turbine designs over the years and, due to the efforts of rotating equipment experts, modern steam turbines can be capable of operation at 70 - 80% efficiency. Operating an efficient turbine and using the least steam possible do not always correlate, as will be seen.

Neglect of the surface condenser or ejectors can turn an efficient turbine into an energy hog.

The energy used by a turbine is dependent on the combined operation of the turbine and its auxiliary equipment. Figure 1 displays a flow diagram of the thermodynamic Rankine cycle; it should be noted that the transfer of energy is accomplished through phase changes in the working fluid. This transfer of energy can be followed by referring to a temperature-entropy (T-s) diagram, as shown in Figure 2.



Figure 1. Rankine cycle diagram.



#### Figure 2. Temperature-entropy diagram.







# The Rankine cycle

The Rankine cycle consists of four steps where energy is transferred:

- Steps 1 2: a condensate pump supplies working fluid (liquid water) to the boiler.
- Steps 2 3: the boiler heats the water to generate high-pressure steam. The boiler fuel can be natural gas, oil, or another energy source including biomass, concentrated solar, etc. The change in state, from liquid to gas, that occurs in the boiler should be noted.
- Steps 3 4: the turbine uses the high-pressure steam supplied by the boiler. The steam is allowed to expand to a high velocity, converting the potential energy of high pressure into kinetic energy. The high velocity steam is used to drive the turbine blades. The resulting work is transferred to the pump, compressor, generator, or other item through the turbine output shaft.
- Steps 4 1: the surface condenser (Figures 3 and 4) receives steam from the turbine. Condensers are typically shell and tube type machines, but are built with special features that provide efficient condensing with negligible pressure drop. The steam enters the condenser shell while cold water is circulated inside the condenser tubes. As the steam comes into contact with the cold tube surfaces, the steam cools and condenses. The condensed steam collapses into a much smaller volume, and it is this change in volume that results in vacuum conditions in the condenser. Special internal geometry in the condenser allows for the removal of any air in-leakage, typically by steam jet air ejectors operating as venting equipment. Common operating vacuum levels for surface condensers are in the range of 3 to 6 inches of mercury absolute (in. HgA). The change in state, from gas (steam) to liquid (water), which occurs in the condenser should be noted. The condensed steam (condensate) is then pumped from the condenser by the condensate pump and returned to the boiler, where the cycle repeats. It will be shown that when the condenser is operating at its deepest vacuum level (lowest absolute pressure) the turbine will require the least amount of steam.

#### Interaction of the components

By looking at the interaction of the components that make up the Rankine cycle, it will be possible to highlight how significant the condenser operating pressure is in determining turbine steam requirements.

#### Turbine steam use

Enthalpy is the thermodynamic measure of the internal energy of steam as well as the product of its pressure and volume. The amount of steam required by a turbine can be estimated using the change in enthalpy between the steam entering the turbine and the steam as it exits the turbine. The inlet enthalpy to the turbine  $(h_{inlet})$  is determined by the boiler conditions. The discharge enthalpy  $(h_{disch})$  is calculated at the exhaust of the turbine and is set by the condenser. The greater the enthalpy change, the less amount of steam is needed for a given power output. The following example will focus on changes to condenser performance to see how



deeper vacuum will decrease the exit enthalpy, which will decrease the amount of steam required to drive the turbine. The physical properties of steam can be used to calculate the steam flow required.

## Example

A US Gulf Coast plant operates a compressor that requires 25 MW. Superheated steam is supplied to the turbine at 900 psig and 900°F. The turbine supplier has provided an efficiency of 77%. However, the condenser that was originally designed to operate at 3 in. HgA is now operating at 5 in. HgA.

At the turbine inlet conditions, a Mollier chart can be referenced to determine steam properties and find the inlet enthalpy (h<sub>inlet</sub>) is 1452 Btu/lbm and inlet entropy (s<sub>inlet</sub>) is 1.624 Btu/lbm degrees R.

Assuming ideal isentropic operation, 's' should be kept constant (point 4 on the T-s diagram) to determine the enthalpy at the turbine's design discharge pressure of 3 in. HgA:  $h_{disch} = 927$  Btu/lbm.

Delta h = 1452-927 = 525 Btu/lbm.

The theoretical steam rate is now calculated based on delta h, remembering that this is the steam rate at 100% turbine efficiency.

The theoretical steam rate = (3412 Btu/kW-hr) / (525 Btu/lbm) = 6.50 lb/kW-hr.

Next, the turbine efficiency – representing the difference between point 4 (ideal) and 4' (actual) on the T-s diagram – is corrected for. At 77% efficiency, the actual steam rate = 6.50/0.77 = 8.44 lb/kW-hr.

Thus for 25 MW output, with the condenser at 3 in. HgA, the turbine will require: 25 MW x 8.44 lb/kW-hr x 1000 kW/MW = 211 000 lb/hr of steam.

Returning to the example, consider the effect with the condenser operating at 5 in. HgA. The same turbine efficiency of 77% will be used. It should be remembered that the actual turbine efficiency can be somewhat less at off-design conditions, making the calculation conservative. To evaluate cases where the turbine efficiency is not known, approximations can be made using 75% efficiency for units that are 20 MW and larger, and 65% for smaller turbines.

With 's' constant at 1.624 Btu/lbm degrees R and a pressure of 5 in. HgA, h<sub>disch</sub> = 954 Btu/lbm. Delta h = 1452 - 954 = 498 Btu/lbm, resulting in a theoretical steam rate of 6.85 and an actual steam rate of 8.90 lb/kW-hr.

Thus, for the same 25 MW output, the turbine will require 222 500 lb/hr steam, 5.5% more than at 3 in. HgA.

## Plant operating costs

The cost of steam will depend on plant location, fuel type, environmental regulations, and other site-specific factors. The following calculation is based on a cost of US\$4.00/1000 lb of steam and should be modified as needed.

Comparing operation at 5 in. HgA instead of operation at 3 in. HgA yields a difference of 11 500 lb/hr steam.

Operating cost difference per year: 11 500 lb/hr x US\$4.00/1000 lb x 8760 hrs/yr = US\$403 000/yr.

# Improvement opportunities



#### Figure 4. Typical condenser.

How can plant energy usage be improved? The issue is often not with the turbine, but with the condenser or ejector package, as these must be operating properly to provide the best discharge pressure for the turbine.

#### Condenser issues

There are a number of potential condenser issues that should be considered:

- Is the cooling water flow at design? The temperature should be at design or cooler.
- Are the tubes clean? Have any tubes been plugged in the past? Was the tube material changed during a previous retubing? Compare the cooling water pressure drop to design: do the results indicate tube fouling?
- Replacement condenser: if a plant needs to replace a condenser, it should be ensured that the new unit is made specifically for vacuum service by a reputable condenser manufacturer.

# Steam jet air ejectors

Ejectors are often one of the most neglected pieces of equipment. The ejector package is correctly described as 'venting equipment'. In a properly operating system, the condenser will set the vacuum level, which will depend on the condenser capabilities. If the system were to be perfectly sealed from the atmosphere, the condenser would always set the vacuum level, as it is the collapse of steam that creates vacuum conditions. In the real world, air can leak into the system. The ejector package must operate properly to remove any air in-leakage, otherwise the condenser pressure will rise. The result is an increase in the steam needed to run the turbine, increasing the plant's utility cost.

Ejector packages are normally supplied as two 100% capacity two-stage ejector trains with a single intercondenser and aftercondenser, often built in a single shell arrangement. These ejectors are referred to as the 'holding ejectors'. Also supplied is a single-stage 'hogging ejector'. The hogging ejector is supplied for rapid start-up to reduce the pressure from atmospheric to a level where the turbine can be safely started. After start-up, one train of holding ejectors should be used to maintain the vacuum level, and the hogging ejector isolated and turned off.

When the ejectors are operating properly, the condenser will run at its best vacuum level. If there are problems with the

ejectors, or they cannot handle the air in-leakage, the pressure will rise in the condenser and the entire system will suffer.

# **Ejector operation**

Items to check to ensure proper ejector operation include:

- Motive steam: the motive steam supplied to the ejectors should be at the design pressure, with a typical tolerance of -0% to +20%.
- Motive steam nozzles and ejector bodies: these items should be inspected during shutdowns and internal throat diameters measured and compared to design. Wear of these items can cause significant capacity loss of the ejectors, with a usual tolerance of only 3.5% on diameters. If worn these items should be replaced.
- Cooling water supply: many ejector packages are cooled with condensate from the main condenser. The cooling water supply, temperature, pressure drop, and tube condition should be evaluated. If necessary, the intercondenser/aftercondenser should be replaced.
- Condensate removal: most often the intercondenser and aftercondenser drains will flow through condensate traps and then discharge to the main condenser before being returned to the boiler. Checking the condition of the traps and associated piping is recommended.
- Air leakage: any air that has leaked into the system will eventually find its way to the ejectors. The air will be discharged through the aftercondenser vent. An air leakage meter should be furnished to allow operators to check air leakage. If leakage exceeds design, the leak should be located and repaired. Maintaining gaskets, flanged joints, turbine glands, expansion joints, valve

packing, and other items throughout the system is important to keep air in-leakage to a minimum.

Hogging ejectors: these items deserve special attention. The hogging ejector is intended to be run only during the initial start-up of the turbine. Too often plants operate the hogging ejector on a full-time basis. There are several disadvantages with this: first, the hogging ejector will use more steam than the holding ejectors, resulting in steam waste; second, hogging ejectors typically are supplied with a silencer, but no aftercondenser. Thus no condensate can be recovered - another waste of energy. The third disadvantage, and the most important, is that hogging ejectors are designed for large capacity at rough vacuum levels, but they are limited and cannot reach the deeper vacuum levels needed for proper condenser operation. This causes the condenser to run at a higher absolute pressure, thus requiring more steam to operate the turbine. Constant operation of the hogging ejector normally indicates that a problem elsewhere has not been taken care of.

# **Summary**

The steam required by a turbine will depend on operation of the surface condenser and venting equipment. Proper functioning of this auxiliary equipment will result in the lowest energy use of the turbine, and the most cost-effective plant operating expense. Performance of these ancillary items is sometimes overlooked, but their role is critical in reducing a plant's overall energy requirements.

# Bibliography

1. Heat Exchange Institute Standards for Steam Surface Condensers,  $12^{\rm th}$  edition.

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