A Method to Assist in Verifying Heat Rate Accuracy

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1.1 *Purpose of Paper*

Coal fired plants largely depend on a mass and energy balance around the boiler versus using the measured fuel firing rate and heating value for the calculation of heat rate. This is primarily because of inaccurate coal flow measurements and unknown heating values, particularly with blending different coal. The mass and energy balance method depends on boiler boundary conditions and is largely a function of the measured feedwater flow. An error in the measurement of feedwater flow, especially from a fouled nozzle, will contribute to error in the heat rate calculation. A fouled nozzle will show an indicated flow higher than actual resulting in an erroneously high heat rate. A tool for detecting errors in the mass and energy balance inputs has been developed for nuclear power stations. This paper discusses the application of such a tool for coal fired plants.

1.2 *Applicability*

The methodology described in this paper is applicable to power plants desiring an alternative means to estimate feedwater flow.

2 Assumptions

2.1 *Process Parameter Linearity with Respect to Feedwater Flow*

There are also various plant parameters in a fossil power plant that are directly dependent on steam flow through the turbine cycle. These parameters typically vary linearly with feedwater flow for small flow and load changes.

The process assumes a linear relationship for each of the instrument inputs to the calculation. In cases where this relationship is not linear, assuming a linear relation is acceptable since this method is used to detect small changes in feedwater flow. Significant (greater than approximately 5%) changes in feed water flow would be identified independently. Inputs used for this calculation must be related to the feedwater flow or have a correlation with these parameters. The relationship between the plant parameters and flow through the turbine cycle are based on the fluid flow characteristics of the turbine cycle [4, 9, 10, 11].

Typical parameters would include, but not be limited to:

- First stage pressure
- Steam flow
- First extraction pressure
- Cold reheat pressure
- Hot reheat pressure
- Final feedwater temperature
- Condensate flow
- Feed pump suction or discharge flow
- Feed pump amps
- Condensate pump amps

It is recommended that 1-hour average of samples are collected each minute, for a total of 60 samples in 1 hour but this may vary depending on the variability of the particular cycle under evaluation and the ability of the computer system collecting the data. All data must be collected at full load conditions avoiding transients in plant operation.

2.2 *Treatment of Systematic Uncertainties*

This process assumes that systematic uncertainties are expressed as a 95% confidence interval. The systematic uncertainties are those uncertainties that are based on the instrumentation characteristics typically as described in the vendor documentation for the instrument itself and the measuring method. Systematic uncertainties expressed in different ways will need to be re-evaluated.

2.3 *Plant Parameter Uncertainty Adjustments*

A basic assumption of this methodology is that each instrument is an independent indicator of feedwater flow. The instruments at the various locations in the cycle may have other influences in addition to feedwater flow. The further the instrument is away (downstream in the cycle) from the beginning of the cycle (main steam flow) the more it can be influenced by problems in the cycle. Therefore for the purposes of this methodology, the instrument uncertainties are adjusted to reflect the confidence level based on engineering judgment for each instrument. These adjustments are applied to account for potential changes in operating conditions that would cause the relationship between the parameter and main steam flow to change. The adjusted uncertainty must always be no less than the instrument uncertainty to ensure conservatism, and are still treated as a 95% confidence interval.

2.4 *Treatment of Random Uncertainties*

Random uncertainties are assumed to be expressed as the standard deviation of the data under consideration.

The data used for this analysis are assumed to have a large enough sample size to estimate t_{95} (student's *t*-value for 95% confidence interval) at 2. This analysis also assumes that a 95% confidence interval for uncertainty is acceptable.

The recommended method would use the standard deviation of the dataset used for each parameter used in the calculation. If this standard deviation is not readily available, using the standard deviations from a known stable time period would be acceptable. This assumes that the standard deviation does not change significantly over the period of time used to calculate the average value for each parameter. It also assumes that the day to day change in standard deviation is also insignificant with respect to the method used to estimate flow. If a significant change to standard deviation occurs, there will likely be a corresponding problem with the flow estimate or the "Fouling Indicator" as described in Section 4. This would alert the user to investigate the reason for the change, and the shift in standard deviation would then be detected.

2.5 *Baseline Feedwater Flow Rate*

It is assumed that the measured feedwater flow is accurate during the time period that the baseline values are being developed. If this is the case for the initial data set then the feedwater flow would be equal to the indicated value. However, if nozzle fouling has occurred or some other known error in the measured feedwater flow exists then an estimation of the feedwater flow is required to ensure that the baseline values adequately represent the actual feedwater flow conditions. The methodology described in Section 3.3 is used as an aid in establishing the validity of this assumption.

2.6 *Feedwater Flow Estimation*

The methodology (Equation 3-6) described for calculation of the estimated feedwater flow assumes that all of the errors in the measured feedwater flow are the result of an error in the feedwater flow measurement. This assumption should be validated before the feedwater flow estimation is considered for use.

3 Methodology

3.1 *Flow Estimate Calculation*

As discussed in Section 2.1, there are several plant parameters that have strong correlation with main steam flow and subsequently feedwater flow. Individually, each parameter used provides an estimate of flow. For example (under normal conditions) if actual main steam flow changes by 1% then flow through the high pressure turbine will also change by 1%. Thus, a ratio of current first stage pressure to a benchmark first stage pressure multiplied by a benchmark main steam flow results in an estimate of main steam flow. Unfortunately, the uncertainty of these individual parameters is typically higher than desired for this type of analysis. However, when many parameters are used and corrections applied for certain plant conditions, these parameters can be combined in such a manner as to provide an overall estimate of flow. The resulting estimated computation of main steam flow can then be used to calculate the feedwater flow and compare to measured feedwater flow to determine if there is a discrepancy between the two that would indicate problems with nozzle fouling or other instrument problems.

3.1.1 Main Flow Estimate Calculation

These combined parameters can be used as an estimate for the actual main steam flow. This estimate can be expressed as:

$$\overline{\overline{X}} = \sum_{i=1}^{N} W_i X_i \qquad (3\text{-}1)$$

Where

- $\overline{\overline{X}}$ = The estimated main steam flow
- W_i= A weighting factor for each parameter
- X_i = The individual parameter
- N = The number of parameters used to estimate main steam flow

3.1.2 Weighting Factors

The weighting factors are calculated by using the combination of the systematic and random uncertainty for each parameter.

Often the instruments are not in the calibration program or their operational history indicates that the uncertainty is higher than indicated by the vendor documentation. In these cases conservative estimates are used. Additionally if there are various measurements at a similar point in the cycle, adjustments must be made to prevent any one point in the cycle from being too heavily weighted in the overall estimate of main steam flow.

These uncertainties are calculated by the following:

$$U_{95} = t_{95}\left[\left(\frac{B}{2}\right)^2 + S_{\overline{X}}^{\;2}\right]^{1/2} \qquad (3\text{-}2)$$

Where:

- U_{95} = 95% Confidence interval for the uncertainty of the parameter
- t_{95} = Student's *t*-value @ 95% confidence and n-1 degrees of freedom (assumed to be 2 for this calculation)
- B = 95% Confidence interval for systematic uncertainty

$S_{\overline{X}}$ = Standard Deviation of the parameter

Using these uncertainties, the weighting factor can be defined by:

$$W_i = \frac{\left(\frac{1}{U_i}\right)^2}{\sum_{i=1}^{N}\left(\frac{1}{U_i}\right)^2} \quad (3\text{-}3)$$

Where

U_i = the individual uncertainty calculated for each instrument using Equation 3-2.

For every parameter except feedwater temperature, the individual parameter values are calculated by multiplying a reference main steam flow value by the ratio of the current parameter value to a reference value for that parameter. This can be expressed as follows:

$$Flow_{predicted\ i} = \frac{X_i}{X_{i_{ref}}} Flow_{ref} \quad (3\text{-}4)$$

Where

$Flow_{predicted_i}$ = Main steam flow predicted by parameter *i*
X_i = Individual parameter *i*
X_{ref} = Reference value of parameter *i* at the reference main steam flow value
$Flow_{ref}$ = Reference value of main steam flow

For feedwater temperature, the sensitivity of flow to feedwater temperature must first be calculated. Using a computer model of the turbine cycle in conjunction with a linear regression model or other suitable method, the ratio of change in flow to change in feedwater temperature is calculated. This ratio is multiplied by the difference of the current temperature to a reference value and then added to the reference flow value. This can be expressed as follows:

$$Flow_{predicted\ FWTemp} = (T_{curr} - T_{ref})S_{FWTemp} + Flow_{ref} \quad (3\text{-}5)$$

Where

$Flow_{predictedFWTemp}$ = Main steam flow predicted by feedwater temperature
T_{curr} = Current value of feedwater temperature
T_{ref} = Reference value of feedwater temperature at the reference main steam flow value
$Flow_{ref}$ = Reference value of main steam flow
S_{FWTemp}= Sensitivity of main steam flow to the feedwater temperature

3.1.2.1 Calculation

The equation used to estimate the feedwater flow using the estimated main steam flow and the measured plant values for a fossil plant is as follows:

The typical feedwater flow equation is as follows. However, this may be different for each plant.

$$FeedwaterFlow = MainSteamFlow + BlowdownFlow - SuperheatSprayFlow \qquad (3\text{-}6)$$

3.2 *Identifying Independent Parameters*

As discussed in Section 2.3, the independent parameters used in this evaluation are integral to the overall quality of the result. The following are used to determine the suitability of a particular parameter:

- Evaluation of any existing uncertainty calculations for the instrumentation
- Verification of instrument calibrations
  - Frequency of calibrations
  - History of calibrations (drift, failures etc.)
- Review of historical data
  - Observation of unexplained shifts and determination, if possible, the cause and frequency of these shifts.
  - Observation of changes after down powers and how long it takes the instrument to stabilize or “settle out.” This is of concern particularly for low pressure measurements where there are water leg issues.
  - Comparisons with plant computer model and turbine tests as described in Section 3.3.
  - Verification that the parameter changes correspond to other plant parameters.

3.3 *Determining Reference Value of Parameters*

A baseline evaluation of the plant is performed to ascertain the values of the plant parameters to be used in the estimated feedwater flow calculation. The ultimate goal is to establish a set of data that can be used and the 100% load values for the calculation. This evaluation consists of the following steps:

3.3.1 Plant Systems Evaluation

An evaluation of the turbine cycle systems and documentation is performed to identify any discrepancies between the turbine vendor thermal kit and the actual plant installed conditions. This analysis identifies any obvious problems with the plant equipment that would go into the evaluation. This evaluation, in conjunction with other evaluations, determines the present condition of the plant irrespective of the influences of feedwater flow.

3.3.2 Historical Plant Data Evaluation

Plant data are evaluated back to the last significant plant modification (usually a turbine retrofit) to identify any plant anomalies that should be accounted for in the calculations. Plant data in the following systems are included in this evaluation:

- Main Feed
- Main Steam
- Condensate
- Extraction Steam
- Blowdown Flow
- Main Turbine

3.3.3 Plant Thermal Kit Evaluation

The thermal kit is a design document typically provided by the turbine vendor and it describes the design thermodynamic parameters of the plant for various loads. The thermal kit also includes various corrections and other information to determine plant parameters for variations from design conditions. Actual conditions are compared to the plant thermal kit to determine the impact of design differences and component degradation. Common differences are the arrangement of feedwater heaters, type of cooling for gland exhaust condensers or vent and drain configurations. Often plants are operated in a manner different than what is assumed on the thermal kit. For example, the original design may have been for partial arc admission but the plant is operated in full arc due to vein passing concerns. Vendor thermal kits may have actual errors that can be detected by plotting the turbine expansion on a Mollier diagram and verifying a reasonable expansion line. This is accomplished by reading the enthalpies and pressures off of the heat balance and plotting them on the diagram. In addition to the plant thermal kit, the following are taken into consideration for this evaluation:

- Plant Piping and Instrumentation Drawings
- Feedwater Heater Design Specifications
- Condenser Design Specifications
- Boiler Design Specifications
- Pump Specifications

3.3.4 Plant Test Data Evaluation

Any turbine performance tests, especially if performed in accordance with ASME PTC-6 guidelines, are evaluated to determine differences between actual plant data and the values as determined by the test.

The calculated estimate of the flow is dependent on the initial estimate of flow for the initial reference set. Ideally the collection of the initial data set would be directly following cleaning and calibration of the flow nozzles.

3.3.5 Plant Computer Model Evaluation

A computer model of the turbine cycle is developed using the vendor thermal kit and other plant models. This model is used to provide assurance that the evaluation would be based on the best design information available and account for plant boundary conditions. The following process is used to develop this model:

1. Build a model of the plant based on the vendor design conditions. This model will exactly match the plant thermal kit
2. Based on the review of other design documentation, change the model for the effects of as-built plant performance versus the turbine vendor expected performance.
3. Tune the model to the best test data available
4. Modify the model for any plant deficiencies or operational differences from the design conditions or the test conditions to which the model was tuned.
5. Once all the corrections are completed the model is used to determine the plant parameters at a particular load. These can be compared to the plant data to evaluate how well they match design conditions.

3.4 *Uncertainty of Feedwater Flow Estimate Calculation*

The estimate method uses as many plant parameters as possible which are independent and thus can minimize the uncertainty of the overall result. The overall uncertainty of the estimated feedwater flow can be much lower than the uncertainty of any of the individual measured parameters.

The systematic and random uncertainties are also weighted using the same method that was used for feedwater flow. Using the weighting factors calculated for the feedwater flow parameters, the systematic and random uncertainties combine as follows:

$$\overline{\overline{B}} = \left(\sum_{i=1}^{N} W_i^2 B_i^2 \right)^{1/2} \quad (3\text{-}7)$$

And

$$\overline{\overline{S}}_{\overline{X}} = \left(\sum_{i=1}^{N} W_i^2 S_{\overline{X}\,i}^{\;2} \right)^{1/2} \quad (3\text{-}8)$$

Where $\overline{\overline{B}}$ and $\overline{\overline{S}}_{\overline{X}}$ are the systematic and random uncertainties, respectively.

The total uncertainty of the estimated flow is expressed as follows:

$$\overline{\overline{U}}_{95} = t_{95} \left[\left(\frac{\overline{\overline{B}}}{2} \right)^2 + \overline{\overline{S}}_{\overline{X}}^{\;2} \right]^{1/2} \quad (3\text{-}9)$$

Where:

$\overline{\overline{U}}_{95}$ = 95% Confidence interval for the uncertainty of the estimated flow
t_{95} = Student's *t*-value @ 95% confidence and n-1 degrees of freedom (assumed to be 2 for this calculation)
$\overline{\overline{B}}$ = Combined 95% confidence interval for systematic uncertainty based on Equation 3-7
$\overline{\overline{S}}_{\overline{X}}$ = Combined random uncertainty based on Equation 3-8

3.5 *Fouling Indicator*

The Fouling Indicator is calculated by taking the difference between the predicted and measured flow and dividing this by the measured flow (Equation 3-10). A positive value for Fouling Indicator indicates that the flow measured is potentially fouled. The resulting value can then be used as a correction to the plant heat rate if the heat rate is calculated by a first principles mass and energy balance approach.

$$FI = \frac{Flow_{estimated} - Flow_{measured}}{Flow_{estimated}} \quad (3\text{-}10)$$

Where:

$Flow_{estimated}$ = Estimated Flow value
$Flow_{measured}$ = Plant Measured Flow value
FI = *Nozzle Fouling Indicator*

4 Results

Once the feedwater flow is estimated using the alternate plant parameters, and the uncertainty of this estimate is established, the estimated values can be compared to the plant measured values .This difference can be related to the reference feedwater flow to determine the “Fouling Indicator,” which is an indication of the current measured feedwater flow to expected results (Section 3.5).

5 References

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