STEAM TURBINE VERSUS PRESSURE REDUCING VALVE OPERATION

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ABSTRACT

A question arising frequently in steam system design relates to the benefits and drawbacks associated with passing steam through a pressure reducing valve or a steam turbine to supply a low pressure steam demand. The most appropriate analysis of the economic benefits of operating the steam turbine utilizes an incremental systems approach.

A case study analysis based on a systems approach was used to demonstrate the role of incremental fuel and electricity costs, boiler and turbine efficiencies, as well as steam flow and thermodynamic properties on the economic performance of the turbine-generator and pressure reducing valve options. An example analysis was performed for a boiler producing superheated steam at 600 psig and 800°F to supply a low pressure steam demand of 30,000 lbm/hr. Overall energy balances were computed for a turbine with an isentropic efficiency of 40%, a 90% efficient generator and an isenthalpic pressure-reducing valve as an alternative scheme. For a fuel unit cost of $\$3.00/10^6$ Btu and an electricity unit cost of $0.035/kWh, it is shown that 408 kW of electricity can be produced while supplying the steam demand. Use of the turbine-generator requires the total steam flow rate to increase to satisfy the process heating demand. The steam flow through the turbine would be 31,261 lbm/hr or about a 4% increase over the low-pressure process base load. Assuming that the modest additional high-pressure steam demand can be met, a net purchased energy saving of $70,000/yr. could be realized. This analysis demonstrates that a substantial plant-purchased energy cost saving may be achieved for typical system operating conditions when a turbine-generator is used to

produce low-pressure process steam rather than a pressure reducing valve.

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A question arising frequently in steam systems relates to the benefits and drawbacks associated with passing steam through a pressure reducing valve or a steam turbine to supply a low pressure steam demand. The most appropriate analysis of the economic benefits of operating the steam turbine utilizes an incremental systems approach. The information of primary importance to the analysis is:

- Incremental electric cost
- Incremental fuel cost
- Boiler efficiency
- Steam turbine efficiency (or the properties of steam entering and exiting the turbine)
- Steam flow rate (or process demand)

The term "incremental electric cost" relates to the rate structure or tariff applied to electrical purchases at a facility. In particular, the actual economic impact of any change in electrical consumption is the incremental cost. Many times the price of electricity is dependent on the amount of electricity consumed, the rate of electrical consumption, as well as the time of use. Most electrical tariffs for industrial sites carry fixed charges, which do not change with respect to electrical consumption. A change in electrical demand will typically not incur the "average" electric cost for a facility but the "incremental" electric cost.

To compare the operation of a steam turbine to a pressure-reducing valve, an example is investigated. The example focuses on a boiler producing high-pressure steam, which is operating in support of a site that demands low-pressure steam and shaft power (or electricity). The investigation considers a facility capable of operating under two different scenarios. In the first operating scenario, the system receives fuel to produce high-pressure steam. The high-pressure steam passes through a pressure-reducing valve to supply the site's low-pressure steam demand. Electricity is purchased to meet the site electrical power demand. In this scenario, both fuel and electricity are purchased to support the activities of the site. In the second scenario, fuel is also consumed to produce high-pressure steam; this high-pressure steam is passed through a steam turbine to produce shaft power. The turbine is connected to an electric power generator, which supplies a portion of the site's electrical demand. Low-pressure steam is exhausted from the turbine and is utilized in site operations. In this scenario, fuel is the only purchased utility for the site.

The example system consists of a boiler, a low-pressure steam demand and a steam pressure reduction component (pressure reducing valve or turbine). The steam turbine drives an electric generator. Figure 1 is a simple schematic of the system.

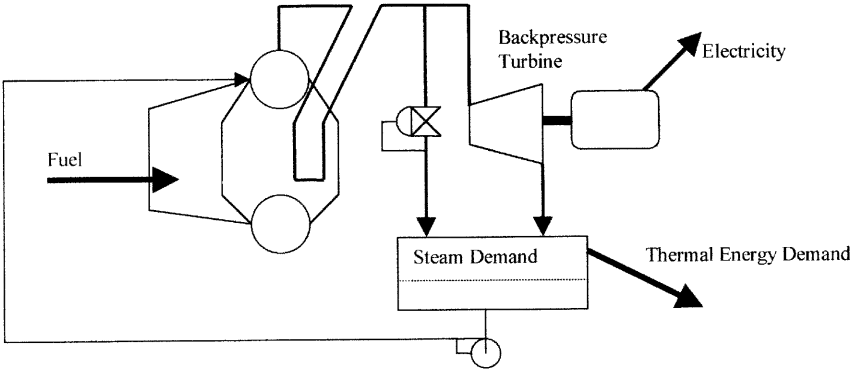


Figure 1

The analysis procedure first determines the cost of fuel supplied to the facility when the pressure-reducing valve is in operation. Electricity purchased during this operating mode is not considered until the amount of electricity produced through the turbine-generator set is determined in the second scenario. The second analysis scenario determines the cost of fuel supplied to the boiler when the turbine is operating and allows the electricity produced in the generator to reduce the total site electrical consumption.

One primary factor is held constant in the analysis; the thermal energy supplied to the low-pressure steam demand. This is not to say the steam flow rate supplied to the steam demand is equal in both cases. In fact, the steam mass flow rate will change because the turbine converts some of the steam's thermal energy into shaft energy. Therefore, the steam exiting the turbine will have a reduced energy content when compared to the steam exiting the pressure reducing valve. As a result, when the turbine is operating, the mass flow rate of steam must increase to supply the same thermal energy to the steam demand. This additional steam flow is provided by the boiler, which requires additional fuel.

Example

In the example scenarios, high-pressure steam is produced in the boiler and is supplied to the pressure reducing valve or the steam turbine. Steam exhausted from these components is supplied to the low-pressure user. For the example analysis, the fuel unit price is \$3.00/10^6 Btu and the electrical unit cost is \$0.035/kWh. High-pressure steam conditions for this example are 600 psig and 800°F at the boiler outlet. The turbine and pressure-reducing valve export steam at 200 psig. Condensate is discharged from the steam user and is returned to the system at 0 psig and saturated liquid conditions. This is a simplified analysis; however, the main operational and economic factors are incorporated. In other words, this analysis accurately represents the economics associated with a typical steam system.

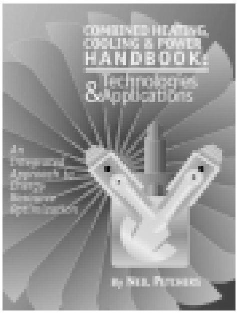
The example analysis provided here does not attempt to explain electric rate structures but merely utilizes a fixed electric cost for simplicity. This may not reflect the actual conditions at a given site. Similarly, fuel unit price is a fixed value in the example. Care should be exercised to accurately incorporate the appropriate fuel and electric costs for a given facility.

The example begins with the pressure-reducing valve in operation and a low-pressure steam demand of 30,000 lbm/hr. This steam flow corresponds to the steam flow exiting the boiler. The cost of fuel supplied to the boiler,, is determined by Equation 1.

$$\dot{K}_{fuel} = \kappa_{fuel} \frac{\dot{m}_{steam}\left(h_{steam} \pm h_{feedwater}\right)}{\eta_{boiler}} T$$

Equation 1

Where, h_{steam} and $h_{\text{feedwater}}$ are the enthalpy values of steam exiting the boiler and feedwater entering the boiler, respectively. These properties can be found in thermodynamic property tables for the given fluid conditions. Boiler efficiency, η_{boiler}, is the first law of thermodynamics efficiency of the boiler; also known as the fuel to steam energy conversion efficiency of the boiler. For the example boiler, efficiency is taken as 85%.



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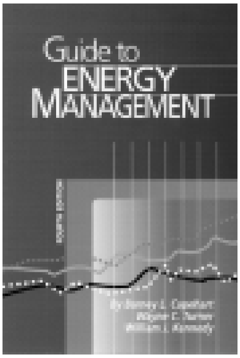

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Fuel cost, κ_{fuel}, and operating period, T, are incorporated in the calculation to allow the fuel consumption of the boiler to be represented as an operating cost. In this example, the period of operation is taken as 90% of a year (7,884 hrs/yr). The steam mass flow rate from the boiler is represented as $\dot{m}_{steam}$. The operating cost of this system is calculated below.

$$\dot{K}_{fuel} = \kappa_{fuel} \frac{\dot{m}_{steam}\left(h_{steam} \pm h_{feedwater}\right)}{\eta_{boiler}} T$$

$$\dot{K}_{fuel} = 3.00 \frac{\$}{10^6 Btu} \left(\frac{30{,}000\frac{lbm}{hr}\left(1{,}407.01\frac{Btu}{lbm} \pm 180.07\frac{Btu}{lbm}\right)}{0.85} \right) 7{,}884\frac{hrs}{yr}$$

$$\dot{K}_{fuel} = 1{,}024{,}220\frac{\$}{yr}$$

Equation 2

The amount of thermal energy, $\dot{Q}$, supplied to the low pressure steam demand is determined by Equation 3. Equation 3 is a representation of the first law of thermodynamics applied to the steam demand.

$$\dot{Q} = \dot{m}_{steam}\left(h_{PRV\ steam} \pm h_{condensate}\right)$$

$$= 30{,}000\frac{lbm}{hr}\left(1{,}407.01\frac{Btu}{lbm} \pm 180.07\frac{Btu}{lbm}\right)$$

$$= 36{,}808{,}200\frac{lbm}{hr}$$

Equation 3

The energy (enthalpy flow) required by the steam demand is held constant for each analysis scenario. An important point to note is the fact that the steam exiting the pressure-reducing valve has the same enthalpy content as the steam entering the valve. The pressure reducing valve is a classic throttling process when heat transfer to the surroundings is negligible, which is most often the case. Therefore, the valve is an isenthalpic (constant enthalpy) process. The isenthalpic process results in steam exiting the pressure reducing valve with a temperature of 767°F.

Recall the steam entering the valve had a temperature of 800°F.

The second scenario begins with the selection of a steam turbine or at least identification of the operating characteristics of the turbine. Steam turbine efficiency is an important parameter in the analysis of the economics of this type of system. Typically, steam turbine performance is defined by "isentropic efficiency." Isentropic efficiency is a comparison of the actual shaft power export of the turbine to that of an ideal, isentropic (or perfect) turbine. The equation for isentropic efficiency of a turbine is provided below.

$$\eta_{\text{isentropic}} = \frac{Actual\ Work}{Isentropic\ Work} = \frac{\dot{W}_{actual}}{\dot{W}_{isentropic}}$$

$$= \frac{\dot{m}_{steam}\left(h_{inlet} \pm h_{exit}\right)}{\dot{m}_{steam}\left(h_{inlet} \pm h_{exit}\right)_{isentropic}} = \frac{\left(h_{inlet} \pm h_{exit}\right)}{\left(h_{inlet} \pm h_{exit}\right)_{isentropic}}$$

Equation 4

Where h_{inlet} designates the enthalpy of the steam entering the turbine and h_{exit} designates the enthalpy of the steam exiting the turbine. The designation "actual" expresses the given turbine's operating conditions; in other words, the conditions of a real turbine operating in the steam system. The designation "isentropic" references perfect turbine operation. Equation 4 has been developed assuming kinetic and potential energy changes are negligible and heat transfer is negligible for the turbine. These are good assumptions for typical steam turbines. Isentropic exit conditions are determined from thermodynamic property references. Isentropic exit conditions are assumed to occur at the same exhaust pressure as the actual turbine operation. The term "isentropic" denotes "constant entropy." Therefore, if the inlet conditions are known (inlet entropy), the isentropic exit entropy is known. Thermodynamic properties can be obtained for the isentropic exit conditions knowing the exit pressure and entropy values.

Isentropic work is the maximum theoretical work output of the turbine, which is the output of a perfect turbine. Isentropic efficiency is typically expressed (as most efficiencies are) as a percentage. Industrial steam turbine isentropic efficiencies range from less than 20% to over 80%, which is an exceptionally broad efficiency range. Isentropic efficiency has a significant effect on the economic evaluation of a steam turbine system. Therefore, actual turbine data or manufacturer's data should be utilized to improve the accuracy of the analysis.

The steam turbine utilized in the example analysis operates with an isentropic efficiency of 40%. This is typical for small industrial steam turbines. Equation 4 will be utilized to determine the exhaust conditions of the turbine.

$$\eta_{\text{isentropic}} = \frac{\left(h_{inlet} \pm h_{exit}\right)}{\left(h_{inlet} \pm h_{exit}\right)_{isentropic}}$$

$$0.40 = \frac{1{,}407.01\frac{Btu}{lbm} \pm h_{exit\ actual}}{1{,}407.01\frac{Btu}{lbm} \pm 1{,}283.31\frac{Btu}{lbm}}$$

$$h_{exit\ actual} = 1{,}357.53\frac{Btu}{lbm}$$

Equation 5

Alternately, if the steam turbine exhaust conditions are known, then an evaluation of isentropic efficiency is not required. The measurements required to determine turbine exhaust conditions are steam temperature and pressure. These values are the only required measurements if the steam exiting the turbine is superheated. If the steam exiting the turbine is saturated, the evaluation is more difficult, requiring the use of a throttling calorimeter, which is a special measuring device for saturated steam. The example turbine would be discharging 670°F superheated steam with a pressure of 200 psig.

Once the steam turbine exit enthalpy value is known, it is used to determine the steam flow through the turbine required to satisfy the thermal demand of the system. A variation of Equation 3 is utilized in this evaluation.

$$\dot{Q} = \dot{m}_{steam}\left(h_{turbine\ exit\ steam} \pm h_{condensate}\right)$$

$$= 36{,}808{,}200\frac{Btu}{hr} = \dot{m}_{steam}\left(1{,}357.53\frac{Btu}{lbm} \pm 180.07\frac{Btu}{lbm}\right)$$

$$\dot{m}_{steam} = 31{,}261\frac{lbm}{hr}$$

Equation 6

This is the steam flow passing through the turbine; it is also the steam production of the boiler. Therefore, Equation 1 can be utilized to determine the operating cost of the boiler.

$$\dot{K}_{fuel} = \kappa_{fuel} \frac{\dot{m}_{steam}\left(h_{steam} \pm h_{feedwater}\right)}{\eta_{boiler}} T$$

$$\dot{K}_{fuel} = 3.00 \frac{\$}{10^{6} Btu} \left(\frac{31{,}261 \frac{lbm}{hr}\left(1{,}407.01 \frac{Btu}{lbm} \pm 180.07 \frac{Btu}{lbm}\right)}{0.85} \right) 7{,}884 \frac{hrs}{yr}$$

$$\dot{K}_{fuel} = 1{,}067{,}270 \frac{\$}{yr}$$

Equation 7

Fuel consumption increases when the turbine is operated. The increase in fuel consumption is seen by comparing Equation 7 and Equation 2. In other words, fuel consumption increases $43,050/yr.

To determine the amount of electrical power produced from the steam turbine generator, the first law of thermodynamics must be applied to the turbine. The shaft power exported from the turbine ($\dot{W}_{shaft}$) is determined by the following equation.

$$\dot{W}_{shaft} = \dot{m}_{steam}\left(h_{inlet} \pm h_{exit}\right)_{actual}$$

$$\dot{W}_{shaft} = 31{,}261 \frac{lbm}{hr} \left(1{,}407.01 \frac{Btu}{lbm} \pm 1{,}357.53 \frac{Btu}{lbm}\right)$$

$$= 1{,}546{,}794 \frac{Btu}{lbm} \left(\frac{1\ kW}{3{,}413\ Btu} \right) = 453\ kW$$

Equation 8

Equation 8 is an expression of the shaft power exported from the steam turbine. If the shaft power is converted into electrical energy, generator efficiency must be incorporated. Electric generator efficiency is an expression of the ratio of electrical power export to shaft power input to the generator and will generally be greater than 80%. In this example, the generator is assumed to operate with 90% efficiency.

$$\dot{W}_{electricity} = \dot{W}_{shaft}\left(\eta_{generator}\right) = 453\ kW\ (0.90) = 408\ kW$$

Equation 9

The electrical power export represents a savings to the site because the amount of electrical power generated reduces the amount of electricity required to be purchased. The generated electricity savings is calculated below.

$$\dot{K}_{elec} = \kappa_{shaft}\left(\eta_{generator}\right) = 453\ kW\ (0.90) = 408\ kW$$

$$\dot{K}_{elec} = 0.035\frac{\$}{kWh}\left(408\ kW\right)7{,}884\frac{hrs}{yr}$$

$$\dot{K}_{elec} = 112{,}580\frac{\$}{kWh}$$

Equation 10

Many times the electric power savings ($112,580/yr) is reported as the potential savings associated with operating the steam turbine because this is the avoided electrical purchase. However, recall the fact that fuel consumption increased to maintain the thermal energy supply to the site. This resulted in an increased fuel consumption of $43,050/yr. Therefore, the actual savings potential is $69,530/yr or approximately $70,000/yr.

Many systems incorporate desuperheaters to control the temperature of the low-pressure steam exported from pressure reducing stations and steam turbines. An analysis of a system including a desuperheater is fundamentally the same as presented here; the difference is the obvious requirement to incorporate the operation of the desuperheater. Because the desuperheater controls steam temperature, the steam flow supplied to the steam demand would be the same for both scenarios. The amount of desuperheater water will change based on turbine operation or pressure reducing valve operation.

In summary, the principal analysis parameters are the incremental cost of fuel and electricity, the efficiency of the boiler and the efficiency of the turbine (or steam properties). Steam flow will not be the same through the turbine and the pressure-reducing valve. This has a significant effect on the analysis results.

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Dr. Greg Harrell is a senior research associate with the Energy, Environment and Resources Center at the University of Tennessee, Knoxville. He has worked as a design and utilities process engineer for BASF Corporation and he has served as the director of technical assistance for the Energy Management Institute at Virginia Tech, as well as an assistant mechanical engineering professor. Dr. Harrell has conducted many energy surveys for industrial clients worldwide. His current areas of specialization are industrial steam systems and compressed air systems.

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