WHAT IS INDIRECT MEASUREMENT PERFORMANCE TESTING OF COAL PLANTS PER PTC 4?

By Nestor Ortega

The current trend in the power generation industry, along with every other type of industry and human activity, is the reduction of generation of harmful emissions such as nitrogen oxides NO_x, carbon monoxide CO, carbon dioxide CO_2, lead Pb, ozone O_3, sulphur dioxide SO_2 and particulate matter (PM). In 2018, the electricity sector generated approximately 27% of the total greenhouse gas emissions in the U.S. From the total of the CO_2 generated by the electricity sector this year, coal fired power plants accounted for the 65.8% of this due the carbon intensive fuel used. Surprisingly, coal plants produced only 28.4% of the total electricity exported to the grid. (United States Environmental Protection Agency (EPA), 2020)

To comply with the increasingly strict environmental policies, coal fired power plants must ensure that the power plants are operating at their optimum point and their emission levels are below the limits set by the environmental protection entities. This can be achieved in various ways, either through implementation of new technologies for pollutants capture, the use of more environmentally friendly fuels or by the improvement or conservation of the power plant cycle efficiency. To keep the plant operating at the optimum point, thermal performance tests must be carried out periodically, to quantify the deviation of the operation of the plant from this optimum point and to take the proper actions in case of the existence of large deviations. Besides the crucial aspect of keeping the emissions controlled, performance tests also help alleviate plant costs and increase savings by providing early detection of equipment malfunction and degradation, which in the long run can have a huge impact on the efficiency of the plant and consequently on the fuel consumption and operation costs.

The execution of performance tests is no easy task, it requires the installation of a vast amount of high precision instruments, the coordination and synergy of plant operators, site engineers and test coordinators. Additionally, it requires careful planning, creation of detailed test procedures, and revision of hundreds of plant documents and station instruments datasheets.

Although the preparations for a performance test are similar in nature, these are never the same as the scope of the tests greatly depends on the objectives of the test. Furthermore, the design of the test will vary from plant to plant, as not all plants are equal, and even plants with the same initial design will have slightly different variations. Moreover, as the plant location varies, the design base reference conditions will also vary and day-to-day conditions will hardly ever match the design base reference conditions, making it even harder to carry out a representative comparison between the actual operating conditions of the plant and the design conditions.

To overcome this challenges, the American Society of Mechanical Engineers created in 1915 a series of test codes known as ASME Power Test Codes which were later renamed to ASME Performance Test Codes (PTC), that established standard procedures for conducting unbiased performance tests on different power generation equipment, with the highest level of accuracy and consistent with the current engineering knowledge and best practices. (American Society of Mechanical Engineers (ASME), 2013) Among the 10 initial power test codes is the Test Code for Stationary Steam Generating Units which is nowadays known as the ASME PTC 4 - Fired Steam Generators Performance Test code. Its purpose is to define a series of standard procedures for the determination of the performance characteristics of most types of fired steam generation units.

This article focuses on the PTC 4 test code and specifically, on one of the methods therein described by which the efficiency of a coal fired, or, in fact, any solid fuel, steam generation unit can be calculated: the indirect method. The following sections will describe stage by stage how a PTC 4 performance test by the indirect method is carried out; what is the philosophy of the method, what are the fundamental equations and definitions, what are the necessary measurements needed, what are the main incoming and outgoing energy streams to the steam generator, and how are the test results interpreted.

The PTC 4 Standard

The purpose ASME PTC 4 Performance Test Code is to establish a standard set of procedures for the conduction of performance test of fuel-fired steam generators. (American Society of Mechanical Engineers (ASME), 2013) This test code has been designed to achieve the highest level of accuracy provided that the performance test is carried out meeting the conditions set forth in the code. Two major conditions described in this code are the following:

- The performance test measurements must comply with all the procedures and be within the maximum allowed variations allowed in the code.
- The uncertainties of the test results are within the previously defined and agreed target uncertainties for the test.

If these two conditions are met, the test is considered to be an ASME Code Test.

A performance test based on the ASME PTC 4 Test Code is usually executed with the intent of obtaining the corrected performance characteristics of a steam generator unit. These performance characteristics depend on the nature of the initial contractual guarantees established prior to the construction of the power plant and can include some of the following: steam generator efficiency, output, capacity, unburned carbon and unburned carbon loss, fuel, air and flue gas flow rates among others. The selected performance characteristics for the test are then used to compare actual performance of a steam generator unit for one or some of the following purposes (American Society of Mechanical Engineers (ASME), 2013):

- compare actual performance to a base reference performance
- compare different conditions or methods of operation
- determine specific performance of individual parts or components
- compare performance when firing alternative fuels
- determine the effects of equipment modifications

The proper application of this test code for the design of a performance test promises the achievement of the highest level of accuracy consistent with current engineering knowledge and practices. Evidently, the level of accuracy achieved will also depend on the type and size of the unit being tested e.g. Large or small utility boilers, fluidized bed boilers, with or without heat trap etc. It will also depend on the type of fuel being burned; coal, oil or gas, and test method used for the calculation of the performance characteristics; either the direct or indirect method. The following table encompasses the general types of steam generator considered by the code, the methods available for the determination of the steam generator efficiency and the uncertainty values associated with each one.

Table 1. Typical Code Test Uncertainties for Efficiency. (American Society of Mechanical Engineers (ASME), 2013)

Type of Steam Generator	Energy Balance Method (%)	Input-Output Method (%)
Utility /large industrial Coal fired Oil fired Gas fired	 0.4-0.8 0.2-0.4 0.2-0.4	 3.0-6.0 1.0 1.0
Fluidized bed	0.9-1.3	3.0-6.0
Small industrial with heat trap Oil Gas	 0.3-0.6 0.2-0.5	 1.2 1.2
Small industrial without heat trap		
Oil	0.5-0.9	1.2
Gas	0.4-0.8	1.2

From Table 1, it is evident that the indirect method (energy balance method) yields the lowest uncertainty for any type of steam generator and fuel selected. This is due to the nature of the methods. The Input-output method is particularly sensible to the measurement of the fuel flow, in particular, for coal, its accurate measurement greatly depends on the precision of the gravimetric feeders, which have to be calibrated before and after the test.

This introduces large uncertainties to the results because the proper calibration of the feeders as well as the accurate measurement of the coal flow is difficult in practice. In contrast, the indirect method or energy balance method, as its name implies, consists of carrying out an energy balance around the steam generator by measuring the remaining incoming and outgoing energy streams, streams which can be measured with high levels of accuracy, and therefore, introducing the least amount of uncertainty to the test results. In the indirect method, the coal flow is not a direct measurement, but a result of the energy balance carried out around the steam generator. The recommended method for testing coal fired steam generators is the indirect method.

Although this test code can be applied to steam generators burning a wide variety of fuels, the focus of this article will be on those fired by coal and tested by the indirect method, also known as the energy balance method.

In the following sections, a more in-depth description of this method and its characteristics will be given.

The PTC 4 Methods
Direct Method

The thermal efficiency of a steam generator unit can be calculated with two different methods: the direct method and the indirect method. The direct method only requires the measurement of the fuel flow for the calculation of heat input to the steam generator and the heat output. In simple terms, the efficiency of a steam generator can be evaluated with the following expression in a percentage basis:

$$\text{Boiler Eff.} = \frac{\text{Heat Output}}{\text{Heat Inut}} \quad (1)$$

The heat output from the steam generator can be calculated by the algebraic sum of all incoming and outgoing heat flows from the steam generator as described in ASME PTC 6. (American Society of Mechanical Engineers, 2004)

Figure 1 shows a simplified view of the energy streams crossing the steam generator boundary, based on this figure, the heat input to the steam generator is calculated from the measurement of the fuel flow and the heating value of the fuel. With this in mind, Equation (1) can be rewritten as:

$$\text{Boiler Eff.} = \frac{\text{Steam Flow Rate (Steam Enthalpy} - \text{Feedwater Enthalpy)}}{\text{Coal Flow Rate x Higher Heating Value}} \quad (2)$$

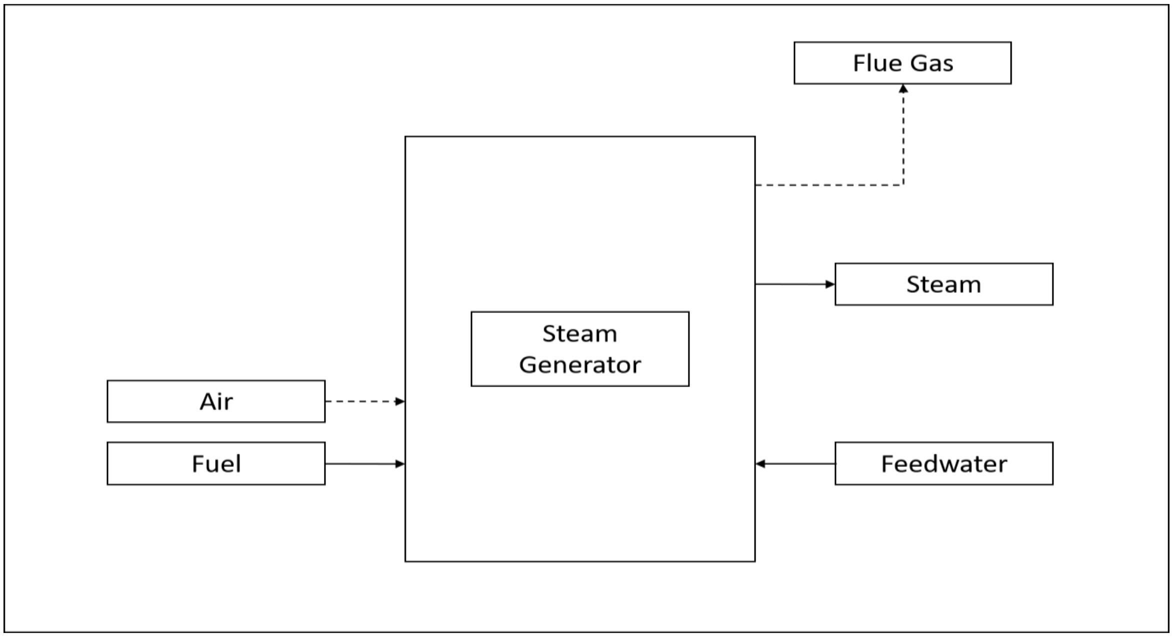

Figure 1 Steam generator boundary for streams definition.

Equation (1) is considered to be the fundamental equation for the steam generator efficiency. This equation can be further elaborated to apply to different
configurations of steam generators and for any of the two methods described in the ASME PTC 4 Test Code and discussed in this article.

As explained in Section 1, the use of the direct method for the calculation of the efficiency of a steam generator unit is not advisable due to the large uncertainty values associated with this method. However, there exist some advantages of using this method over the indirect method, some of these advantages are listed below:

- the direct method allows for the rapid evaluation of steam generator efficiency when precision is not crucial
- fewer parameters, in comparison with the indirect method, are needed for the evaluation of the steam generator efficiency
- as fewer parameters, and thus, fewer instruments are needed, the direct method provides a rapid and cheaper way of evaluating the efficiency of a steam generator unit

The next section describes in detail the characteristics of the indirect method for the calculation of the efficiency of a steam generator unit.

Indirect Method

In a general sense, the indirect method for calculating the thermal efficiency of a steam generator unit consists of carrying out a heat and mass balance around the steam generator unit by quantifying all the incoming and outgoing energy streams, as well as a bookkeeping of the credits and losses of heat.

In contrast with the direct method, this method requires the installation of a vast number of high precision instruments which are required for measuring all the parameters needed for the proper bookkeeping of the heat losses and heat credits of the cycle. It is true that this method demands several times the work required for the direct method, but the gains in precision are evident. Figure 2 depicts the envelope of a steam generator unit, along with the energy streams crossing this envelope for the energy balance.

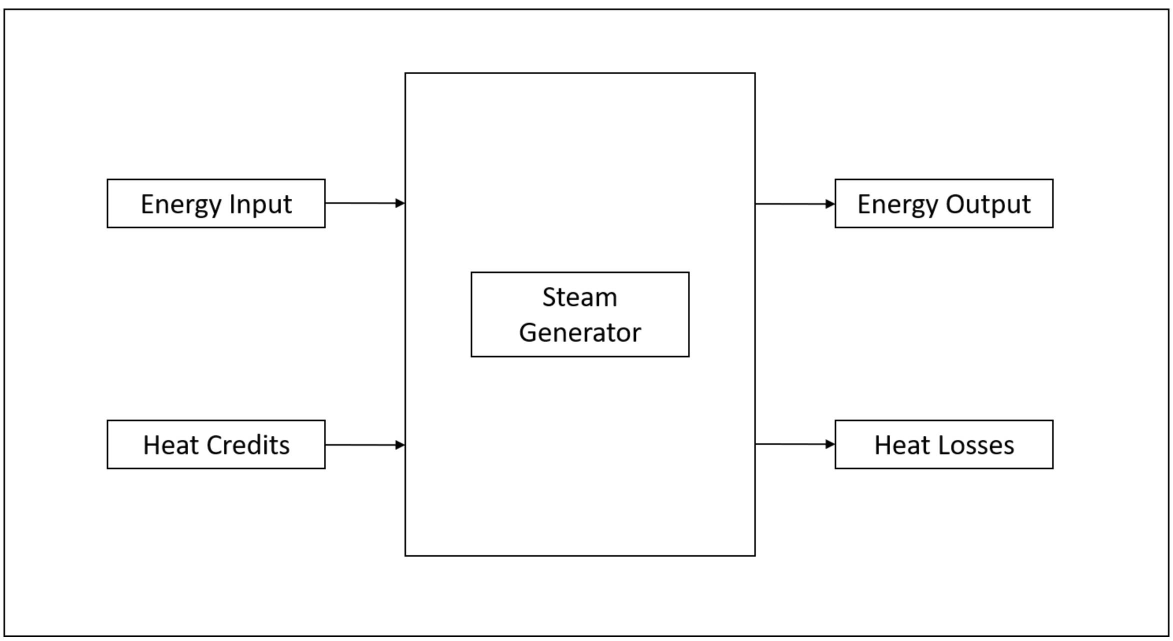

Figure 2. Steam generator energy balance.

From Figure 2, four main streams can be observed: energy input, energy output, heat credits and heat losses. The energy input and energy output streams are the same as in the direct method, i.e. the energy input (QrF) to the steam generator is the heat input from the fuel and the energy output (QrO) is the algebraic sum of all incoming and outgoing heat flows from the steam generator. This method also requires the determination of all the heat losses (QpL) and heat credits (QpB) of the cycle. From this figure, the energy output can be defined as:

$$\mathrm{OUTPUT} = \mathrm{INPUT} - \mathrm{LOSSES} + \mathrm{CREDITS} \qquad (3)$$

Or

$$\mathrm{QrO} = \mathrm{QrF} - \mathrm{QrL} + \mathrm{QrB} \qquad (4)$$

And

$\mathrm{QpL} = 100(\mathrm{QrL}/\mathrm{QrF})$

$\mathrm{QpB} = 100(\mathrm{QrB}/\mathrm{QrF})$

With the above definitions in mind, the steam generator efficiency (fuel efficiency) can be expressed in a percentage basis in the following fashion:

$$\mathrm{EF}(\%) = 100\mathrm{QrO} - \mathrm{QrF} = 100 - \mathrm{QpL} + \mathrm{QpB} \qquad (5)$$

The evaluation of Equation (5) requires the determination of the heat credits and heat losses of the cycle. Table 2 and Table 3 show in more detail what are the credits and losses required to be determined to calculate the efficiency of a coal fired steam generator.

Table 2. Heat Credits.

Parameter	Symbol
Entering dry air	QpBDA
Moisture in entering air	QpBWA
Sensible heat in fuel	QRBF
Sulfation	QoBSIF
Auxiliary equipment power	QrBX

Parameter	Symbol
Sensible heat in sorbent	QrBSb
Energy supplied by additional moisture	QrBWAd

Table 3. Heat Losses

Parameter	Symbol
Dry gas	QpLDFg
Water from burning hydrogen	QpLH2F
Water in solid fuel	QpLWF
Moisture in air	QpLWA
Summation of unburned combustibles	QpLSmUb
Pulverizer rejects	QpLPr
Unburned hydrocarbons in flue gas	QpLUbHc
Sensible heat of residue	QpLRs
Hot air quality control equipment	QpLAg
Air infiltration	QpLALg
NOx formation	QpLNOx
Surface radiation and convection	QrLSrc
Additional moisture	QrLWAd
Calcination and dehydration of sorbent	QrLClh
Water in sorbent	QrLWSb
Wet ash pit	QrLAp
Recycled streams	QrLRy
Cooling water	QrLCw
Internally supplied air preheater coil	QrLAc

These tables show the most common heat credits and heat losses encountered in coal fired steam generators, but additional credits or losses may be present and should be determined for a particular unit with different arrangement. It is the responsibility of the engineer designing the test and the test committee to account and agree for all credits and losses of a particular unit that may have a relevant impact on the final value of efficiency.

If it is determined that if a credit or loss will have a minor impact on the final results, the test parties can agree to estimate its value instead of measuring it, as long as the uncertainty introduced by this estimation do not exceed the uncertainty budget for the test.

Most of the time, the indirect method yields the most accurate results because this method requires several parameters for the calculation of the efficiency and each of these parameters individually have a smaller impact on the final result than one main parameter as it is the fuel heat input in the direct method. This allows for flexibility in the estimation of some losses and credits without compromising the target uncertainty of the test.

Another major advantage of the indirect method is that it allows for the evaluation of individual losses, which in turn, permit the detection of under-performing equipment that is contributing to the decrease of the unit efficiency. Finally, an important aspect of the indirect method is that it permits the correction of the test results to design or guaranteed conditions. This is a crucial point as it allows for the normalization of all measured results.
The downside of the method lies in that it requires the installation of large numbers of high-precision instruments and most of these instruments have to be installed in locations of difficult access. This tends to greatly elevate the costs of the performance test. Furthermore, some of the losses required for the calculation of the efficiency are practically immeasurable and consequently, must be estimated.

The indirect method is the recommended method for the evaluation of steam generator efficiency. This is due to its capacity of yielding lower uncertainty in the results in comparison with the direct method. Furthermore, it allows for the correction of the test results to any condition, which makes it very valuable for the evaluation of contractual guarantees compliance.

In situations where the accuracy of the results is not crucial, and no compliance of guarantees is necessary, the choice between methods can be based upon available resources and time frame.