# Steam turbine efficiency calculation pdf


The Impact of Condenser Performance, Feeding Water Heating and Steam Reheating By Brad Buecker, Contributing Editor The word thermodynamics evokes visions of complex mathematics for many people, even some with technical training. However, relatively simple thermodynamics formulas can be used explain a lot about the fundamentals of the steam generator. Thermodynamics is built around two laws. The first law is energy conservation. It says that the energy used within a system is not created or destroyed, but only transferred. The classical energy equation for a simple system (defined as a volume of control in textbooks)1,2 is: Q – WS = m2[V22/2 + gz2 + u2 + P2v2] – m1[V12/2 + gz1 + u1 + P1v 1] + dEc.v./dt Eq. 1 Where, Q = Unit time heat input WS = Shaft work as done by a turbine per unit time m2 = Outflow system per unit time m1 = Flow to the system by unit time (V22 - V12)/2 = Change in kinetic energy gz2 - gz1 = Change in potential energy u2 = Internal energy of the output fluid u1 = Internal energy of the input fluid P2v 2 = Flow flow of fluid when it leaves the system (P = pressure, v = specific volume) P1v 1 = Fluid workflow as it enters the dEc.v./dt system = Power change within the system per zero time unit This equation can be easily understood through some definitions and simplifications. First, in many systems and especially steam generators, potential and kinetic energies are very small compared to other energy changes and can be overlooked. Secondly, in a constant flow process, such as a steam generator, the system does not accumulate power, so dEc.v./dt is zero. Removing these terms leaves the internal energy of the fluid (u) plus its flow (Pv) capabilities. Scientists have combined these two terms in the very useful property known as enthalpy (h). Enthalpy is a measure of the available energy of the fluid, and the inenthalpies have been calculated for a wide range of steam and saturated liquid conditions. These values can be found in the standard ASME steam, where water saturated at 0C has been designated as having zero enthalpy. Using these simplifications and definitions, the energy equation for constant operation reduces to: Q - WS = m(h2 - h1) Eq. 2 But this equation represents the ideal scenario and here is where the second law comes in. The second law describes the direction of the process. For example, a cup of hot coffee placed on a kitchen table does not get any hotter while the room gets colder. Many other examples are possible, but this conveys the essence of the second law. The second law is based on the concept of the Carnot cycle, which says that the most efficient engine that can be built operates with a high temperature heat input (QH) (TH) and a low temperature heat discharge (QL) (TL), in which QH/TH – QL/TL = 0 Eq. 3 This equation represents a theoretically ideal engine. In all processes known to humans, some energy losses occur. Scientists have defined a property known as entropy(s), which, in its simplest terms, is based on the ratio of heat transfer in a process to temperature (Q/T). In all processes, the general change of entropy (of a system and its surroundings) increases. Thus, in the real world, Equation 3 becomes QH/TH – QL/TL < 0 Eq. 4 Although entropy may seem a somewhat abstract term, it is of great benefit to determine the efficiency of the process. Like enthalpy, entropy values are included in the steam tables. Two important points should be noted about the Carnot cycle and all real-world processes. First, no process can be done to produce work without some process heat extraction (QOL) in Equation 3. QL in a conventional steam generator is removed heat in the condenser. Second, the efficiency (η) of a Carnot engine is set to η = 1 - TL/TH Eq. 5 Thus, as the input temperature rises and/or the exhaust temperature decreases, efficiency increases. This concept has some limitations in complex systems and an example is outlined later. So how does this discussion apply to the normal operation of the steam plant? First, let's examine the performance of the condenser. Condensers Why should the turbine exhaust steam be condensed? Why not transport it directly back to the boiler? The reason is efficiency. For the sake of cities, consider the system shown below with a turbine that has no friction, heat, or other losses, which means there is no change in entropy (isentropic). In reality, turbines are typically 80 to 90% efficient, but this factor does not need to be included here to show the importance of condenser performance. Conditions are: Main steam pressure (turbine inlet) – 1,000 psia Main steam temperature - 1,000 F Turbine output steam pressure – Atmospheric (14.7 psia) Let's call this Example 1. The steam tables show that the turbine inlet steam notch is 1,505.9 Btu per kilogram of fluid (Btu/lbm). indicate that the inenthalpy turbine output is 1,080.9 Btu/lbm (steam quality is 93%). Equation 2 (the first law, stable state energy equation) becomes for the wT = m(h1 - h2). Thus, the unit work available from this ideal turbine is (1,505.9 Btu/lbm – 1,080.9 Btu/lbm) = 425.0 Btu/lbm. To put this into practical perspective, take steam flow (m) to be 1,000,000 lb/h. The total work is then 425,000,000 Btu/h = 124.5 MW. Now consider example 2, where the system has a condenser that reduces the turbine exhaust pressure to 1 psia (approximately 2 inches of mercury). Again assuming an ideal turbine, the turbine exhaust case is 923.4 Btu/lbm. The unit's working output is equivalent to 1,505.9 – 923.4 = 582.4 Btu/lbm. With steam flow of 1,000,000 lb/h, the total work is 582,400,000 Btu/h = 170.6 MW. This represents a 37% increase in terms of the previous example. Obviously, vapor condensation has a huge effect on efficiency. This is a practical illustration of how the condenser lowers tl of equation 5. Another point is that if the steam from Example 1 were redirected directly to the boiler, the power and size requirements for the feed pump would be enormous. Much less work is required to pressurize a liquid than a gas. One can also look at this example from a physical perspective. Calculations indicate that the quality of steam in the turbine exhaust (1 psychopressure psia condenser) is 82%. This means that 18% of the steam condensed into the water. However, the remaining steam occupies a specific volume of 274.9 ft3/lbm. The corresponding volume of water in the condenser hotwell is 0.016136 ft3/lbm. Thus, the condensation process reduces fluid volume more than 17,000 times. The condenser steam generates the strong vacuum in the condenser, which actually acts as a driving force to pull steam through the turbine. Let's take this concept one step further in Example 3. Consider whether the incrustion or scale (or excess air in the leak) causes the condensing pressure of the previous example to increase from 1 psa to 2 psa. Thermodynamic calculations show that turbine work production drops from 582.4 to 546.1 Btu/lbm. Thus, at 1,000,000 lb/h of steam flow, an increase of 1 psia in condenser recoil pressure equates to a loss of 36,300,000 Btu/h or 10.6 MW of work. That's why proper chemical treatment of cooling water and condenser performance monitoring are important.3 Click here to enlarge the image For simple steam generation systems, overall efficiency is represented by this equation: η = (wT – wP)/qB Eq. 6, where wT = Work produced by the turbine wP = Work required by the feed water pump qB = Thermal input into the zero boiler The energy required by the feed water pump is much lower than the work produced by the turbine, so it is often left out in the basic energy calculations. The heat input (qB) is equivalent to the in the enthalpy of the condensate entering the boiler versus that of the main steam coming out of the boiler. For examples 2 and 3 described above, qB calculates for 1,436.2 and 1,411.9 1,411.9 Respectively. From the simplified efficiency equation (η = wT/qB) the respective efficiencies are 40.6% and 38.7%. Overheating mechanics Consider the boiler common drum, where the steam coming out of the drum is saturated. If this steam were immediately injected into a turbine, very little work would occur, as the steam would immediately begin to condense water after passing through the blades. For this reason, all utility steam generators include several tube circuits, which reside in the boiler backpass, through which saturated steam passes for additional heating. These tubes make up the superaquecite. The temperature at which steam is high above saturation represents the degree of overheating. Remember that it takes almost 1,000 Btu to convert a pound of water into half a kilo of steam into utility steam generators. As the examples from the previous section illustrate, it should come as no surprise that the efficiency of standard utility boilers is in the range of 30% to 35%. Research on tube materials more resistant to temperature and reheat continues, in the direct application of the equation,η = 1 - TL/TH. Maximum steam temperatures in even the most advanced supercritical units were limited to about 1,100 F due to material performance issues. However, new allusions are being developed that may allow for higher steam temperatures, especially for future supercritical boilers. Click here to enlarge the image Ideally, the energy of the superaquecito is almost completely consumed in the latest low pressure turbine blades. A balance is necessary to extract all available energy from steam, but to avoid excessive condensation on the turbine blades. Thermodynamics shows that the work and efficiency of a steam generator will improve with increased pressure. We will increase the steam pressure to 2,000 psia from example 2, where the condenser pressure was 1 psa. Note this as example 4. The main steam enthalpy becomes 1,474.1 Btu/lbm and the turbine exhaust is 871.0 Btu/lbm. Turbine production rises to 603.1 Btu/lbm (176.7 MW to 1,000,000 lb/h of steam flow), and efficiency increases from 40.6% to 42.9%. (Gaining efficiency through higher pressure is the main reason supercritics have become popular for coal boilers.) But at 2,000 psia, the steam quality of the turbine output is only 77%. This means that 23% of the fluid comes out as droplets of condensed water. This high moisture content can damage the turbine blades of low pressure. Ten percent moisture in the turbine exhaust is typically an upper limit. Reheating the steam helps alleviate this difficulty. Consider Figure 2, which shows a steam generator and a turbine with a reheated system. The main steam is at 2,000 1,000 F, and has an enthalpy of 1,474.1 Btu/lbm. The steam extraction pressure (cold reheated) is 300 psia, which is equivalent (isentropically) to a 485 F and 1,248.1 Btu/lbm. Suppose no pressure drop through reheating and a hot reheating temperature of 1,000 F, producing reheated steam with an enthalpy of 1,526.5 Btu/lbm. Calculations show that the reheating process improves the quality of the turbine exhaust steam from 77% to 90%. As the quality of the steam increases, the turbine exhaust encase increases slightly to 1,003.9 Btu/lbm. Click here to enlarge the image Calculation of the working output, boiler heat input and efficiency of this example becomes a little more complicated, because in this case the work is done by two separate steam rations for the turbine and the heat is added to two separate steam systems in the boiler. The unit's working equation is wt = (inlet steam enthalpy – cold reaquecing enthalpy) + (enthalpy hot reheats – turbine exhaust enthalpy). In this case, wt = (1,474.1 – 1,248.1) + (1,526.5 – 1,003.9) = 748.6 Btu/lbm. As can be seen, reheating considerably increases work production compared to the example of non-reheating. The heat inlet of the boiler is defined as (main steam plug – feed water enthalpy) + (hot reheating enthalpy – cold reheating notch). For this example, QB = (1,474.1 - 69.7) + (1,526.5 – 1,248.1) = 1,682.8 Btu/lbm. An obvious conclusion is that the reheated increases energy production, but also the fuel requirements for the boiler. Efficiency is calculated to 44.5%, which is 2% higher than the example of non-reheated. The increased fuel requirement is counterbalanced by increased working production and better steam quality of turbine leakage. A well-designed reheated system can reduce moisture to low levels in turbine exhaust steam. Supercritical units can have two reheated units to maximize turbine performance. Heating the feed water A general rule suggests that for a single heater, the steam flow rate of extraction should be designed to raise the temperature of the feed water to a midway point between the condensate temperature and the boiler saturation temperature. In this scenario (condensing pressure of 1 psia and boiler pressure of 2,000 psia) the condensate temperature is 69.7 F and the boiler saturation temperature is 636.0 F. The intermediate point between these two temperatures is 353 F. If steam is extracted from the turbine at a pressure of 500 psia, energy/mass balance calculations show that the flow rate for the heater should be 20.8% of the total steam flow. The steam extraction is 1,299.7 Btu/lbm. Heat exchange produces feed water with an enthalpy of 325.0 Btu/lbm. The work of the turbine is equivalent to the enthalpy difference between the main and extraction (1,474.1 – 1,299.7 Btu/lbm), plus the remaining steam (79.2%) passing into the turbine exhaust (0.792 *[1,299.7 – 871.0] Btu/lbm). In this case, the turbine work is equivalent to 513.8 Btu/lbm. This is less than the work obtained in Example 4 (603.1 Btu/lbm), Btu/lbm), had no feed water heater. One can logically ask how heating the feed water improves the process. The benefits are related to efficiency. The heat input required by the boiler to produce the necessary steam is only 1,149.1 Btu/lbm (1,474.1 – 325.0), as the feed water temperature is much warmer. Thus, the efficiency of this system is (513.8/1,149.1) * 100 = 44.7%. This represents an 11% increase in terms of example 4. The main concept behind the efficiency gain is that much of the heat reused in the feed water heater would have been exhausted in the condenser. Putting it all together A large utility steam generator usually has several feed water heaters, at least a single reheating and condenser that has excess surface for cooling. Proper monitoring and chemical treatment programs are vital to keep these systems free from unscrupulous or corrosion. My co-workers and I have personally been involved with performance improvement projects for condensers that resulted in net savings of $500,000 to $1,500,000 a year in just one factory. To borrow an old phrase, such savings are not chicken feed. References : 1. Van Wylen, G., and R. Sonntag, Fundamentals of Classical Thermodynamics, 3rd Ed.; John Wiley & Sons, 1986. 2. Potter, M., and C. Somerton, Thermodynamics for Engineers; Schaum Contour Series, McGraw-Hill, 1993. 3.B. Buecker, Chemical Condenser and Performance Monitoring: A Critical Need for Reliable Plant Operation; proceedings of the 60th International Water Conference, Pittsburgh, Pennsylvania, October 18-20, 1999. Author: Brad Buecker specializes in air quality control at a large Central American power plant. Buecker has a BS in Chemistry from Iowa State University. He is a member of ACS, AIChE, ASME and NACE. Nace.