Heat Rate and Feedwater Heater LEVEL CONTROL

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Objective

To minimize controllable losses tied to feedwater heater performance by gaining additional insight into the basic feedwater heater and power cycle operations; associated performance indicators and the positive or negative impact of level control on overall plant efficiency as related to net unit heat rate and cost containment.

Overview

- Heat Rate
- Cost of Heat Rate Deviation
- Feedwater Heaters
    - Basic Power Cycle
    - Level Control
    - Monitoring Performance
- Instrument Induced Errors and Heat Rate
- Case Studies
- Level Optimization

Heat Rate

The advent of climate change protocols and the Clean Air Act has put fossil fuels in the forefront of the political debate. Adhering to these standards while improving bottom-line performance has made heat rate a common term at all power plants. An understanding of heat rate, its value to the business and the impact of enhanced technologies on efficiency is crucial when linking the features and benefits of any technology to a return on investment relative to the whole as well as the intended application.

Heat rate is a measurement used in the energy industry to calculate how efficiently a power plant uses heat energy and is expressed as the number of Btus of heat required to produce a kilowatt hour of energy. There are several different calculations for heat rate. The following equations offer the basics of heat rate calculation. Note that the most commonly used calculation is Net Unit Heat Rate.

General heat rate:

Heat Rate (Btu/kWh) = Energy Input (Btu) ÷ Energy Output (kWh)

Energy input:

Energy In Fuel (Btu/hr) = Fuel Flow (lbm/hr) × Fuel Heating Value (Btu/lbm)

Net unit heat rate:

Fuel Flow (lbm/hr) × Fuel Heating Value (Btu/lbm) ÷ Net Power Output (kW)

Another variation on heat rate calculation specific to the area of interest is turbine cycle heat rate. Turbine cycle heat rate determines the combined performance of the turbine, condenser, feedwater heaters and feed pumps. Knowing the unit heat rate and the turbine cycle heat rate allows the plant to determine the boiler efficiency.

Turbine Cycle Heat Rate:
Turbine Cycle Heat Rate (Btu/kWh) =
Energy Input (Btu) ÷ Energy Output (kWh)

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In an ideal world Performance Engineers would like to see the heat rate at 3,412 Btu/kWh. This would imply that all of the available energy in the fuel source is being converted into usable electricity; hence, the plant is running at 100% efficiency. Although this is not a practical expectation, the reality is that the closer the net unit heat rate is to 3,412 Btu/kWh, the more efficient and cost-effective the operation.

An increase in heat rate results in an increase in fuel consumption; whereas, decreasing heat rate equates to a reduction in the fuel required to produce a given number of kWh of energy. Although heat rate is a key consideration in any purchasing decision, other factors play a role as well: maintenance costs, reliability, safety, emissions, hardware cost, etc. Understanding the impact of instrumentation technology across the spectrum will assist in rationalizing the full return on investment to aid in containing costs and maximizing profitability.

Cost of Heat Rate Deviation

Calculating the annual fuel cost associated with slight deviations from the plant's target heat rate can be enlightening since small changes have a more profound impact than one might expect. If a plant's target heat rate is 12,000 Btu/kWh and the actual value is 12,011 Btu/kWh, what is the increase in annual fuel cost? The following equation and assumptions are used to calculate the impact of a 1 Btu/kWh deviation.

General Guidelines for Heat Rate

- An increase in heat rate from design, increases fuel consumption
- A 1% improvement (reduction in heat rate) = $500K annual savings for a 500MW plant
- A -5° F reduction in final feedwate temperature increases heat rate by 11.2 Btu/kWh resulting in an average increase in annual fuel cost of $59,230.00 (500MW plant)
- The maximum efficiency or rock bottom number for heat rate is noted in CCGT plants with a net unit heat rate starting at 7,000 Btu/kWh
- Heat rates for coal-fired power plants range from 9,000 – 12,000 Btu/kWh (22% of domestic coal-fired plants have a heat rate of at least 12,000 Btu/kWh)

Multiplying $8,503.64 by any heat rate deviation will yield the annual cost or savings for the particular deviation. The increase in annual fuel cost in going from a heat rate of 12,000 Btu/kWh to 12,011 Btu/kWh results in a deviation of 11 ($8,503.64 * 11) or a $93,540.00/year increase in annual fuel cost.

Change in Annual Fuel Cost ($/year) = HRD/BE × FC × CF × UGC × T

Where:

HRD Heat Rate Deviation (net unit or turbine cycle heat rate)
BE Boiler Efficiency = 0.88
FC Fuel Cost/1,000,000 Btu = 2.01[1]
CF Unit Capacity Factor = 0.85
UGC Unit Gross Capacity = 500,000 kW
T 8 760 hrs/year

Annual Fuel Cost:
(1 Btu/kWh ÷ 0.88)(2.01 ÷ 1,000,000)(0.85)(500,000)(8760) = $8,503.64/year for a 1Btu/kWh heat rate deviation.

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[1] The average commodity price for all grades of coal ($14.35 – $71.00) was used to determine the fuel cost per 1,000,000 Btu. Average price per short ton of $48.31 as of September 17, 2010. Assumed 12,000 BTUs per pound. Cost per ton/24 = Cost/MBtu

Feedwater Heater Operation

Since feedwater heaters are a fundamental component in the determination of net unit and turbine cycle heat rate, a basic understanding of how they operate is critical to realizing the impact of this hardware and subsequent level control on plant efficiency. There are normally six to seven stages of feedwater heating.

However, at a capital cost of $1.2 million per feedwater heater, the actual number may vary based on the upfront calculations used to determine the long-term return on investment.

Feedwater heaters take advantage of the heat of condensation (energy available from the change from saturated steam to saturated liquid) to preheat water destined for the boiler. This reduces the amount of fuel required to bring the water up to temperature.

These shell and tube heat exchangers (Figure 1) allow feedwater to pass through the tube side while extraction steam from the turbine is introduced on the shell side. This method is far more efficient at heating water than using hot gas and takes advantage of energy already available rather than relying strictly on a fuel source to bring water up to temperature.

Figure 1 shows a standard high pressure feedwater heater; low pressure heaters are similar in design less the desuperheating zone. The three main zones of the feedwater heater are the desuperheating, the condensing and the drain cooler or sub-cooling. Boiler feedwater is pumped to the feedwater inlet while extraction steam flows into the steam inlet. The desuperheating zone cools the superheated steam to the point that the steam is saturated. The condensing zone extracts the energy from the steam/water mixture to preheat the boiler feedwater passing through the tube side. A drain cooler is incorporated to capture additional energy from the liquid.

The key to efficient operation is to optimize the condensing zone in an effort to transfer as much of the available energy as possible to the boiler feedwater while maintaining sufficient cooling of the tubes to prevent premature damage of the hardware due to thermal overload – all of which are an inherent part of the feedwater heater design.

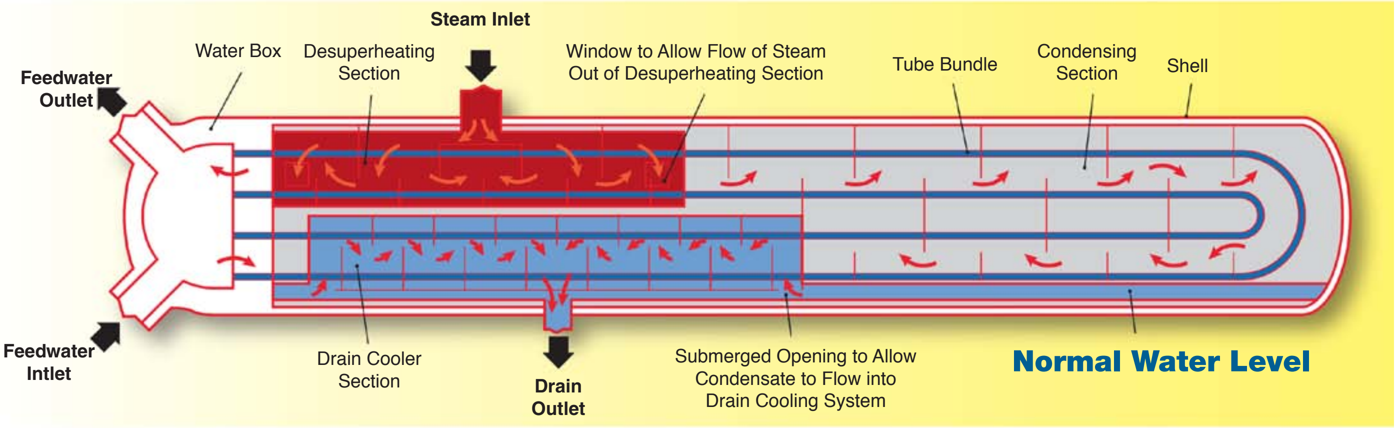


Figure 1

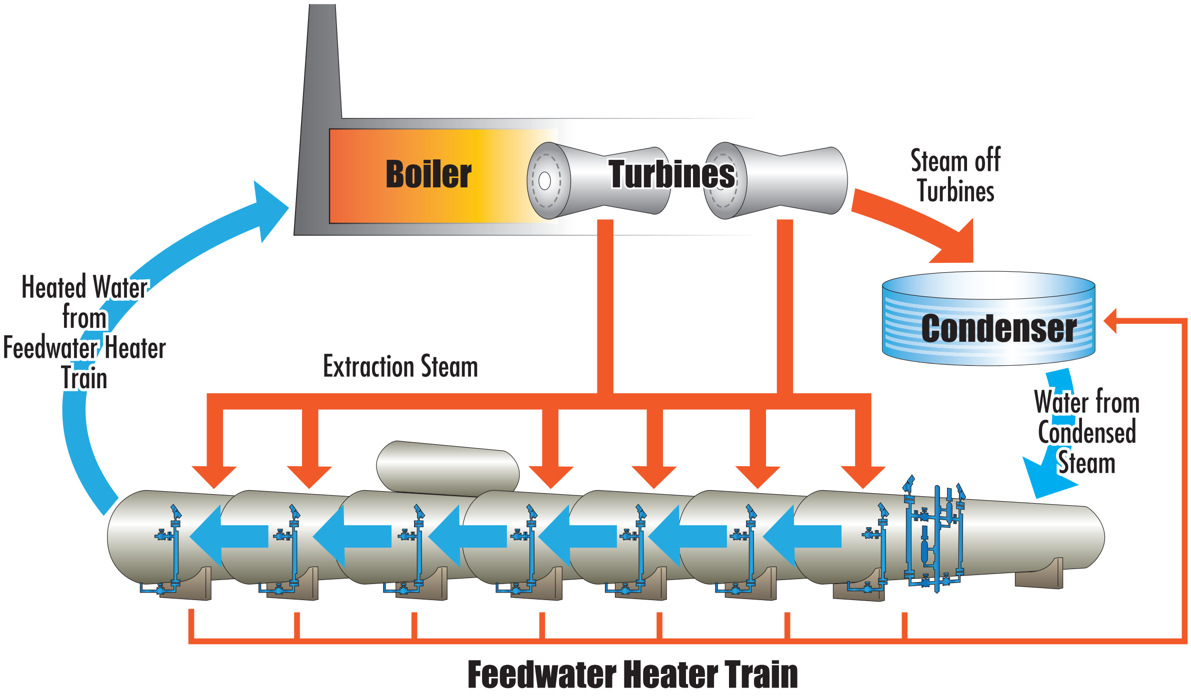


Figure 2

Basic Power Cycle

Although the Rankine Steam-Water cycle for a typical steam plant will vary somewhat depending upon whether it is a reheat or non-reheat unit, the basic flow diagram (Figure 2) delineates how the cascading feedwater heater stages fit into the general process layout. Reference Figure 1 and Figure 3 (on page 5) to revisit feedwater heater inputs/outputs.

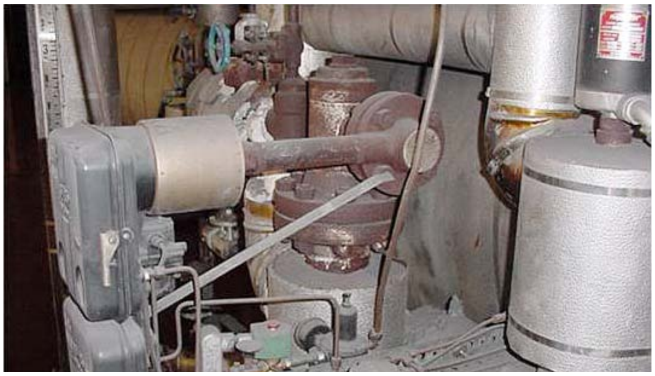
A good starting point for the process flow is at the condenser, where condensed steam from the feedwater heater drains and LP Turbine is routed through each successive stage of feedwater heaters. At the same time extraction steam from the HP, IP and LP turbines is sent to the appropriate feedwater heaters where the transfer of energy discussed in the previous section takes place. Maintaining accurate and reliable level controls throughout the individual stages is critical to achieving the required final feedwater heater temperature prior to water arriving at the economizer. As mentioned in the general guidelines for heat rate, a modest -5° F reduction in final feedwater temperature increases heat rate by 11.2 Btu/kWh contributing an additional $59,230.00 to annual fuel cost (500MW plant).

Feedwater Heater Level Control

Arguably the most important aspect to feedwater heater performance is precise and reliable level control under all operating conditions. Accurate level control ensures the unit is operating in the area of greatest efficiency (straight condensation) to optimize heat transfer while preventing undo wear and tear on the feedwater heater and other system components.

Aging level instrumentation coupled with the deployment of technologies vulnerable to instrument-induced errors limit the ability of operators to manage controllable losses associated with feedwater heater level control, i.e., maintaining and controlling to the ideal or design level with a high degree of confidence. Consequently, accuracies of ± three and four inches off the design are commonplace – a trade-off in efficiency to accommodate the shortfalls of the instrumentation while mitigating risk of damage to the expensive hardware.

Operating a feedwater heater at levels higher or lower than the design has an effect on performance and ultimately the net unit heat rate. The need for additional fuel and over-firing of the boiler to recover the lost energy have immediate financial ramifications. Conversely, if the level fluctuates to the extremes of the envelope, activation of protective measures to bypass a feedwater heater is the minimum response with the outside possibility of a unit trip. Each scenario, in one way or another, negatively impacts the heat rate and profitability of the plant.



Modernizing feedwater heater level controls allows operators to better manage controllable losses while significantly reducing maintenance costs. Torque tube displacers (above) are common in the industry and one of the easiest to retrofit.

If the heater level is higher than the design, the active condensing zone is effectively decreased and tubes in the heater that should be condensing steam are sub-cooling condensate. Exacerbating the problem is the risk of turbine water induction from the feedwater heater. Although fail-safe measures are in place to prevent such occurrence, the impact on efficiency is sufficient to warrant concern.

In addition to exposing the tubes to excessively high temperatures and causing premature wear or worse, a lower than acceptable level introduces excessive amounts of high temperature steam to the drain cooler which causes the condensate to flash to steam. The resulting damage to the drain cooler section increases maintenance cost and unscheduled downtime. Another issue tied to low heater levels is having a mixture of steam and water blown through the heater. The subsequent reduction in heat transfer will reveal itself as an increase in the net unit and turbine cycle heat rates.

The design of the feedwater heater itself (horizontal versus vertical) and the drain cooler section (snorkel inlet versus full length) can challenge some level technologies. Level control on horizontal heaters and those with full length drain cooler sections is easier since more volume is required for a given change in level. Human factors can also intervene when operational decisions are based on questionable instrumentation. These subtleties need to be taken into account during the instrumentation selection process as well.

Monitoring Feedwater Heater Performance

Accurately controlling feedwater heater levels is fundamental to realizing the benefits of incorporating these elements in the process design. As is always the case, assurance of proper performance can only be determined with a feedback reporting system in place.

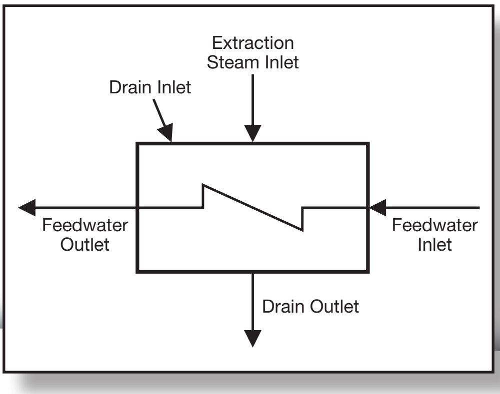
The primary parameters used to monitor individual heater performance are the feedwater temperature rise, the terminal temperature difference (TTD) and the drain cooler approach (DCA). The following definitions and diagram highlight these parameters.

- **Feedwater Temperature Rise** is the difference between the feedwater outlet temperature and the feedwater inlet temperature. A properly performing heater should meet the manufacturer's design specifications, provided the level controls are up to the task.

- **Terminal Temperature Difference (TTD)** provides feedback on the feedwater heater's performance relative to heat transfer and is defined as the saturation temperature of the extraction steam minus the feedwater outlet temperature. An increase in TTD indicates a reduction in heat transfer while a decrease an improvement. Typical ranges for TTD on a high-pressure heater with and without a desuperheating zone are -3° F to -5° F and 0° F, respectively. The TTD for low-pressure heaters is typically around 5° F. Steam tables and an accurate pressure reading are required to complete this calculation.

- **Drain Cooler Approach (DCA)** is a method used to infer feedwater heater levels based on the temperature difference between the drain cooler outlet and the feedwater inlet. An increasing DCA temperature difference indicates the level is decreasing; whereas, a decreasing DCA indicates a rise in level. A typical value for DCA is 10° F.

Figure 3



Instrument Induced Errors and Heat Rate

Although there are a number of physical anomalies that degrade heater performance, this section focuses on issues tied in some way to inadequate level control resulting in a below-design final feedwater temperature. The problems can range from something as simple as inaccurate or fluctuating readings across several instruments which leave the "real" level in question to those that justify taking a feedwater heater out of service. Regardless of the severity, the intention is to show the ripple effect that poor feedwater heater level control has on overall boiler and turbine cycle efficiency (increase in net unit or turbine cycle heat rate). Following are two primary sources of instrument-induced errors.

- **Drift** (mechanical or electronic) associated with aging instrumentation, moving parts or intrinsic to the design: Torque Tube/ Displacers. Calibration between shutdowns are a must to achieve reasonable accuracy and prevent nuisance deviation alarms between multiple level transmitters. Responsiveness to rapid level changes can be slow due to dampening affects fundamental to the principle of operation.

- **Measurement Technology** vulnerable to process conditions, e.g., shifts in specific gravity and/or the dielectric constant of the media related to variations in process pressures and temperatures. Certain technologies cannot provide accurate level from startup to operational temperatures without applying external correction factors or the specified accuracy is only realized at operational temperatures: Differential Pressure, Magnetostrictive, RF Capacitance and Torque Tube/Displacers. Furthermore, the calibrations accomplished on differential pressure, RF capacitance and torque tube/displacer technologies by "floating" the chambers during a shutdown often require adjustment when the process is up to temperature in order to maintain acceptable control and prevent unnecessary deviation alarms.

Lower than expected final feedwater temperature occurs when a feedwater heater is taken out of service due to unreliable level input to the control system or the level is too high or low. If the condition is a result of high feedwater heater level, the operator would note a decrease in feedwater heater temperature rise, a decreasing DCA temperature difference and an increasing TTD. The inverse is true if feedwater heater levels are too low. In either of the scenarios, risk of damage to hardware increases; heat transfer is impaired and feedwater to the economizer is not at the required temperature. The probable responses and impact to a low final feedwater temperature are listed below.

- Over-fire boiler to increase temperature (level too high/low or out of service):
    - Increase in fuel consumption and emissions
    - Increase in gas temperature exiting the furnace – reheat and superheat sprays, premature fatigue of hardware
    - Flows through IP and LP stages of turbine increase 10% (HP heater out of service)
    - Flashing – damage to drain cooler section
    - Thermal effects on tubes

- Emergency drains open to lower level (level too high):
    - Loss in efficiency
    - Potential damage to hardware if water enters extraction tube
    - Potential flashing due to sudden pressure drop
    - Turbine Water Induction Protection (TWIP) trips unit – lost production, startup and unscheduled maintenance costs

Deploying measurement technologies immune to common sources of instrument induced errors provides operators with the reliable process feedback needed to decisively manage controllable losses. Thus, preventing the ripple effect these errors have on plant operations and maintenance.

Case Studies

The case studies cover two key topics relative to feedwater heater performance. The first details the annual fuel cost associated with an off-design final feedwater heater temperature at a 500MW coal-fired plant. Although this particular situation does not fall into an extreme case warranting a heater bypass, it exemplifies how seemingly minor trade-offs in level control. Thus, final feedwater heater temperature in an effort to minimize risk of damage to hardware, can impact a plant's profitability.

The second case study brings to light the day-to-day operational risks and costs that ineffective or aging instrumentation technologies have on the bottom line. In both situations, the return on investment for modernizing the instrumentation on their feedwater heaters fell in the 1.0 to 1.5 year timeframe. Lastly, the case studies do not take into account additional emissions cost, affects on boiler and turbine efficiencies, over-firing conditions, lost production and other factors, mentioned in the previous section.

Case Study #1

Off design final FWH Temperature at a 500MW Coal-fired Plant

Outlet Temperature Target	**+438.4° F**
Actual	**+417.4° F**
Difference	**-21° F**

Based on 21° F Low Temperature

- Heat rate impact was 47 Btu/kWh
- Cost impact was **$243,000** annually

CHECKED PERFORMANCE PARAMETERS	
Temperature Rise Target	**81**
Actual	**64**
DCA Target	**10**
Actual	**3**
TTD Target	**10**
Actual	**19.5**

Instrument-induced errors common to the technology used indicated lower than actual level in the feedwater heater

Case Study #2

Cost justification to replace aging level controls/technology due to excessive bypassing of LP heaters

Feedwater Heaters Replaced in 2002;
Original Instrumentation (1966) Reused
(Pneumatic Level Controls/Sight Glass)

Unreliable Instrumentation Caused Feedwater Heater Level Fluctuations

- Bypassed all LP heaters as part of TWIP
- Placed unit at risk of tripping offline

COST JUSTIFICATION	
Cost of LP Heaters Out of Service for Two Weeks	**$45,190**
Units Trip (TWIP) Caused By Heater Issues (2 Startups)	**$42,712**
Replacement Power Cost for Two Events	**$100,000**
ROI Total Project: 1.5 Years	

Level Optimization

As the political climate continues to unfold, the capacity to manage controllable losses by leveraging state-of-the-art instrumentation and hardware technologies to improve efficiency and profitability can only be realized when all parties, manufacturers included, with a vested interest in performance strive to meet the challenges and opportunities of a changing industry. Gone are the days of throwing more fuel on the fire and the one dimensional view of presenting solutions.

Magnetrol®, a global company, pioneered the mechanical switch in 1932 for boiler applications. Over time, our expertise in this arena gave access to the power industry where today it is a rare case that one cannot find our transmitters or switches monitoring a critical level in nuclear and fossil plants around the world.

This entrepreneurial and innovative spirit continues today. As the need for improved instrumentation and control increased, so did our product offering. It has evolved to include a range of level and flow technologies to satisfy the most complex applications.

A key development was the ECLIPSE® Guided Wave Radar (GWR) transmitter. Magnetrol introduced this technology to the process world and was the first to leverage its unique capabilities in the Power Industry. Unaffected by process variations, the ECLIPSE accurately and reliably monitors feedwater heater, deaerator and hotwell levels without the need for calibration.

In 2001, we started Orion Instruments®, a subsidiary of Magnetrol, after noting stagnation in the advancement of Magnetic Level Indicators (MLI). In this short period of time, Orion Instruments revolutionized the MLI industry with the release of the AURORA® integrated MLI/GWR – an instrument widely accepted in the power industry.

It is an unwavering commitment to quality, safety and continuous improvement that has lead to our past and present success and will be foremost in our mission to support the Power Industry in the future.

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References:
Heat Rate Improvement Guidelines for Existing Fossil Plants, EPRI, Palo Alto, CA; 1986 CS-4554
Heat Rate Improvement Reference Manual, EPRI, Palo Alto, CA; 1998 TR-109546
Heat Rate Awareness, Seminar Notes, General Physics Corp, Amherst, NY; December 2009

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