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Indirect NO_x emission monitoring in natural gas fired boilers

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ABSTRACT

New emission regulations will increase the need for inexpensive NO_x emission monitoring solutions also in smaller power plants. The objective in this study is to find easily maintainable and transparent but still valid models to predict NO_x emissions in natural gas fired hot water boilers utilizing existing process instrumentation. With a focus on long-term applicability in practical installations, the performance of linear regression is compared in two municipal 43 MW boilers with three widely used nonlinear methods: multilayer perceptron, support vector regression, and fuzzy inference system. The linear models were the most applicable providing the best estimation results (relative error of <3% in all cases), generalizability and simplicity. Therefore, the approach fulfils the requirements of the Industrial Emission Directive and is valid to be applied as a soft sensor in PEMS[1] applications in practise. However, each boiler model should be identified individually.

1. Introduction

There is an increasing demand to protect the environment from harmful emissions. One of the main sources of air pollution are combustion processes, which emit sulphur dioxide (SO_2), particulate matter, carbon monoxide (CO) and dioxide (CO_2), unburned hydrocarbons (C_xH_Y), and nitrogen oxides (NO_x). NO_x emissions are considered as primary pollutants, since they can cause health issues in addition to environmental problems, e.g. photochemical smog, acid rain, tropospheric ozone and ozone layer depletion (Skalska, Miller, & Ledakowicz, 2010).

As energy production is a major source of emissions, authorities have set further tightening emission limits to power plants. In the European Union (EU), flue gas emissions, i.e. SO_2, NO_x and dust, are restricted by the Industrial Emission Directive (IED, 2010), which came into effect in 2016. It is applicable in all existing power plants exceeding 50 MW. Additionally, the combination of plants where flue gases from multiple individual plants with rated thermal input over 15 MW could be discharged through a common stack are considered as a single combustion plant and their capacities are combined when calculating the total thermal input. This aggregation rule extended the scope of the IED to combustion plants with rated thermal power between 15 and 50 MW. Especially in Nordic countries, these <50 MW boilers typically have low operation hours. They are typically remotely operated and built for peak load and reserve capacity generation in district heating networks. Their role, however, might change in the future, as district heating networks and their components become more intensively interlinked with renewable energy generation systems.

According to the IED, the concentrations of SO_2, NO_x and dust in flue gases must be measured continuously in all combustion plants exceeding total thermal capacity of 100 MW. Otherwise these emissions (and, CO for gas fired plants) must be measured periodically at least once every 6 months. However, the IED provides an alternative to discontinuous SO_2 and NO_x measurements through other procedures if they are verified and approved by a competent authority. Such procedures must rely on CEN or other international standards, which ensure the provision of data of scientific quality.

There are three options to monitor flue gas NO_x emissions from a combustion unit, i.e. by periodic measurements, CEMS (Continuous Emission Monitoring System) or PEMS (Predictive Emission Monitoring System). Periodic measurements are typically performed with calibrated equipment and conducted by an emission-testing laboratory with moderate costs. However, it is not guaranteed that the emission levels are valid in actual operation between the campaigns. As illustrated e.g. by Korpela, Kaivosoja, Majanne, Laakkonen, Nurmoranta, and Vilkko (2016), heat only boilers may increasingly be operated with fast power transients to stabilize the district heating networks when nearby combined heat and power (CHP) plants contribute to balancing of the

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[1] Predictive Emission Monitoring System.

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electric power system. In these cases, the periodic measurements are not able to determine the actual NO_x emissions (although this is not yet required in IED). In CEMS, the emission monitoring equipment is installed on-site and is active during plant operation. CEMS provides online and actual information on emissions, when maintenance and calibrations are conducted according to standard procedures. However, purchase and maintenance costs of CEMS are relatively high, especially compared to their benefits in boilers that have low power outputs and few operation hours. PEMS combines the positive properties of the former methods, as PEMS is a software based monitoring system, which utilizes existing process measurements and calculation models to estimate power plant emissions. There is no accepted CEN standard for PEMS at present but preparation is under way by CEN/TC 264/WG 37.

Indirect measurements, such as those calculated in PEMS, require a model to be driven with the online measurements. The model can be based on first principles and the physical properties of the boiler, measurement data correlations, or the combination of them. Derivation of an accurate first principle model for NO_x emissions is a complex task due to several factors, for example, complex nitrogen reactions. Hence, data based models are dominating in NO_x emission estimation. The purpose of NO_x emission estimation is primarily to study and predict the emissions in different operating conditions from process perspective, to derive indirect NO_x emission monitoring solutions to provide analytical redundancy to online measurements, or to estimate the emissions when no NO_x measurement is available. Numerous data based NO_x emission models have been presented in literature for various combustion applications (e.g. pulverized coal boilers, fluidized bed boilers, grate boilers, gas boilers, gas turbines, engines) in various power ranges and fuels (e.g. coal, biomass, waste, oil, and gas). These aspects significantly affect NO_x emissions and therefore also NO_x emission estimation. These NO_x models typically utilize existing process measurements. The amount, quality and type, and the maintenance procedures of the measurements that can be utilized in NO_x estimation applications are dependent directly or via environmental permits on the power rating of the plant, its location and the operation purpose (e.g. hot water or steam only, power generation). Therefore, the variety of applied modelling methods in data based NO_x estimation is vast, covering linear multivariate regression and nonlinear multivariate methods, such as radial basis function (RBF), multilayer perceptron (MLP), partial least squares (PLS), least squares support vector machine (LSSVM), Fuzzy Inference Systems (FIS), Kohonen's self-organizing maps (SOM), and so on. The NO_x models are mainly static, but dynamic models also exist when the dynamics have a significant role in NO_x formation.

Data based models are, in general, only valid in the operating conditions which exist in the identification data used in their training. Therefore, the collection of the training data should be carefully considered. The data for model derivation can be generated by measuring normal operation of the combustion plant, by conducting separate trial runs to stimulate the processes, or by simulating the process with some other models. The first approach typically requires input data collection over a long period; however, the data may then not cover all potential operating conditions. Separate trial runs may improve this situation significantly, but the amount of data collected with this approach is usually much smaller than in the case of online process data collection. In the third approach, the input data to the models may be derived from complex combustion models, e.g. Computational Fluid Dynamic (CFD) models, but this approach is hardly a general solution in PEMS applications. In this study, separate and comprehensive trial runs were conducted to enable a reliable identification of the models. The models were validated by data collected from normal process operation but with increased excitement of the processes by frequent set point changes. This allows the performance of the models to be evaluated in realistic conditions, which is a prerequisite for the presented approach.

In summary, there are numerous approaches and NO_x models for different kinds of combustor applications. Selection of suitable NO_x modelling methods is case specific taking into account all relevant aspects determining the appropriate modelling approach for the task. This paper focuses on indirect NO_x emission estimation in natural gas (NG) fired boilers. The applicable literature on the topic is reviewed next. In Iliyas, Elshafei, Habib, and Adeniran (2013), a three-dimensional (3D) CFD model for a 160 MW gas boiler was developed to produce data for computational NO_x and O_2 sensors. The system utilized 6–8 input variables and RBF and MLP neural networks, of which the RBF model with six input variables performed best (Ferretti & Piroddi, 2001) utilized a 3D CFD model and developed a neural network-based strategy utilizing two different learning strategies to NO_x emission estimation for an oil and methane fired 320 MW thermal power plant. Eng-genes and MLP neural networks were applied to the same power plant by Li, Peng, Irwin, Piroddi, and Spinelli (2005), utilizing Arrhenius type equations in a semi-empirical model. The last two papers utilized cell temperatures derived with the CFD model as model inputs, which are usually not available in real systems (Li et al., 2005). Another semi-empirical model was presented in Bebar, Kermes, Stehlik, Canek, and Oral (2002), where simplified kinetic equations utilizing six input variables describing the formation of nitrogen oxides were developed for a testing facility. There, the average estimation error was 9.1%, with the maximum of 25%. In another study, a NO_x soft sensor for NG fired water tube boiler was developed by Shakil, Elshafei, Habib, and Maleki (2009). This model utilized static and dynamic neural networks. A principal component analysis (PCA) was used to reduce model inputs from 9 to 6, and genetic algorithms were used to identify the system's time delays. The estimation accuracies of 83% and 99% were obtained with static and dynamic models, respectively. In another case, application of linear models was studied with full or limited operation regions (Korpela, Kumpulainen, Majanne, & Häyrinen, 2015) and linear and non-linear models were compared (Kumpulainen, Korpela, Majanne, & Häyrinen, 2015) in natural gas fired 43 MW hot water boilers.

Though linear models were considered in the last two articles, the literature on prediction of NO_x emission in NG combustion is focused on nonlinear and multiple input variable models. These models can provide quite accurate NO_x predictions but are arguably not generally applicable nor inexpensive solutions to PEMS applications. As this paper is a significant extension to the last two articles, there are no other published NO_x models meeting the objectives of this paper. The objective of this study is to evaluate the accuracy, generalizability and long-term applicability of indirect NO_x estimates in existing NG fired boilers, in order to apply the methods in practise in a cost effective way. For the study, trial runs were conducted with two similar 43 MW NG fired hot water boilers. The studied boilers are structurally relatively simple with a single burner with fixed air distribution simplifying the modelling task. The goal is to find maintainable and transparent but still valid models for NO_x estimation and to evaluate the performance in varying operating conditions. Requiring easy maintainability and transparency promotes the application of simple models, e.g. linear regression models, which require tuning only a few parameters. As the performance drop cannot be too significant, the simple models have to be compared with models that are more complex in order to estimate the differences in performance. Hence, the linear multivariate regression models are compared with commonly used nonlinear models, which are identified with automatic procedure without any manual fine-tuning. Additionally, the number of input variables and selection of data sets are examined together with model sensitivity analysis.

2. NO_x formation, control and identification

The abbreviation NO_x refers to nitrogen monoxide (NO) and nitrogen dioxide (NO_2), which are present in the flue gas because of chemical reactions of nitrogen and oxygen. Approximatively 95% of the NO_x emitted from combustion processes consists of NO and c. 5% of NO_2. As the majority of NO reacts to NO_2 in the atmosphere, the environmental effects are practically the same for both of the NO_x components (Van Loo & Koppejan, 2008), and hence the emission limits for NO_x are typically set for NO_2, e.g. in IED.