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DETERMINATION OF FUEL INPUT FOR A COAL FIRED PLANT PERFORMANCE TEST

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ABSTRACT

In applying ASME PTC 46 “Overall Plant Performance” to a coal-fired steam plant, it is mandated that the heat input to the plant is determined by the product of heat input to the steam and the inverse of the steam generator fuel efficiency. Steam generator fuel efficiency is to be determined, per PTC 46, by the energy balance method as detailed in ASME PTC 4 “Fired Steam Generators”.

ASME PTC 4 (1998) superseded an earlier Code, ASME PTC 4.1, which is no longer an ANSI standard or an ASME Code (as this paper was being written, PTC 4- 2008 has been published as a revision of PTC 4-1998). PTC 4.1 made use of a simplified “short form” to determine efficiency by what was known as the heat loss method, used by the industry for many years due to its ease of use. The energy balance method is fundamentally different from the heat loss method even in terms of the definition of efficiency and heat input. This paper explores the major differences between the two PTC’s (the defunct PTC 4.1 and PTC 4). Without knowing these differences, a direct comparison of PTC 4 and PTC 4.1 results is meaningless and could lead to false conclusions.

INTRODUCTION

The ASME performance test codes provide guidelines for test procedures that yield results of the highest level of accuracy based on current engineering knowledge, taking into account test costs [1]. Minimizing test uncertainty within reasonable economic limits is taken very seriously by the industry when PTC’s are referenced in contracts as the means to determine compliance with contract guarantees. Any departure from Code requirements could introduce additional uncertainty beyond what is considered acceptable to meet the objectives of the Code users. In applying PTC 46 to a coal-fired steam plant overall performance test, it is required by the Code that the heat input to the plant is determined by the product of heat input to the steam and the inverse of the steam generator fuel efficiency [2]. Steam generator fuel efficiency is to be determined, per PTC 46, by the energy balance method as detailed in PTC 4-1998 Code for fired steam generators [4].

PTC 4 superseded an earlier Code, PTC 4.1-1964 (R1991) [3], which made use of a simplified short form to determine efficiency by what was known as the heat loss method, used by the industry for many years due to its ease of use. The PTC 4 Code was totally rewritten to reflect advances in steam generator technologies, e.g., increased size, complexity and emission control of modern steam generating units, and in performance testing technology such as the consideration of test uncertainty analysis as a tool for designing and measuring the quality of a performance test. The use of an abbreviated test procedure commonly known as “The Short Form” from PTC 4.1 is discouraged, as PTC 4 adopted a new philosophy on the best test being one which requires the testing stakeholders to agree on the performance test work scope that best meet test objectives. The scope of PTC 4 was expanded to a wide configuration of steam generators, from small industrial and commercial units to fluidized bed boilers, and large utility units.

FUNDAMENTAL EQUATIONS FOR STEAM PLANT PERFORMANCE TEST

The fundamental equations for an overall plant performance test are expressed as the following equations [1]. The fundamental equations are generalized and applicable to any of the types of power plants. [2].

Corrected Net Power is expressed as:

$$P_{corr} = \left(P_{meas} + \sum_{i=1}^{7} \Delta_i\right) \prod_{j=1}^{6} \alpha_j$$

Corrected Heat Input is expressed as:

$$Q_{corr} = \left(Q_{meas} + \sum_{i=1}^{7} \omega_i\right) \prod_{j=1}^{6} \beta_j$$

Corrected Heat Rate is expressed as:

$$HR_{corr} = \frac{Q_{corr}}{P_{corr}}$$

Where:

P_{corr} = Corrected net plant output
P_{meas} = Measured net plant output
Q_{corr} = Corrected steam generator output
Q_{meas} = Measured steam generator output
Δ_i, ω_i = Additive correction factors, i=1, …,7
α_j, β_j = Multiplicative correction factors, j=1, …,6

The fundamental performance equations, which are generalized, can then be simplified to be specific to the particular plant type and test program objectives. For a steam turbine plant, if the test goal is tied to a specified disposition, it is usually based on either a valve point operating mode, or on the throttle flow rate [8][9]. The steam generator calculation is first done separately from the overall plant calculations in order to calculate PTC-46 measured thermal input. The multiplicative correction factors for inlet air conditions and fuel analysis and conditions are embedded in the steam generator performance analysis.

For a coal fired steam plant without thermal efflux (e.g., process steam), the corrected net output is determined per Equation 5.3.3 of ASME PTC 46:

$$P_{corr} = (P_{meas} + \Delta_2 + \Delta_4 + \Delta_5 + \Delta_6 + \Delta_7) * \alpha_6$$

Where:

P_{corr} = Corrected net plant output
P_{meas} = Measured net plant output
Δ_2 = Correction for power factor
Δ_4 = Correction for secondary heat inputs
Δ_5 = Correction for heat sink
Δ_6 = Correction for auxiliary load
Δ_7 = Correction for specified disposition
α_6 = Correction for grid frequency

Corrected net heat rate is calculated from Equation 5.3.4 of ASME PTC 46:

$$HR_{corr} = \frac{Q_{corr}}{P_{corr}} = \frac{(Q_{meas} + \omega_7)}{P_{corr} * \eta_{fuel\_corrected}}$$

Where:

Q_{corr} = Corrected steam generator output
Q_{meas} = Measured steam generator output
ω_7 = Correction for specified disposition
$\eta_{fuel\_corrected}$ = Corrected steam generator fuel efficiency
P_{corr} = Corrected net plant output

Two methods for determining the efficiency of a steam generator per PTC 4 are the input/output method and the energy balance method [3][4]. PTC 46 calls for the energy balance method for solid fuels. The choice between the methods should be based upon the available instrumentation and acceptable test uncertainty. The energy balance method in almost all cases yields a much lower overall test uncertainty because the quantities used to determine efficiency, i.e., losses, are a much smaller portion of the total energy than is output, which is used to determine efficiency with direct measurement method. Typical code test uncertainties of 0.4~0.8% can be achieved using the energy balance method for coal fired steam generator efficiencies, while typical 3.0~6.0% test uncertainties can be achieved using the input-output method [4]. In addition to low test uncertainties, the energy balance method allows for corrections of test results to standard or guarantee conditions.

STEAM GENERATOR OUTPUT

The steam generator output is defined per PTC 4 as the energy absorbed by the working fluid that is not recovered within the steam generator envelope. The determination of steam generator output requires measurements of certain steam and water flow. The preferred method is to use testing techniques and measurement elements as described in the ASME PTC 6-2004 steam turbine test Code [6].

Output in main steam is equal to the difference between the main steam and spray mass flow rates multiplied by the difference between the main steam and feedwater enthalpies and added to the spray mass flow rate multiplied by the difference between the main steam and spray water enthalpies.

For a reheat steam cycle, the reheat steam output is the reheat mass flow rate times the difference between the reheat enthalpies entering and leaving and added to the reheat spray mass flow rate times the difference between the reheat steam and reheat spray water enthalpies. To determine the reheat steam flow, the steam extractions to high pressure feedwater heaters are either calculated by the heat balance method across the heaters, or estimated from the corresponding Heat Balance Diagram. The gland steam flow of the high pressure turbine will be estimated according to PTC 6 Chapter 3.5.7. [6].

STEAM GENERATOR EFFICIENCY

For many years, PTC 4.1 heat loss method and the abbreviated efficiency test short form had been the most practical and acceptable method in the industry for testing the efficiency of industrial boilers and small utility steam generators. PTC 4.1 was written in view of the continuous increasing size and complexity of steam generating units and development of test methods / technologies in the 1960's.

In 1981, a committee was formed under the direction of the Board of Performance Test Codes to review PTC 4.1. It was soon recognized by the Committee that the Code should be totally rewritten to reflect several changes in steam generator technology and in performance testing technology [4]. PTC 4 adopted a new philosophy on the best test being that which requires the parties to the test to deliberate on the scope of the performance test required to meet the objective(s) of the test. Measurement uncertainty analysis was selected as the tool whereby the parties could design a test to meet the test objectives.

As this paper was being written, PTC 4-1998 has been superseded by PTC 4-2008. All the Code Sections were reviewed to correct minor errors and omissions, to update references and to revise text for better clarity, such as the procedure for the entering air temperature corrections [5]. It was brought into compliance with the definitions and terminology used in the revised PTC 19.1 Test Uncertainty. The major issue in this regard was to change all references to "bias" and "precision" to 'systematic" and "random" respectively. Also, "precision index" was changed to "standard deviation". In addition to these changes,

Since PTC 4 superseded PTC 4.1 over a decade ago, PTC 4.1 is no longer an ANSI standard or an ASME Code. In author's experience, PTC 4.1 is still referenced in some test procedures. Following section will discuss the major differences between the two PTC's (the defunct PTC 4.1 and PTC 4) and explains why utilization of the over-simplified or modified PTC 4.1 for overall plant performance tests with large scale super-critical coal-fired utility steam generators may result in a high uncertainty level unacceptable form contractual requirements or lead to false conclusions.

PTC 4-1998 VERSUS PTC 4.1-1964 (REAFFIRMED 1991)

(1) Code Object

The purpose of PTC 4.1 was to establish procedures for conducting performance tests to determine efficiency, capacity, and other related operating characteristics such as steam temperature, and control range, exit gas temperature, draft loss, steam-water- and air – pressure drops, solids in steam and air leakage [3]. It is noted that the fuel input or fuel flow rate was not part of PTC 4.1.

PTC 4 has expanded on the performance parameters covered by the PTC 4.1Code. PTC 4 can be used to determine almost all major performance parameters including efficiency, output, capacity, steam temperature/control range, exit flue gas and entering air temperature, excess air, water/steam pressure drop, air/flue gas pressure drop, air infiltration, sulfur capture, calcium to sulfur molar ratio, fuel, air, and flue gas flow rates [4]. The fuel heat input or fuel flow rate can be determined by the product of the steam generator output and the fuel efficiency.

(2) Steam Generator Output

PTC 4.1 defined the output of steam generating units as the heat absorbed by the working fluid or fluids. In PTC 4, the output is defined as energy absorbed by the working fluid that is not recovered within the steam generator envelope. For example, energy supplied by the steam generator to the air pre-heater coils to heat the entering combustion air is not considered to be output because the energy is recovered within the steam generator envelope.

(3) Gross vs. Fuel Efficiency

Efficiency can be defined in many different ways depending on the purpose and objective. Both gross efficiency and fuel efficiency can be used to assess how effective a steam generator can be in terms of steam generation using chemical energy from fuel. The efficiency of steam generating units determined within the scope of the PTC 4.1 Code was the gross efficiency, defined as the ratio of heat absorbed by the working fluids to the total heat input. The gross efficiency in PTC 4.1 was expressed by the following equation:

$$\begin{aligned}\eta_{gross} &= 100 \times \left(\frac{Output}{Total\ \ Input} \right) \\ &= 100 \times \left(\frac{Output}{Fuel\ \ Input + Credits} \right) \\ &= 100 \times \left(1 - \frac{Losses}{Fuel\ \ Input + Credits} \right),\ \%\end{aligned}$$

The efficiency of fired steam generators determined within the scope of the PTC 4 is fuel efficiency – the ratio of output energy to fuel input energy as described in the following equation:

$$\begin{aligned}\eta_{fuel} &= 100 \times \left(\frac{Output}{Fuel\ \ Input} \right) \\ &= 100 \times \left(1 - \frac{Losses - Credits}{Fuel\ Input} \right),\ \%\end{aligned}$$

Fuel efficiency includes all energy absorbed by the working fluid as output but counts only chemical energy of the fuel as input. Fuel efficiency on a higher heating value basis is the preferred definition of efficiency supported by PTC 4. With the fuel efficiency, the fuel flow may be calculated directly from the product of the output and the fuel efficiency as specified by PTC 46.

Gross efficiency used by PTC 4.1 included all energy absorbed by the working fluid as output and counted all energy inputs entering the steam generator envelope as input. Thus, the gross efficiency could not be used directly to yield the fuel input or fuel flow rate. To calculate the fuel flow, the PTC 4.1 efficiency formula would have to be revised by neglecting the heat credits terms on the denominator. This simplification may increase the uncertainty in the fuel flow calculation.

(4) Losses and credits

PTC 4.1 had an abbreviated efficiency test form (ATF) that considered only five major losses, and only the chemical heat in the fuel as input. All other heat loss items mentioned in PTC 4.1 were assessed as a total estimated value of unmeasured items. A full PTC 4.1 Code test considered more minor losses and heat credits ignored by the abbreviated test form. PTC 4 further expands the scope of heat losses and credits to reflect changes in the latest steam generator technologies such as utilization of sorbent and SCR for emission control. Table 1 lists all loss and credit terms supported by the PTC 4.1 abbreviated test form, PTC 4.1 full test, and PTC 4.

Table 1 Comparison of Losses/Credits

Losses/Credits			PTC 4.1 ATF	PTC 4.1	PTC 4
Losses	1	Energy in dry gas	√	√	√
	2	Water in fuel	√	√	√
	3	Water from burning hydrogen	√	√	√
	4	Unburned carbon	√	√	√
	5	Surface radiation/convection	√	√	√
	6	Moisture in air	×	√	√
	7	Sensible heat of residue	×	√	√
	8	Radiation to wet ash pit	×	√	√
	9	Pulverizer rejects	×	√	√
	10	Unburned hydrocarbons flue gas	×	√	√
	11	Carbon monoxide in flue gas	×	√	√
	12	Hot air quality control equipment	×	×	√
	13	Air infiltration	×	×	√
	14	Losses for sorbent reactions	×	×	√
Credits	1	Entering dry air	×	√	√
	2	Moisture in entering air	×	√	√
	3	Sensible heat in fuel	×	√	√
	4	Auxiliary equipment power	×	√	√
	5	NO_x formation	×	×	√
	6	Credits for sorbent reactions	×	×	√

It should be noted that the calculation procedures of PTC 4 for some losses are different than those from PTC 4.1. Some of these differences will be discussed in the following sections.

There may be also differences due to the use of enthalpy functions in PTC 4 versus specific heat curves in PTC 4.1. In PTC 4, un-measured losses must be estimated individually if not measured, with appropriate associated uncertainty values.

(5) Test Uncertainty

In preparing for an ASME Code test, a pre-test uncertainty analysis has to be conducted to ensure that adequate instrumentation is selected so that the test uncertainty likely will be within acceptable limits. The uncertainty level for each individual measurement should be chosen in reasonable relationship with the influence of the reading on the test results. A post-test uncertainty analysis will be performed to enable calculation of the actual uncertainty interval of the results.

A test uncertainty analysis was not a part of PTC 4.1. It is conceivable that instrumentation and data sampling procedures could be selected to yield a test result of equal uncertainty with regard to instrumentation as if PTC 4 was used. The calculation procedures of PTC 4, however, are intended to produce more accurate loss results and reduce the uncertainty. For example, the surface radiation and losses are measured instead of estimated, and the un-measured minor losses must be estimated individually if not measured, with appropriate uncertainty values. Therefore, the level of uncertainty associated with the estimate of unmeasured losses commonly included in the PTC 4.1 Abbreviated Test Form would normally be greater than that associated with the individually estimated losses as part of PTC 4 (or a full PTC 4.1 Code test).

One of the hallmarks of PTC 4 that set it apart from other Performance Test Codes is Section 3-2.1 [4] which, because of the complexity and expense of accounting for all losses, allows the Code users to elect their own level of testing, depending on the uncertainty requirements of the test. As such, the users of PTC 4 may eliminate some of the smaller losses/credits (or relax some of the instrumentation accuracy or calculation requirements) if the uncertainty requirements of the test are met. In any commercial test, those requirements should be spelled out in the Contract, or other prior agreement must be reached prior to testing. The PTC 4.1 full scale test procedures are thus allowable, but the impacts on uncertainty must be clearly understood. Further, PTC 4.1 must not be referenced because it is no longer a Code. PTC 4 should always be referenced, either noting any simplifications that are acceptable, or noting the limiting uncertainty of the results.

(6) Reference Temperature

The reference temperature is the base temperature to which air, fuel and sorbent entering the steam generator envelop are compared for calculation of sensible heat losses and credits. The reference temperature for PTC 4 is 77^{o}F (25^{o}C) and the calculation of both losses and credits are required to determine the efficiency. The energy credit will be negative for any stream entering the steam generator envelope at a temperature lower than the reference temperature.

PTC 4.1 allows the use of any arbitrary reference temperature. The entering air temperature is usually used as the reference temperature. An advantage of using the entering air temperature as the reference temperature is that it eliminates the need to calculate the credits for entering air and moisture in air. Credits for other streams would then have to be calculated, or neglected in the case of the PTC 4.1 Abbreviated Test Form.

It should be noted that a comparison of steam generator efficiency values based on different reference temperatures is meaningless. Only with a fixed reference temperature, all results are on the same basis and are directly comparable.

(7) Heat Loss due to Surface Radiation and Convection

This is the heat loss from surfaces including the boiler casing, flues and ducts, piping and other surfaces above ambient temperature. It is a function of the average velocity and the difference between the average surface temperature and average ambient temperature.

There is a significant change in the calculation procedure for heat loss from surface radiation and convection from PTC 4.1 to PTC 4. In PTC 4, the heat loss is based on the actual flat projected area of the unit and measured or estimated average temperature difference and surface velocity / heat transfer coefficients. In PTC 4.1, the American Boiler Manufacturers Association (ABMA) standard radiation loss chart is used for an approximation of the heat loss.

The ABMA curve expresses the radiation loss on a percent of gross heat input basis as a function of steam generator output. The ABMA curve is the basis for the surface radiation and convection loss prior to the release of PTC 4 and is approximately the same as PTC 4 for oil- and gas-fired units. For coal-fired steam generator units, due to the requirement for a larger furnace and convection surface area (to lower gas velocities), the PTC 4 radiation loss calculation method is deemed to be more accurate.

(8) Flue Gas Measurement for Combustion Calculations

One of the most critical parameters for steam generator efficiency calculation is percent excess air. Excess air is needed to ensure complete combustion. Too little air can be a source of excessive unburned combustibles and too much excess air increases dry air losses. For efficiency calculations, excess air must be determined at the steam generator exit as well as at the air heater gas inlet.

Excess air, air heater leakage and corrected flue gas exit temperature excluding air leakage can all be determined by measuring the flue gas constituents. It may be calculated stoichiometrically based on O_2 or CO_2 and analytically based on CO_2 and carbon burned in the fuel. Measurement of O_2 is the most common and preferred continuous analysis method. In PTC 4, measured flue gas O_2 content is the basis for the combustion calculations as opposed to measured O_2 and CO_2 in PTC 4.1.

The current industry standard for boiler operation is continuous monitoring of O_2 in the flue gas with in situ analyzer that measure oxygen on a wet basis. The PTC 4 calculation procedure allows both dry and wet O_2 measurement.

(9) Enthalpy Function vs. Specific Heat

The specific energy of many different flow streams such as steam, water, air, flue gas, sorbent, coal, and residue is required to evaluate energy losses and credits for efficiency calculations. In PTC 4, specific energy of a flow stream is evaluated by the enthalpy function of the flowing material as related to temperature and pressure. In PTC 4.1, changes of specific energy of streams were evaluated using instantaneous specific heat.

Accurate determination of enthalpy at all values of temperature and pressure requires the use of tables, charts, or computer software. Calculation of steam generator efficiency per PTC 4 usually requires use of computer and computer programs, while use of the specific heat curves supported by PTC 4.1 were more convenient for hand calculations.

CORRECTING STEAM GENERATOR EFFICIENCY

It is usually not possible to test a unit with the standard or guarantee fuel and at the exact standard or guarantee operating conditions. By correcting the test results to standard or contract conditions, it is possible to make a more meaningful comparison and evaluation of efficiency and performance.

There are two different methods for steam generator efficiency corrections; Substitution Method and Correction Curve Method [10]. The current PTC 4 Code supports only the Substitution Method. In PTC 4, however, corrections to the base reference conditions are more comprehensive than those of PTC 4.1 were.

For an overall steam plant performance test, correction of steam generator efficiency to the plant base reference condition is to be done per PTC 4 method, but only considering the plant boundary conditions. Corrections for PTC 4 correction parameters inside the plant test boundary such as feedwater temperature are not taken for the overall plant performance test.

The Substitution Method for efficiency corrections consists of repeating efficiency calculations using the standard or guarantee air inlet temperature, corrected air heater gas outlet temperature for deviations between the test and guaranteed conditions. Adjustments for the guarantee atmospheric conditions consist of substituting the guaranteed inlet dry and wet bulb temperatures for the measured inlet dry and wet bulb temperature. Fuel adjustments consist of substituting the guarantee fuel constituents for the as-fired fuel constituents in the required equations. The amount of excess air has a significant impact on the fuel efficiency calculation and should be maintained as close as possible to the specified value during the test runs, with no corrections made.

The corrected entering air temperature is the test entering air temperature plus the difference between the design air temperature entering the fan(s) and the test air temperature entering the fan(s) as defined in the following:

$$TAEnCr = TA_8 + (TA_{6d} - TA_6),\ ^oC$$

Where;

TAEnCr = Corrected entering air temperature, ^oC
TA_8 = Test entering air temperature, ^oC
TA_{6d} = Design air temperature entering the fan(s), ^oC
TA_6 = Test air temperature entering the fan(s), ^oC

The corrected flue gas outlet temperature assumes constant air heater gas-side efficiency and is given in the following formula per ASME PTC 4:

$$TFgLvCrd = \frac{TAEnd\,(TFgEn - TFgLvCr) + TFgEn(TFgLvCr - TAEn)}{TFgEn - TAEn},\ ^oC$$

Where;

TFgLvCrd = Exit gas temperature corrected to design conditions, ^oC
TAEnd = Design entering air temperature, ^oC
TFgEn = Gas temperature entering air heater, ^oC
TFgLvCr = Exit gas temperature excluding leakage, ^oC
TAEn = Air temperature entering air heater, ^oC

For tri-sector air heaters, the air flow is the sum of the primary and secondary air leaving the air heater. The entering air temperature is the mass weighted average air temperatures entering the primary and secondary air heaters, weighted on the basis of the airflow mass flow rates leaving the primary and secondary air heaters.

CONCLUSION

This paper discussed the calculation procedure for a coal fired steam plant overall performance test and use of fired steam generator test Codes to determine the fuel heat input to the plant. There are significant differences between ASME PTC 4-1998 (revised 2008) and the superseded PTC 4.1-1964 (Reaffirmed 1991) in code philosophy and objectives, calculation procedures, efficiency and output definitions, reference temperature, uncertainty requirements, flue gas measurements for combustion calculations, radiation loss estimation, credits/losses for emission control, and efficiency corrections. Without knowing the differences, a comparison of PTC 4 and PTC 4.1 results are meaningless and would lead to false conclusions.

In conclusion, PTC 4 is a more comprehensive Code than PTC 4.1 was and is based upon modern test measurement, data reduction, calculation and uncertainty analysis technology. Simplification should be done with appropriate caution, by utilizing a full pre-test uncertainty analysis to ensure that test requirements will be met.

PERMISSION FOR USE

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