



An Alternative Approach to Continuous Compliance Monitoring and Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

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Abstract

Quantifying emissions and complying with environmental regulations are important issues for gas turbine plants. These objectives can often be met with either a CEMS (Continuous Emission Monitoring System) using gas analyzers or a software only PEMS (Predictive Emissions Monitoring System). PEMS interface directly to the turbine control system and represent a lower cost alternative to traditional CEMS. PEMS are a compliance monitoring alternative consisting of a model of the turbine operations and its emissions. PEMS can be used to track plant combustion efficiency. PEMS can allow for more efficient operation of the plant because the PEMS system tracks excess emissions and can be used to determine the causes of and reduce pollution. This paper not only reviews the use of PEMS at three different turbine facilities and highlights the costs and benefits of using a PEMS for documenting emissions of priority pollutants and Green House Gases (GHG).

1 Introduction

What do the owners of an independent cogeneration plant in Dearborn, Michigan; a large frame peaking utility generator in Minnesota; and a fleet of base-loaded combined cycle turbines in Texas have in common? . A predictive emission monitoring system (PEMS) was used to generate and collect emissions data for these units under U.S. EPA regulations.

U.S. regulations require continuous emissions monitoring systems (CEMS) for certain operations that discharge pollutants in to the air and allow for the use of predictive approaches as an alternative to CEMS. The installed predictive emissions monitoring system (PEMS) must meet rigorous performance specification criteria and the site performs ongoing quality assurance tasks such as periodic audits with portable analyzers and annual accuracy testing.^{1,2} Prior to the promulgation of CEMS requirements in the U.S., turbine emissions were verified using simple parametric equations or manual stack test procedures (U.S. EPA Reference Methods). CEMS have been used predominantly under the Clean Air Act, although PEMS are gaining acceptance internationally as the preferred alternative method for gas turbine compliance monitoring.³

Modern empirical PEMS have evolved to meet the need for continuous monitoring of gas turbine emissions at the lowest possible cost. PEMS are significantly less expensive to install, operate, and maintain over the standard gas analyzer based continuous emissions monitoring system which provides a known level of accuracy, drift, and downtime.

1.1 PEMS Classifications

PEMS can refer to both parametric and predictive emissions monitoring systems. Parametric and predictive systems share a common functional relationship with the turbine combustion and emissions. These approaches to emissions monitoring take input data from the process control system and generate emissions data without actually contacting the stack gas or analyzing its pollutant content in real-time. Although parametric and predictive emissions monitoring systems share a common functional block diagram, they provide dramatically different results.

1.2 Theoretical Systems – Parametric or First Principle

A parametric system utilizes one to three key input parameters. Parametric systems utilizing three inputs or less are generally not very accurate and tend to over-predict the emissions. This includes the linear methods such as applying an emission factor which typically has a positive bias. Parametric systems require a few critical inputs that are used in formulaic calculations of the pollutant emission rate. A parametric formula is described for each pollutant, p , such that the emission rate, E , can be expressed as a function of up to three input parameters, I :

$$\text{Parametric } E_p = f(I_1) \text{ or } = f(I_1, I_2) \text{ or } = f(I_1, I_2, I_3)$$

$$\text{Example } E_{NOx} = I_1 \times K_{NOx} \text{ where } I_1 = \text{heat input}$$

In this example the NOx emission rate is defined as a linear function of heat input, when applying an emission factor (K_{NOx}) to a low mass emitter. Parametric systems are not used on base-loaded gas turbines in U.S. emissions trading programs where continuous compliance monitoring is required (see Figure 1 below).

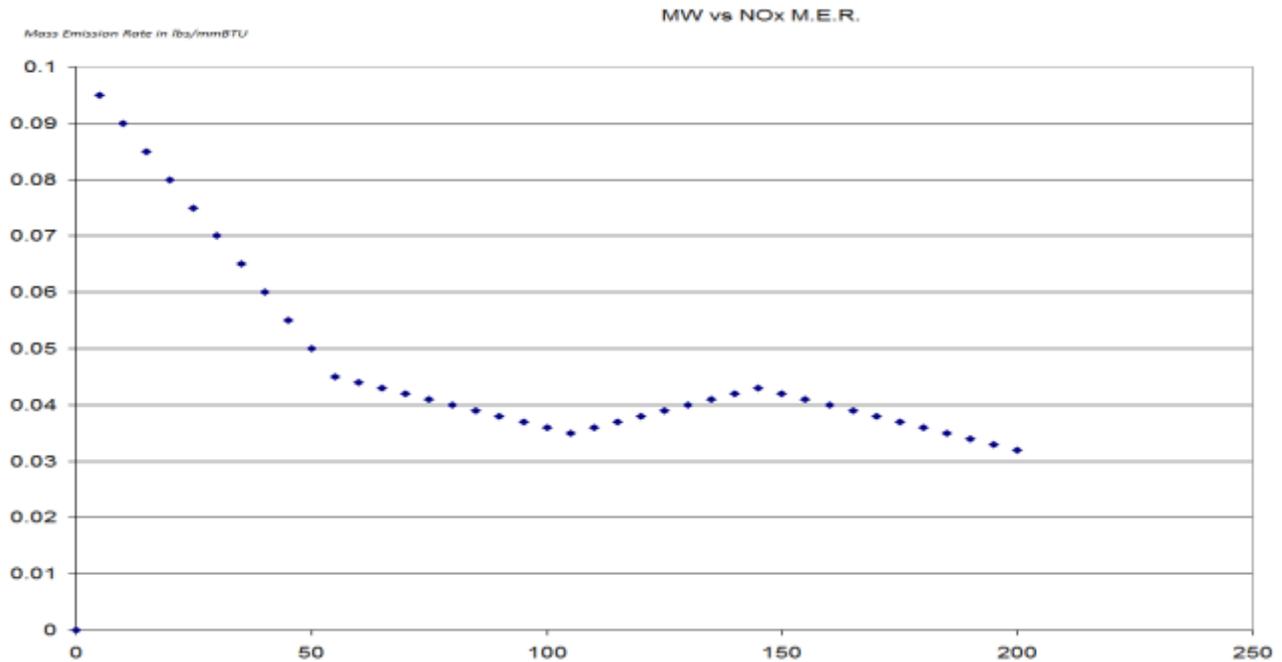


Figure 1: Continuous Parametric NOx Estimation System

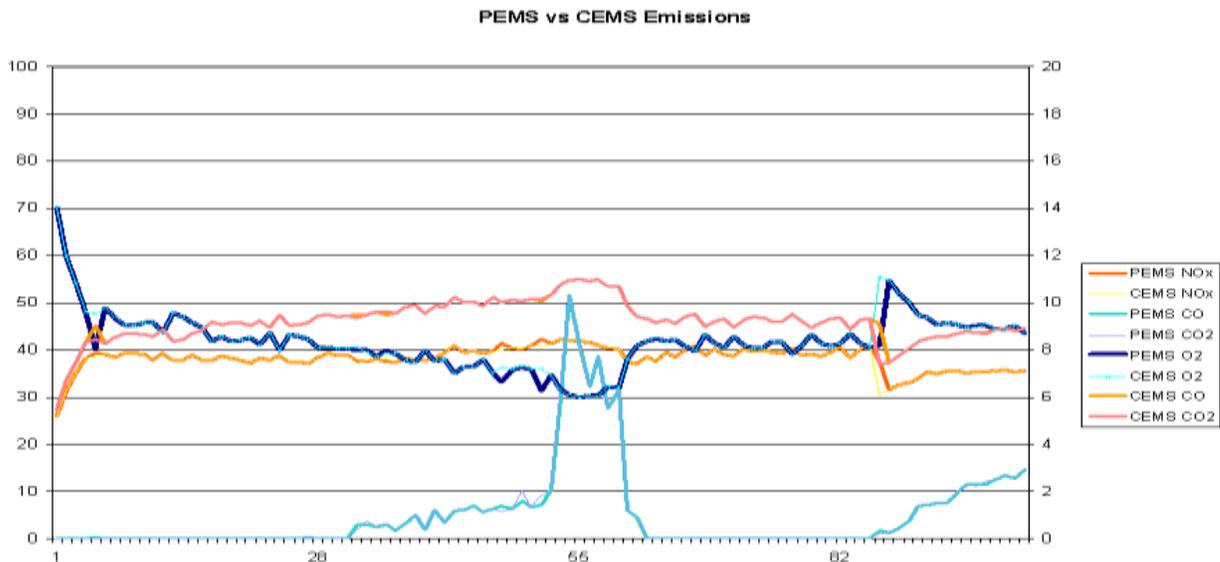
An alternative Approach to Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

1.3 Empirical Predictive Systems

Modern empirical predictive systems achieve very high levels of accuracy and can maintain that accuracy over many years (see Figure 2 above). Empirical approaches (such as the neural network or statistical hybrid) require a historical dataset that is collected prior to deployment containing emissions data from CEMS and process data readily available from the control system. A predictive formula is described for each pollutant, p , such that the emission rate, E , can be expressed as a function of n (greater than 3) number of input parameters and intermediate nodes, I , as:

Empirical models use historical operating data correlated with emission data to predict the emission rates in real-time with accuracy comparable to a CEMS. Empirical systems have demonstrated accuracy equivalent to a CEMS. Two empirical approaches have been certified by U.S. EPA under 40 CFR Part 75, Subpart E to date. Empirical systems unlike parametric and other theoretical predictive systems utilized in the past for compliance have demonstrated capability to pass the strict requirements of 40 CFR Part 75, Subpart E³. In the following discussion, the use of the acronym 'PEMS' is restricted to the predictive type of system that can be used in U.S. compliance programs for continuous monitoring of all types of processes under existing federal regulations.

Figure 2: Empirical NO_x/CO/CO₂/O₂ Statistical Hybrid PEMS



1.4 Neural Network Predictive Systems

One system that was certified used a formulaic first principle approach, but failed to accurately predict startup and shutdown emissions as was the case with the neural network model that was certified under Subpart E.

Predictive $E_p = f(I_1, I_2, I_3, \dots I_n)$

Example $E_{NO_x} = f(I_1, I_2, I_3, \dots I_n)$ or

(Neural $E_{NO_x} = I_1 \times w_1 + I_2 \times w_2 + I_3 \times w_3 + \dots I_n \times w_n$

Network) where w_n is the weight for the input or intermediate node n

1.5 Statistical Hybrid PEMS Model

The statistical hybrid approach has been used in more than 95% of the certified 40 CFR Part 75 PEMS and the same statistical hybrid empirical software has been used in over all of these certified systems. All statistical hybrid PEMS can predict startup and shutdown emissions accurately as long as the historical training dataset is 'robust'.

The statistical hybrid approach is an empirical predictive system that requires only a fixed sample of paired process and emissions data. A statistical hybrid PEMS has the following features:

- Robust model that is accurate across the full load range of the unit
- Valid for normal operating conditions and during startup and shutdown
- Equivalent accuracy as a CEMS with superior reliability tied to the plant DCS
- Flexibility to be implemented using existing instrumentation and standard interfaces
- Has been certified as an alternative system under U.S. regulations for CEMS
- Has met the requirements of 40 CFR Part 75, Subpart E and 40 CFR Part 60, PS-16
- Can be assessed using quality control procedures to meet the requirements of EPA
- Can be developed and retrained by non-technical onsite staff or consultants
- Can be tested against EPA reference methods

The statistical hybrid method directly leverages the power and agility of the personal computer and a relational database containing paired historical emissions and process parameter data. It requires no specialized staff to develop or maintain. The model is a single deterministic method within a core application module. This module is the same for all process types, configurations, and control systems. The current state of the process is analyzed every minute at a minimum by the core module and an accurate emission rate is generated using the stored historical training dataset.

Unlike the more complicated empirical systems, the statistical hybrid model can be developed for any given process without a great deal of knowledge of its design or the chemistry involved in the generation of pollutant emissions. A statistical hybrid predictive formula is described for each pollutant, p, such that the emission rate, E, can be expressed as a function of n number of input parameters depending on the availability of those input parameters, I, as:

- Predictive $E_p = f(I_1, I_2, I_3, \dots I_n)$
- Example $ENO_x = f(I_1, I_2, I_3, \dots I_n)$ or
- (Statistical Hybrid) $ENO_x = f(I_2, I_3, \dots I_n)$ if Input1 fails or
- $ENO_x = f(I_1, I_3, \dots I_n)$ if Input2 fails or
- $ENO_x = f(I_3, I_4, \dots I_n)$ if Inputs 1 and 2 fail or
- $ENO_x = f(I_1, I_4, \dots I_n)$ if Inputs 2 and 3 fail or
- ... with many other possible paths to an accurate prediction

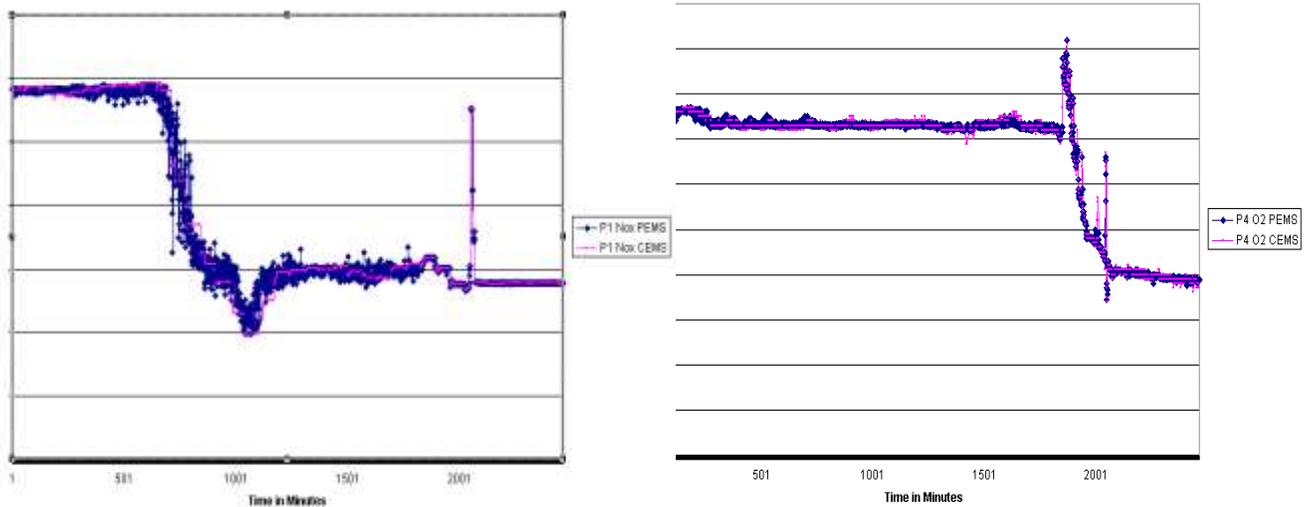
An alternative Approach to Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

2 PEMS Applications

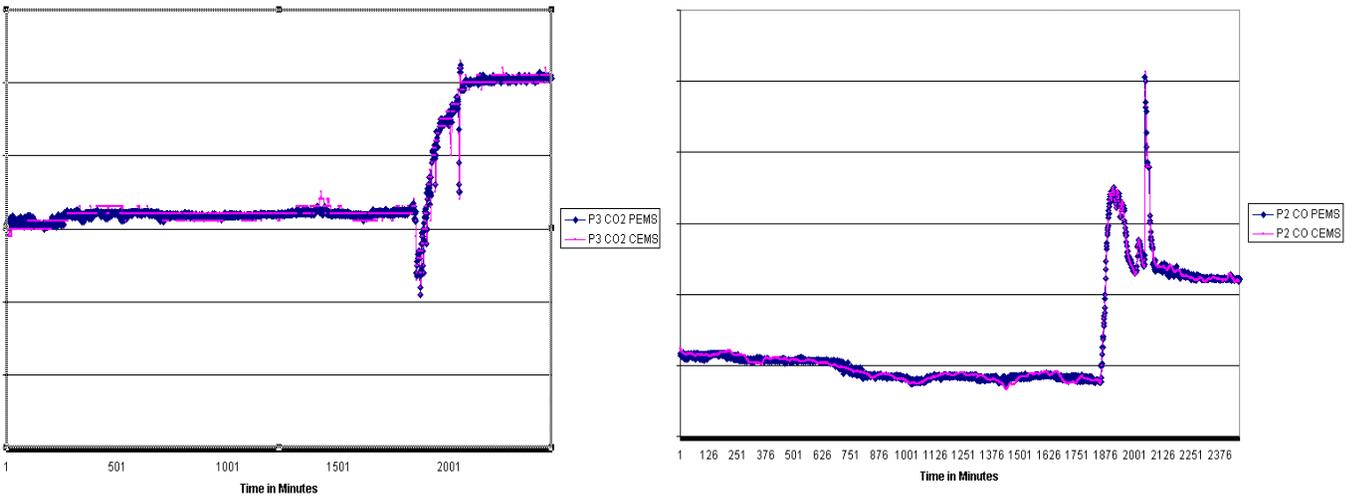
The statistical hybrid PEMS was chosen due to its low cost and non-proprietary method. The statistical hybrid PEMS, an empirical model completely defined by its historical training dataset has been applied to a variety of classes of gas-fired turbines from the smallest micro-turbines to the largest frame generators. The same core module with statistical hybrid predictive engine was deployed in each instance. Gas turbines included in the study range in size from 60kW – Capstone C60, 1.1 MW – Kawasaki M1A-13D, Solar Mars, Solar Taurus, Solar Titan, GE Frame 5, GE Frame 6, GE 6B/E, GE LM2500, GE LM6000, GE Frame 7, GE 7FA, and Siemens V84.

2.1 Small Turbines

The statistical hybrid PEMS was applied to several small turbines less than 25 MW (Solar Mars, Taurus, and Titan - see Figures 2 through 5). The turbines were tested at the factory prior to shipment in the final integration stage of the package. Each unit was run up and down in load under lean and rich fuel conditions. A PEMS model was built on the initial factory test data and validated in the final emissions testing. The PEMS successfully passed the performance tests and provided real-time and historical emissions predictions for each small turbine class. Pollutants evaluated include nitrogen oxides (Figure 2 - NO_x), oxygen (Figure 3 - O₂), carbon dioxide (Figure 4 – CO₂), and carbon monoxide (Figure 5 - CO). The small turbine PEMS was also trained with total hydrocarbon emission data. This data was used in the historical dataset and allowed the PEMS to accurately model these emissions. The model configuration provided accurate emission predictions for all parameters using one singular methodology for all pollutant parameters.



Figures 2 and 3: Small Turbine NO_x and Oxygen PEMS



Figures 4 and 5: Small Turbine CO₂ and CO PEMS

2.1 Mid to Large Frame Turbines

The statistical hybrid PEMS was applied to a larger gas turbines in the range of 50 MW to 180 MW power generation capacity. The turbine sizes included GE Frame 6, GE Frame 7 and Siemens V84, some of the largest gas turbines manufactured. These turbines were equipped with a variety of modern pollution control technologies including DLN, steam and water injection, and SCR. A variety of control systems were used.

A PEMS was deployed in each case along with a CEMS to collect continuous emission monitoring system data. Following the collection of the required 720 operating hours on each unit, a Subpart E application was prepared and submitted to the Administrator of U.S. EPA approval of the installed PEMS on the simple and combined cycle turbines.

The alternative monitoring system was installed just prior to the start of the Subpart E demonstration to determine average hourly emission data for NO_x using a statistical hybrid model as specified under Subpart E of 40 CFR, Part 75. The data from each of the units was pooled to create one master PEMS historical training dataset or model (Figure 6).

The data presented in this class certification is from one single model that covers all six units. Following the demonstration run on all units, the data confirmed that the installed alternative monitoring system has the same or better precision, reliability, accessibility, and timeliness as that provided by the CEMS.

Figure 6 depicts a typical demonstration project using the methods prescribed in Subpart E. Each of the peaks represents a startup with base-load operations following. Baseload operations are in compliance with the emission standard. The base-load emission rate from the gas turbine is very low (< 0.02 lbs/mmBTU or < 4 ppmv NO_x).

An alternative Approach to Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

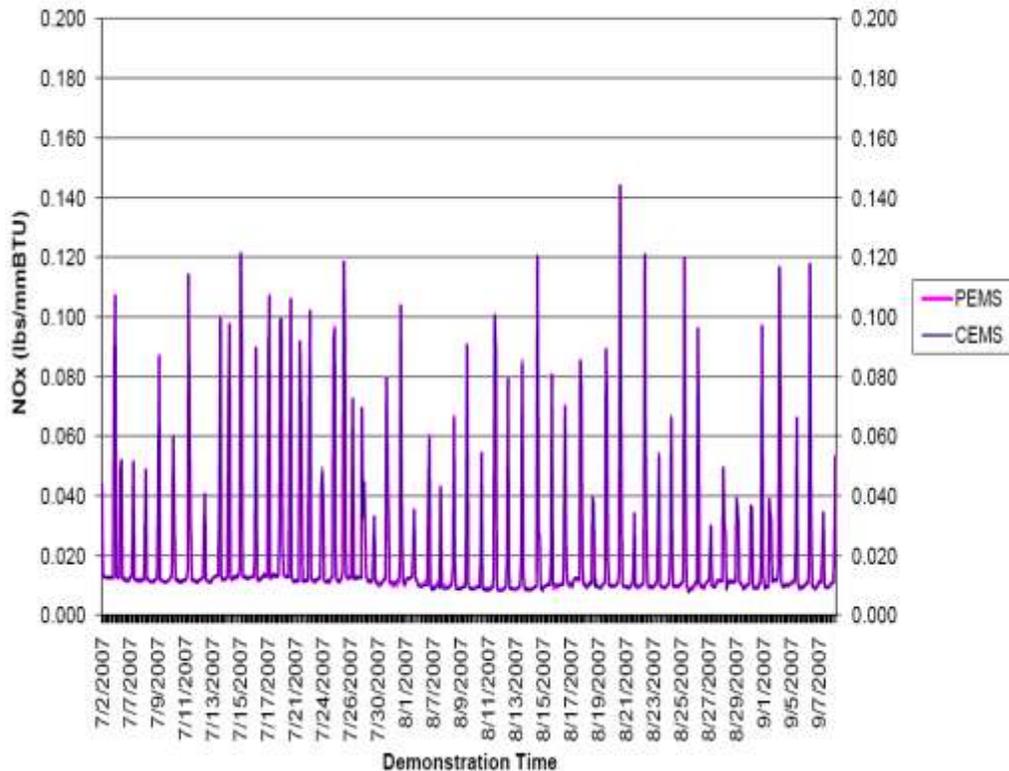


Figure 6: Large Frame Gas Turbine NOx Emission Rate PEMS

3 PEMS Certification

Certification under 40 CFR Part 75 requires a Subpart E demonstration and comparison of the data with a quality assured CEMS. The temporary CEMS were operated throughout the required 720 hour demonstration to compare with the PEMS. The initial certification consisted of a single-load (9-run) data set using EPA Method 7E and Method 3A. Each certification test included a nine run RATA. Data from the reference method tests were used to generate a relative accuracy result against the installed temporary CEMS and also the PEMS.

Field data and notes were collected during each day of operation and daily calibrations were performed. At the conclusion of these demonstrations, the relative accuracy test audit was repeated using reference method data from EPA Method 7E and Method 3A to assess the accuracy of the installed PEMS. PEMS data was produced in minute increments, but averaged hourly for analysis. Statistical analyses were performed and graphs of the results were plotted based on the paired hourly data sets consisting of a minimum of 720 records for each unit firing natural gas only.⁴

Performance specification testing was conducted to assess the quality and accuracy of data generated by the CEMS and PEMS. The performance specification test procedures under Subpart E are detailed in U.S. EPA 40 CFR Part 75, Appendices A, B, and F. A certification was performed using the applicable test methods including the relative accuracy audit. Daily calibration at two levels was conducted each operating day.

4 PEMS Quality Assurance

The PEMS data is fed into a compliance database provided by a third party vendor. This package allows for quality assurance and secure processing of the data in order to provide facility wide and unit specific total pollutant emissions. The system tracks the unit specific, flexible groups, and facility total pollutant and GHG emissions using the installed PEMS.

INPUT	DESCRIPTION	MIN	MAX
Input14*	Mega-Watt Load	0.00	63.9
Input29*	Gas Flow	0.00	38445.2
Input10	Guide Vane Position	50.20	84.4
Input13	Firing Temperature Reference	0.0	1997.7
Input15	Fuel Stroke Gas	0.0	73.1
Input17	Fuel Stroke Reference	0.0	74.5
Input24	IGV Temperature Cont Rev	0.0	1259.9
Input25	Average Exhaust Temp	74.06	1099.0
Input3	Bell-mouth Differential Pressure	0.00	68.6
Input4	Comp Discharge Pressure	0.00	132.6
Input6	Air Flow	0.0	548.6
Input7	Air Flow Dry	0.0	546.5
Input19	Splitter Valve Position	0.0	101.0
Input30	Turbine Exhaust Press	0.0	16.55

Figure 7: PEMS Model Envelope

A quality assurance program was established for the site and for each pollutant parameter or critical input parameter used in the deployed PEMS compliance monitoring system. The instrumentation used in the PEMS model is subjected to a minimum annual check and calibration. The statistical hybrid PEMS interfaces directly with the process control system for data acquisition. A Quality Assurance program is put in place in accordance with 40 CFR Part 75, Appendix B or 40 CFR Part 60, Appendix B. The Quality Assurance Manual is located next to the PEMS server. System maintenance, database maintenance, and data backup procedures have been instituted onsite and are conducted quarterly. All PEMS quality control activities are documented in the Quality Assurance Manual.

In addition to the daily quality control review, periodic quality control procedures as specified in 40 CFR Part 75, Appendix B for the turbine are utilized. These quality control activities include an annual inspection/calibration of the orifice plate used for the gas flow input signal. The temperature and pressure compensation sensors used by the process control system to correct the gas flow to standard conditions are calibrated each quarter. The data is validated and averaged by hour and day using a defined model envelope based on the statistical hybrid historical training dataset (Figure 7). RM is the reference method for which the PEMS data was compared against. This data shows minute average run data that is not reflective of overall PEMS bias, but an instantaneous snapshot of PEMS accuracy.

An alternative Approach to Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

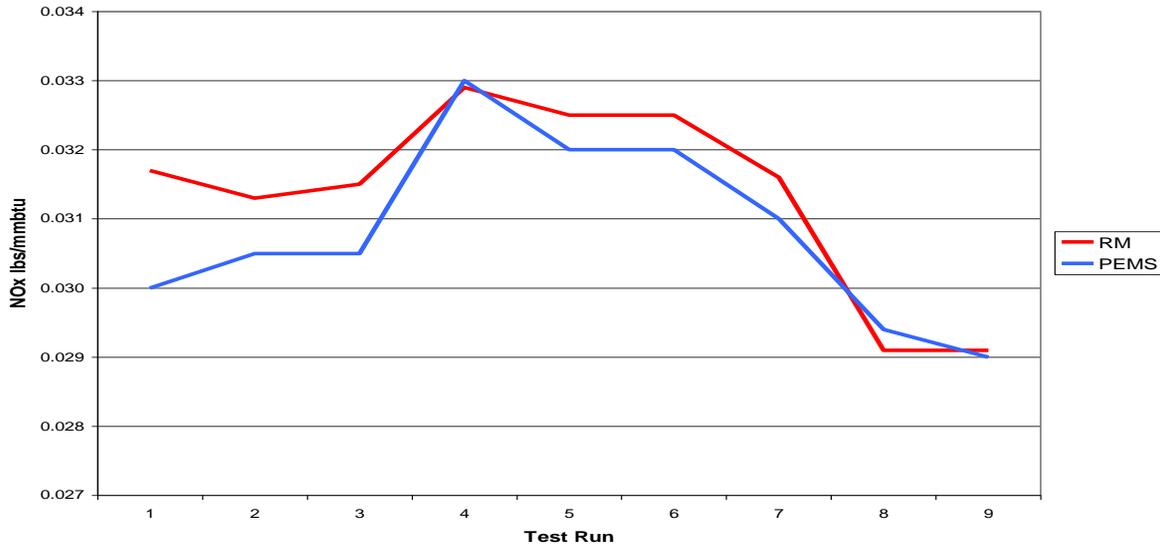


Figure 8: PEMS Relative Accuracy Test

5 PEMS Costs

The PEMS initial capital costs were less than 50% of the alternative – using continuous emissions monitoring with gas analyzers. The ongoing operating costs of the PEMS at these sites are less than 10% of the cost of the alternative continuous emission monitoring system. The overall cost of ownership of the PEMS solution was significantly less than other options. A comparison of the cost of quality assurance programming and calibration activity for continuous emissions monitoring was comparable with the deployed PEMS solution.⁵

6 Optimization – PEMS Advantages

A PEMS can provide accuracy that is more reliable than a CEMS. PEMS do not drift. PEMS rely on process inputs and instruments that typically drift no more than 1% to 2% per year. A typical model will use 10 or more input parameters that are in some cases redundant such that the impact of drift is further minimized. The resulting emissions prediction is resilient to input failure and drift such that no single input parameter is critical to the accuracy of the predicted emission. CEMS analyzers can drift 1% to 2% daily. Long-term CEMS drift is experienced through contamination of sample transport and the sampling train and component failure.

PEMS have lower startup costs. Installation of a PEMS requires the installation of a computer with the PEMS software that is interfaced to the gas turbine control system. Normally one day onsite or less is required to startup a PEMS including hardware installation. Depending on complexity and location of the CEMS, delivery generally is 90 to 120 days at best and installation up to 6 months after all the equipment arrives onsite using skilled trades to install ports, probes, umbilical, cable tray, CEMS rack, environmentally controlled shelter or area, gas cylinders, cylinder racks, gas tubing runs, drain and exhaust lines, plus interconnecting wiring and low dew point clean air supply.

PEMS require less spare parts and onsite training than CEMS. CEMS training is usually three to five times longer in duration and scope as PEMS training. PEMS should require no on site emergency service. A direct modem to the system should take care of most problems incurred. On site emergency service for a CEMS is inevitable and typically expensive.

PEMS do not rely on any one process input to maintain system uptime or accuracy of emissions data quality. The PEMS uses numerous and redundant inputs obtained from a direct interface to the turbine control system. Therefore, very little, if any, down time or missing data should ever be reported. CEMS typically are considered doing well if they maintain 95% uptime which is a minimum requirement. If an analyzer fails (NO_x, CO or O₂ etc) or a critical sampling component fails, the system is consider down and down time is logged. Emergency service can and will be required.

PEMS are typically configured to predict CO, HC, and CO₂ along with NO_x and O₂ compliance data. PEMS can display process and combustion efficiency reports. CEMS provide information about the content of stack gas emissions and do not typically provide process data or combustion efficiency. PEMS can be used to determine the source(s) of excess emissions. Combustion input parameter(s) that are out of normal range can be identified and provide critical information to avoid excess emission events. CEMS do not provide any insight as to the cause of an excess emission nor do they have the ability to facilitate process control adjustments or correction of the problem.

CEMS are indispensable for certain applications where continuous emissions monitoring with gas analyzers is required (for example, municipal waste combustor or hazardous waste combustors). CEMS have an advantage to measure the pollution content when the process is operated outside the normal load range or in abnormal conditions. This can be important in certain process and pollution control applications.

7 Summary

Advanced empirical methods have been successful at meeting the requirements of U.S. emission trading programs such as EPA Title IV Acid Rain (40 CFR Part 75) regulations that require continuous monitoring for nitrogen oxides and carbon dioxide to demonstrate compliance. Empirical PEMS achieve very high accuracy levels and have demonstrated superior reliability to CEMS for various types of continuous process applications under existing U.S. air compliance regulations. At several gas turbine sites, the PEMS predictions are typically within 5% of the reference method during annual accuracy testing.

PEMS can be certified as an alternative to gas analyzer based CEMS for nitrogen oxides and carbon dioxide compliance in the United States and for GHG trading purposes. A robust statistical hybrid model has been proven to be a cost-effective continuous compliance monitoring solution in nitrogen oxides and carbon dioxide emission trading programs for many types of industrial processes such as gas turbine and boilers. These solutions are extremely cost-effective when compared to conventional continuous emission monitoring equipment.

An alternative Approach to Turbine Plant Optimization using a PEMS (Predictive Emission Monitoring System)

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