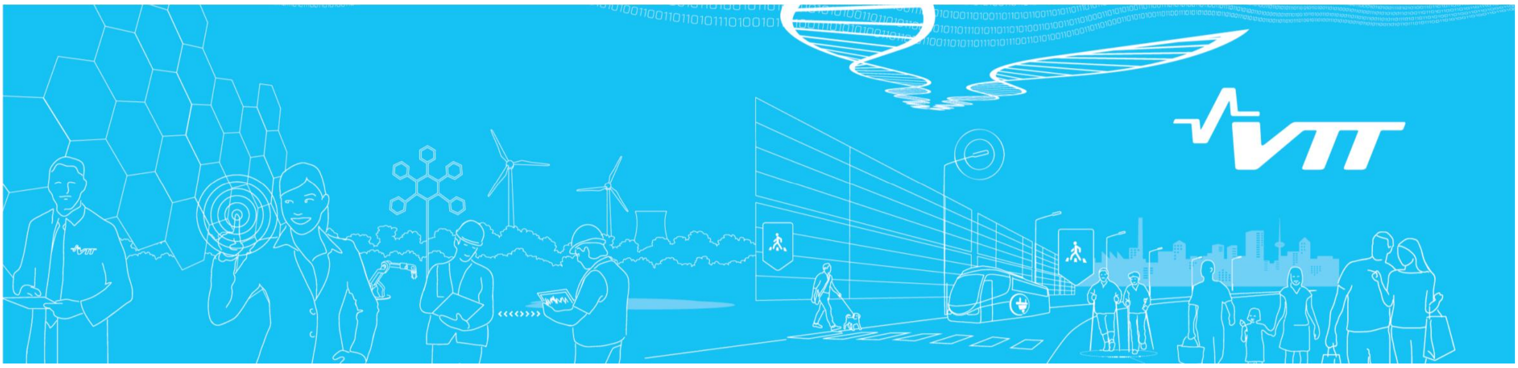

RESEARCH REPORT

VTT- R-04313-14

Predictive Emission Monitoring Systems, PEMS and their acceptance and use in Europe

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Confidentiality: Confidential

Report's title	
Predictive Emission Monitoring Systems, PEMS and their acceptance and use in Europe	
Customer, contact person, address CLEEN MMEA	**Order reference**
Project name	**Project number/Short name**
Author(s) Olli Antson, Tuula Pellikka	**Pages** 12/
Keywords emission measurements, CEM, PEMS	**Report identification code** VTT- R-04313-14

Summary

This literature study describes the main features of PEMS in estimating gas and particle emissions from engines and power plants. The basic principles of PEMS implementations are given. We consider also the main advantages of using PEMS instead of direct measurements of emissions.

In CEN the preparation of a new standard on “Predictive Emission Monitoring Systems- Execution and Quality Assurance” has been started in 2012. This standard will include guidance and norms for building a PEMS and requirements for its quality assurance aspects.

The present situation of acceptability of PEMS from legislation aspect in some European countries is clarified by a questionnaire study which was sent by VTT to environmental experts and authorities. At this moment, use of PEMS is not directly regulated in European legislation. However, PEMS is mentioned as one option in the LCP BREF- draft text that it could be used instead of continuous monitoring for some pollutants and sources. The possibility to use PEMS is also mentioned in the draft text of Reference Report on Monitoring, (ROM 2013), however, this text is not legally binding.

At the moment, the use and acceptance of PEMS seems to vary a lot in Europe. The Netherlands, Denmark and UK accept the use of PEMS and on the other hand, for example Germany, Italy and France seem to have the opinion that PEMS are not maybe the most cost-efficient systems for the monitoring of emissions and that they are not confident with the quality of the results given by PEMS. So, PEMS need to still be proven that they are applicable for a certain process. The work that is carried out in CEN/TC264/WG37 to standardise the quality assurance of PEMS will support this.

This review is written for CLEEN MMEA-program WP4.

Confidentiality	Confidential

Espoo 27.10.2014

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Distribution (customer and VTT)

Contents

1. PEMS vs. CEMS

PEMS (predictive emission monitoring system) is a software based system which uses existing process sensors and mathematical or statistical models for estimating gas and particle emission. In some applications it has replaced emission monitoring equipment or CEMS (continuous emission monitoring system).

Typically the main argument given for using PEMS instead of CEMS is the reduction of installation and maintenance costs. The reduction of costs is estimated to be more than 50% for installation and maintenance /1/. The other argument which supports the use of PEMS is the information on combustion efficiency. This information can be used to enhance operation and reduce emissions.

Reduction of costs in PEMS is a consequence of using only process sensors which are already installed in the process control system, and thus, there is no need to invest on new instruments as in CEMS. Extra costs can also be avoided in the maintenance of those instruments. However, installation of PEMS requires sometimes long test periods with the use of continuous emission monitoring devices. In specific cases the operating costs of the PEMS have been less than 10% of the costs of the alternative CEMS /2/.

On the other hand, changes in the combustion process may require a new installation of the parameters of PEMS but in similar case there are possibly no changes at all in CEMS. The new standard which is being developed by CEN on PEMS should give guidelines in these cases.

Data reconciliation is typically included in PEMS in order to eliminate or reduce errors on input signals making the prediction model more robust and reliable. Moreover, in PEMS which is based on first principles method a performance monitor can also be used to detect deviation between actual and expected efficiency. With performance monitor one can track the reasons for lower efficiency or larger emissions and improve operation which is not possible with traditional CEMS /2/.

2. Applications of PEMS

Today there are several hundreds of PEMS in use globally, and e.g. in USA they have been applied mainly in gas turbines and in coal power plants. Chien /3/ lists several other applications such as boilers, continuous catalyst regeneration (CCR) reformers, coker heaters, crude heaters, ethylene furnaces, gas turbine-heat recovery steam generators (HRSGs), pyrolysis furnaces, etc. Some special PEMS are used in biomass-fired plants, glass furnaces, lime kilns, passenger ferries, in-service marine diesel engines and waste-fuel incinerators.

PEMS is typically used to predict emissions of NO_x, O_2, CO and HC /1/. There are also PEMS which include particles, TRS and SO_2 in their models /3/.

The two main producers of PEMS are Pavilion Technologies Inc. /4/ (owned by Rockwell Automation) and CMC Solutions Inc. /5/. Both companies have installed hundreds of PEMS with compliance to PS-16 (Performance Specification) by U.S. EPA for predictive emissions monitoring systems

3. Methods used in PEMS systems

Typically PEMS uses the existing plant instrumentation and sensors as input to the calculational model of emissions. The parameters of this model are obtained by minimizing the difference between the predicted and measured emission values.

Two different approaches can be used for the prediction of emissions /1/:

- first principles method (or parametric system)

- data driven method (or statistical hybrid method)

First principles method is based on thermodynamics and reaction kinetics and it consists of equations describing the physical properties and conditions for the formation of emission products. The parameters of the equations can be tuned to obtain a good correspondence between a set of operation data and corresponding emissions. Several advantages can be found for first principles methods /1/. During the implementation phase a substantially shorter measurement campaign is needed in comparison to data driven method. Also fewer tests are required for the calibration of the model if the model describes comprehensively the physical conditions for the formation of emissions products. Moreover, a first principles model can be used to give additional information of the process e.g. in the form of a performance monitor for gas turbines. A performance monitor can detect deviation between actual and expected efficiency, and by that identify e.g. optimal washing cycles and filter replacements /1/.

According to Swanson & Lawrence /2/, the data driven method (statistical hybrid method) has been used in more than 95% of the certified 40 CFR Part 75 PEMS. This method is characterized as being a robust model that is accurate in the full load range of the unit. The method gives valid results for normal operating conditions and during start-up and shutdown. The accuracy of the method is equivalent to a CEMS with superior reliability tied to the plant distributed control system. This method has been certified as an alternative system under U.S. regulations for CEMS, and it meets the requirements of 40 CFR Part 75, Subpart E and 40 CFR Part 60, PS-16. These systems can be assessed using quality control procedures to meet the requirements of EPA, and they can be tested against EPA reference methods.

The data driven method can be implemented after a learning and testing period of the model (e.g. neural network). A large amount of data is needed for various scenarios of the operation and the corresponding emission data obtained by actual emission measurements. This may make the implementation time consuming and rather expensive as some operations might be applicable only for certain periods of time (for instance determined by seasonal conditions) /2/.

A good understanding of the physical properties of the process is crucial for a reliable data driven PEMS, especially if the data material on operation is limited. In such cases there is a risk of developing a model that will predict emissions with serious errors when conditions are substantially different than any conditions present in the data material used for learning /2/.

4. Principles of artificial neural networks

Data driven models are typically based on the use of neural networks. A neural network consists of several interconnected neurons which mimic the operation of a biological neuron. Kalogirou /6/ describes the analogy between a biological and artificial neuron with corresponding elements as shown in Fig. 1.

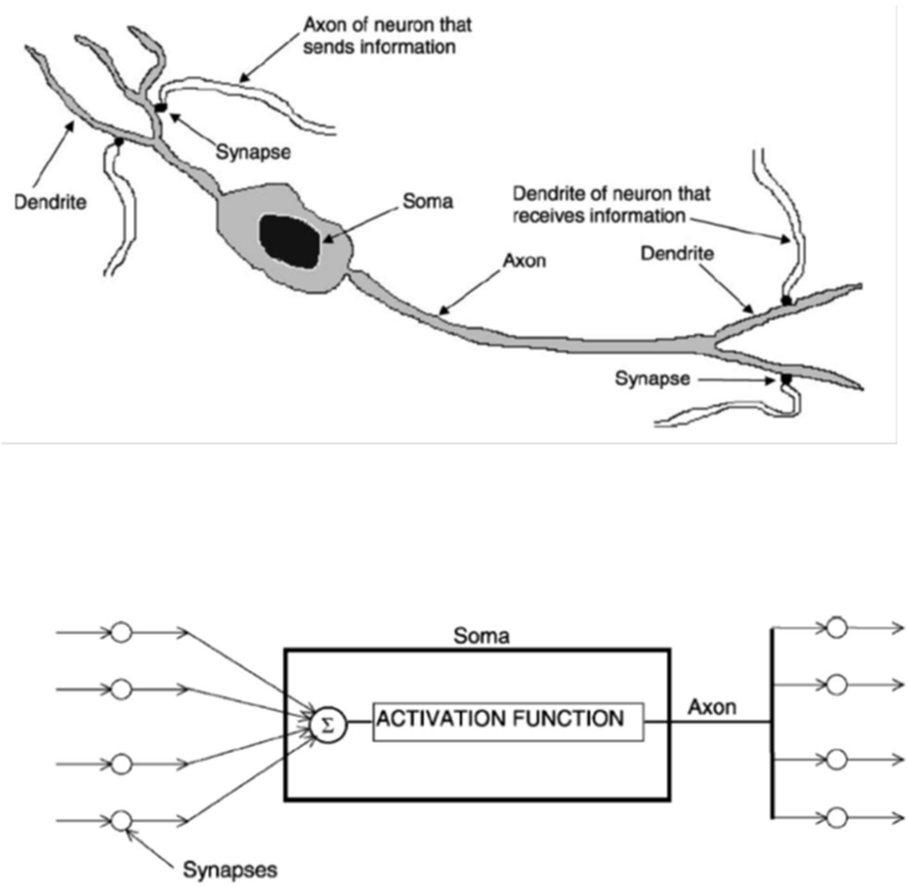

Figure 1. A simplified picture of a biological and artificial neuron /6/

As in the biological case, an artificial neuron receives signals from many other neurons and sensors, sums the information, processes it with an activation function, and transmits it to other neurons.

An example of connection of several neurons in a multi-layer feed-forward neural network is shown in Fig. 2.

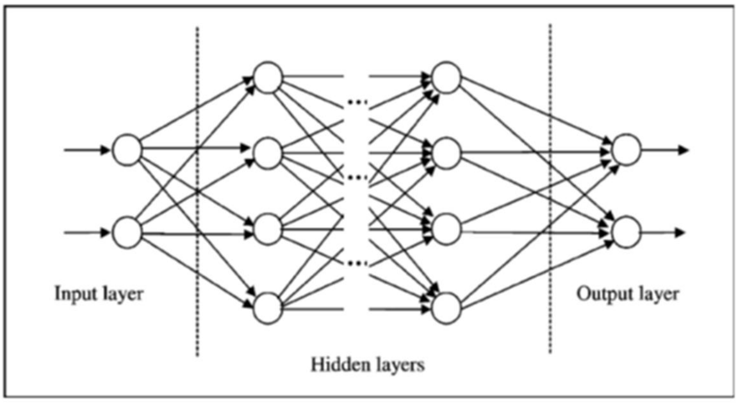

Figure 2. Layout of an artificial neural network with input layer, hidden layers and output layer /6/.

In Fig. 2 the input layer collects the signals from sensors, each signal is multiplied by a weight factor Wij, and weighed signals are summed up. The result is transformed by an activation function f and sent forward to the next layer. By using non-linear activation functions and multiple hidden layers a non-linear relationship between input variables and output variables can be created.

The process of transferring information from input to output in a single node is shown in Fig. 3.

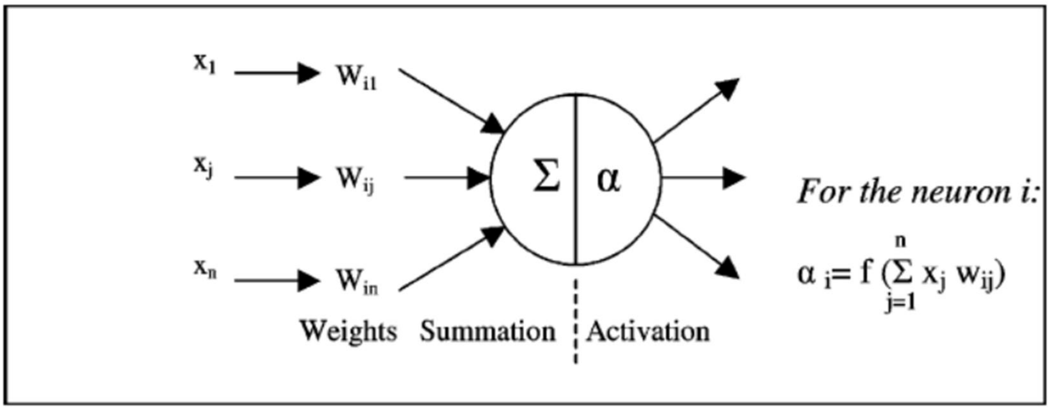

Figure 3. Processing of input information xi to output αi in a single node /6/.

The training of a neural network is accomplished by setting the weight factors Wij in such a way that for a specific set of input values the output layer gives a value close to a measured value or desired value. In emission prediction tasks the input values are process control variables and process sensor data, and the output is the predicted concentration value of a gas component at the stack.

Besides the modification of weight factors Wij, the learning may include also modifications of the structure of the network and choice of activation functions.

The optimal values of the weight factors can be found by minimizing an error function which can be expressed as follows /3/:

$$E = \frac{1}{2}\left[\sum_{p}\sum_{i}|t_{ip} - o_{ip}|^2\right]^{1/2}$$

where t denotes output of the neural network, o denotes desired output (e.g. measured gas concentration), and the summing indices i and p refer to output neuron i and to data pattern p. If in the minimization process the error function is decreased to zero, then the neural network perfectly matches the desired output and it can be used for predicting emissions from other data patterns.

It is obvious that the data patterns used in the training process must be a representative collection of input-output values obtained in different process stages. It is important that data in the calibration set are varied in a wide range in order to have a robust model also in abnormal situations /1/. These aspects raise also the question of usability of a trained neural network model if the process is somehow changed, or the portability of a model to all products of the same product series. From the quality assurance point of view it is necessary to know which process changes require a new measurement campaign and training of the PEMS. The new PEMS standard (prEN264153/WG37) will include instructions for these cases.

An example of a practical implementation of neural network PEMS is given by a patent of Pavilion Technologies Inc. /7/. This technology uses a sensor validation system, a training module for weight factor adjustments, a virtual sensor module or neural network, and connection to the control system of the process as inherent parts of the PEMS.

5. Portability of PEMS in gas engines, gas turbines and in diesel engines

Portability of PEMS means here the utilization of the same PEMS software in other similar engines or power plants. Investment costs of PEMS could, in principle, be reduced by developing such portable PEMS models.

Nielsen et al. /1/ reports on a test of a gas engine PEMS model which is based on a first principles method. The engine was refurnished with new pistons, piston rings and cylinder linings and the cylinder head was cleaned. After the changes new emission measurements were performed and the results were compared with data before engine changes. The authors state that the PEMS results for O_2 and NO_x are quite accurate and not necessarily need to be recalibrated when refurnishing an engine.

In another test, a PEMS model calibrated for one engine (M1) was used to predict emissions from another engine (M4) of the same type and age /1/. The engines were claimed to be basically identical. Surprisingly the measured NO_x level of M4 is significantly higher than NO_x level measured at M1. The authors suspected that in this case there have been some modifications in the motors or the control systems have been adjusted differently in each engine.

The authors concluded that the models need to be calibrated on the specific engine, or, alternatively, the model needs to be trained on data from both engines. The latter alternative was then tested and a new model was created by using the data from both engines M1 and M4. Now the model showed a good performance in prediction the NOx levels on both engines /1/.

Chien /3/ has studied a PEMS based on first principles method (multiple linear regression model) for a large gas turbine and its portability to other similar power plants. A PEMS developed for a CCGT unit at Hsinta power station was tested in a similar CCGT unit at Nanpu power station. The authors concluded that the form of the model could be applied to other CCGT units of the same type and size. However, because of the different ages of the CCGT units, different operation modes, and accumulated running times, the parameters of the PEMS model must be modified case by case. This requires measurements of onsite emission data for each unit by using CEMS.

Lövholm /8/ considers several aspects of utilizing PEMS in diesel and gas engines in power production and in marine applications. Concerning the portability of a PEMS from a diesel engine to other engines of exactly the same model, he has found similar data as in previous gas turbine and gas engine cases. The portability depends on the required accuracy: if high accuracy is required then the parameter adjustment or calibration must be done separately for all the engines.

6. Use of PEMS in Europe

6.1 Standardisation

Technical Committee CEN/TC264 “Air Quality” produces standards for European standardisation organisation, CEN. TC264 focuses on the standardization of methods for air quality characterization of emissions, ambient air, indoor air, gases in and from the ground and deposition, in particular measurement methods for air pollutants (for example particles, gases, odours, micro-organisms) and methods for the determination of the efficiency of gas cleaning systems. Excluded from the scope of TC264 are the determination of limit values for air pollutants, workplaces and clean rooms and radioactive substances.

Standardisation work is carried out in the Working Groups, WG. In each Working Group there are interested experts from Member countries present, the number of experts varies and it depends on the topic.

New preliminary Work Item focusing on the Predictive Emission Monitoring Systems-Execution and Quality Assurance, PEMS, was proposed by standardisation organisation of the Netherlands, NEN, year 2012 to TC264. In the scope of the standard, it was stated that the standard should give guidance and norms:

- building a PEMS
- quality assurance while building PEMS (uncertainty determination for PEMS)
- quality assurance while using PEMS (monitoring the quality of input parameters)
- application of EN 14181 and ISO 14956 for performing QAL1 uncertainty calculation when required

In the proposal, it was also mentioned that PEMS are used primarily to determine NOx emissions from combustion processes but the standard should apply to other components and other sources. NEN also wrote as a justification for the standardisation work that the use of PEMS is nowadays prohibited in many member countries since there is a lack of normative standards and that PEMS can be used in these sources where CEMS cannot be applied, like off-shore measurements, highly contaminated flue gases and harsh environmental conditions.

The proposal was accepted in the meeting in London May 2012 and a new Working Group 37 was established, secretariat and convenor (Mr Arend Smit) provided by NEN. WG37 had their first meeting in December 2012 and year 2013 they have met twice, in July and November 2013. Year 2014 WG37 has met twice, so it can be considered as an active working group.

Since WG37 is under the title “preliminary Work Item”, it does not have specified deadline when the standard should be ready. According to the rules of CEN, when the WG has the status of New Work Item, then it has 36 month time to produce a standard. So, according to very rough estimate it will take at least 4-5 years before the standard on this topic would be published.

6.2 PEMS in LCP BREF

First draft of revised LCP BREF document was published in June 2013. In this document it is proposed that PEMS could be used instead of continuous monitoring for the control of BAT-associated emission levels for NO_x and CO emissions to air from the combustion of natural gas in gas turbines (see Table 10.27) and for the control of BAT-associated emission levels for NO_x and CO emissions to air from the combustion of gaseous fuels in open-cycle gas turbine on offshore platforms (see Table 10.37). In Table 7.29 some techniques are listed to consider in the determination of BAT for NO_x and CO emissions for offshore installations, and here PEMS is mentioned as one option. It is stated, however, that the use of PEMS requires high operational experience.

This draft document /9/ can be found:

http://eippcb.jrc.ec.europa.eu/reference/BREF/LCP_D1_June_online.pdf

More than 8000 comments were received when this draft version nr 1 was sent for comments. Therefore, it is expected that final version of LCP BREF will be ready only year 2015.

6.3 PEMS in Reference Report on Monitoring (ROM)

The European Commission decided in the period 2011/2012 to develop a JRC Reference Report on Monitoring (ROM) based on the revision of the reference document on the General Principles of Monitoring (MON REF 2003). The final draft of ROM text was published in October 2013, the draft document can be found /10/:
http://eippcb.jrc.ec.europa.eu/reference/BREF/ROM_FD_102013_online.pdf

The ROM summarises e.g following topics:

- General aspect in monitoring in different environmental media
- Monitoring of emissions in different environmental media
- Concluding remarks and recommendations for future work

It is mentioned, however, in the preface of this text that: “The ROM is not a legally binding interpretation of the IED - the legally binding text is that of the Directive itself. However, the ROM can act as a reference to enhance the consistent application of the Directive by those involved. Therefore, the document aims to both inform those involved in implementing the Directive about the general aspects of emission monitoring, and also it brings together information on monitoring that may be of use in the production of BREFs and their BAT conclusions”.

PEMS is mentioned in ROM-text chapter 4.2.3.4. It is written that:

- The calibration of these systems with direct measurements is complex, because it has to be done and validated under a broad range of conditions, but the advantage is that calculated values can be determined based on the continuous process control parameters and systems operating in the control room. In any case, PEMS need to be proven, as to whether they are applicable for a certain process and
- In some industrial sectors it might be useful to apply PEMS. In the definitions of the BAT conclusions of the "Mineral Oil and Gas Refineries" (REF 2013) BREF, PEMS are already mentioned as an indirect monitoring method

6.4 Use and acceptance of PEMS

VTT sent a questionnaire to seven European countries and following questions were asked:

1. Is PEMS used in your country? If yes, for which components, what processes it is used?
2. Is PEMS approved by your authorities to be used to evaluate emissions? If yes, what kind of requirements you have for the QA of PEMS? Do you have your national guidelines for them? Are these guidelines available?
3. How do you see the future for PEMS?
4. Any other relevant comments on this topic or materials

Below are presented the answers from different countries.

6.4.1 Denmark

1. PEMS are allowed to be used on gas turbines and for NO_x. Both onshore and offshore.
2. There is a Danish guideline which is "in the hearing process" right now. It is appendix B in the Danish method implementation document MEL-16. The document can be found here: http://www.ref-lab.dk/ref-lab_docs/showdoc.asp?id=140212103726&type=doc&pdf=true
3. It is definitely the future for offshore purposes, difficult to say how about on-shore applications, maybe.
4. In Denmark, there is a small firm producing PEMS. Weel & Sandvig. Jan Sandvig from this firm is participating in WG37. More information can be found here: http://www.weel-sandvig.dk/

6.4.2 The Netherlands

1. & 3. PEMS are widely used in the Netherlands, most of the PEMS are for NOx.
2. The Netherlands has their own guideline for the use and quality assurance of PEMS data. This document is used as the background document for the Working Group 37.

6.4.3 Germany

“We had a project in Germany between VGB, TÜV Rheinland and a PEMS provider (CMC-Solutions) which was finished end of 2013. The item was to check PEMS for usability as an instrument for surveying industrial plants (gas turbines, Power Plant) instead of the traditional CEMS and to find a way for suitability test according EN 15267 or to establish an additional way for suitability testing. The result of the project was not so positive as I expected from some results about PEMS used USA. But from my view, there is also a heavy influence of weather conditions (dry weather, rain, temperature, air pressure) additional to the different working conditions of the plants”.

1. No, PEMS is not used in Germany as a regular surveying system.

2. PEMS is not approved by the authorities in Germany.

3. From my opinion in the near future it will not be approved due to the result of the project described above. There is a lot of work to use PEMS in these very difficult plant working conditions in Germanys Power plants and gasturbines (many plant start-stops the day, different fuel conditions, many parameters have influence on the emissions)

4. I think there is not enough work from power plant owners, to know their processes in detail and to find the relevant factors/parameters which control the emissions. PEMS only work when you find the right parameters as input and if you have enough time to learn the system all these working conditions of the plant you want to survey.

   These were the problems we find during the project with PEMS. However, there can be possibilities to use PEMS provided that all partners, especially the power plant owners want to solve the problems with finding the right parameters and to learn the PEMS all working condition of the plant and weather conditions like temperature and moisture in the ambient air.

6.4.4 Italy

1. & 3. In Italy PEMS is not widely used and most probably it will not be used in the future either (situation like in Germany…). It is relatively easy to record all the necessary parameters for processes but how to take into account e.g if there are failures in the abatement system (this is not an issue for NOx).

2. PEMS can be used for indicative measurements but not for legal measurements

6.4.5 France

1. Some PEMS have been used by TOTAL and EDF on combustion facilities (Oil and gas) but they seem to have stopped the experimentation.

2. These PEMS are not well considered by the Ministry of Environment for PEMS. However, AFNOR has made a transposition of EN 14181 in order to be sure that these PEMS will provide data with an acceptable level of quality : see NF XPX 43-420. PEMS can be used only for emission measurement from combustion process and for NO and CO

3. The Ministry of the Environment in France is not in favour of these types of monitoring process.

6.4.6 Sweden

Most probably only PEMS projects in Sweden are reported at www.varmeforsk.se. (see “Rapportdatabas” , sök “PEMS). Most of the reports are relatively old.

6.4.7 UK

1. Yes, PEMS are used in England but their use is limited to compressor-turbines on the national gas distribution system. They are used for NO_x emissions.

2. We permit their use if the operator can demonstrate that the PEMS produce valid results. We apply the USEPA guidelines unofficially. The US experience shows that PEMS are very effective for NOx measurements from gas turbines, but they are not necessarily less expensive overall because of the validation work that is needed.

3. Our position is that an operator can use them in cases where AMS are difficult to use and where PEMS provide valid results. They also have the potential to be used as back-up systems when an AMS is not working.

4. Work on a European standard for PEMS is progressing well. I estimate that a final draft for comment should be available in about 12 months time.

7. Summary

At the moment, the use and acceptance of PEMS seems to vary a lot in Europe. The Netherlands, Denmark and UK accept the use of PEMS and on the other hand, for example Germany, Italy and France seem to have the opinion that PEMS are not maybe the most cost-efficient systems for the monitoring of emissions and that they are not confident with the quality of the results given by PEMS.

So, PEMS need to still be proven that they are applicable for a certain process. The work that is carried out in CEN/TC264/WG37 to standardise the quality assurance of PEMS will support this.

Some countries (The Netherlands, Denmark, France) have written their own guidelines for PEMS. These documents describe how to apply standard EN 14181 “Quality Assurance for Automated Measuring Systems” for PEMS, in all levels (certification, QAL1, QAL2, QAL3 and AST).

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