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Modeling NO_x emissions from coal-fired utility boilers using support vector regression with ant colony optimization

Hao Zhou [a,*], Jia Pei Zhao [a], Li Gang Zheng [a,b], Chun Lin Wang [a], Ke Fa Cen [a]

[a] State Key Laboratory of Clean Energy Utilization, Institute for Thermal Power Engineering, Zhejiang University, Hangzhou 310027, China
[b] School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China

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ABSTRACT

Modeling NO_x emissions from coal fired utility boiler is critical to develop a predictive emissions monitoring system (PEMS) and to implement combustion optimization software package for low NO_x combustion. This paper presents an efficient NO_x emissions model based on support vector regression (SVR), and compares its performance with traditional modeling techniques, i.e., back propagation (BPNN) and generalized regression (GRNN) neural networks. A large number of NO_x emissions data from an actual power plant, was employed to train and validate the SVR model as well as two neural networks models. Moreover, an ant colony optimization (ACO) based technique was proposed to select the generalization parameter C and Gaussian kernel parameter γ. The focus is on the predictive accuracy and time response characteristics of the SVR model. Results show that ACO optimization algorithm can automatically obtain the optimal parameters, C and γ, of the SVR model with very high predictive accuracy. The predicted NO_x emissions from the SVR model, by comparing with the BPNN model, were in good agreement with those measured, and were comparable to those estimated from the GRNN model. Time response of establishing the optimum SVR model was in scale of minutes, which is suitable for on-line and real-time modeling NO_x emissions from coal-fired utility boilers.

1. Introduction

Nitric oxide (NO) and nitrogen dioxide (NO_2) are collectively known as NO_x, they have a number of negative effects on air quality: they contribute to photochemical smog, visibility reduction, acid rain and also have a negative impact on human health (Muzio and Quartucy, 1997). Coal is the most popular fuel used in power plants due to its low cost and availability. However, the emission of the nitrogen oxides during coal combustion is a significant pollutant source in the environment (Hill and Smoot, 2000).

The main driver for investigations into modeling NO_x emissions from coal fired utility boilers is two-fold. On the one hand, with the increasing demand for electricity especially in developing countries, many power plants would need to be built. To satisfy the strict environmental regulation, these power plants are faced with one of the most critical issues for regulations conformity concerning the availability of suitable measurements to monitor the NO_x emissions (Tronci et al., 2002). Commonly, continuous emission monitoring systems (CEMSs) are used to measure the emissions. Though this hardware-based CEMS is capable of measuring stack gases with high credibility, they are still relatively expensive to purchase, install and maintain. Besides, due to the harsh environment the analyzer is frequently off-line for maintenance and some redundancy to improve system reliability is also highly desirable. A potentially attractive alternative to installing a CEMS is the use of a PEMS, which estimates the NO_x emissions on the basis of their dependence on other relevant system variables using suitable algorithms. That means stack gases from the combustion chamber are possible to be predicted indirectly. At present, the majority of industrial facilities are equipped with distributed control systems (DCSs), which supply a great deal of information on what is happening in the plant (Copado and Rodriguez, 2002). Once a suitable model between the NO_x emissions and the various process parameters of the boiler is determined, information downloaded from DCS can be used to infer the emissions at the stack. PEMS offers a number of advantages over expensive CEMS such as in parallel with hardware sensors (Yang et al., 2000), easily implemented on existing hardware (Graziani et al., 2004), real time estimation of NO_x emissions (Matsumura et al., 1998), the advantages of lower cost, lower maintenance and higher reliability than more traditional hardware CEMS (Baines, 1999; Tronci et al., 2002). PEMS has been successfully applied to many different combustion processes including boilers, furnaces and turbines (Kamas and Keeler, 1995).

On the other hand, combustion optimization (Radl, 2000; Zhou et al., 2005) has been proved to be an effective way to realize low NO_x combustion in coal fired utility boilers, in which low NO_x

* Corresponding author. Tel.: +86 571 87952598; fax: +86 571 87951616.
E-mail address: zhouhao@cmee.zju.edu.cn (H. Zhou).

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emission is achieved by carefully setting operational parameter of the boiler using artificial intelligence such as neural network, expert system, fuzzy logic and genetic algorithms. Core of the combustion optimization system will be a NO_x emissions model of the boiler incorporated in the software. In other words, the relation between the NO_x emission and various operational parameters such as coal quality, load, primary and secondary air velocity, speed of mills and others must be well known. Therefore, in order to reduce NO_x emissions, a model predicting NO_x emissions from various parameters of the boiler must be established at first. This model can be derived from the physical processes in the boiler. However, consisting of many combustion dynamics, fluid mechanics, heat transfer and nitrogen conversion chemistry, the overall dynamics of the boiler shows the strong non-linear inter-relations and the mutual dependence of various variables; building such an accuracy model for NO_x emissions is not a trivial task and sometimes impossible.

Because of the complexity of NO_x emissions modeling, neural network models represent a valid alternative to this issue in the last ten years. Multi-Layer Perceptron (MLP) models were used to develop PEMS (Baines, 1999; Graziani et al., 2004), software sensors (Dong et al., 1995; Matsumura et al., 1998; Tronci et al., 2002) and have been successfully applied to industry (Kamas and Keeler, 1995). The operation experience showed that PEMS predications closely match measured CEMS results with the predicted NO_x values typically within 20% of the actual data as measured by hardware CEMS (Kamas and Keeler, 1995). Fuzzy neural network was proposed to model NO_x emissions (Ikonen et al., 2000). Liu and Huang (1998) proposed a fuzzy logic model to generate a reliable emissions model and dealt with environmental and economic dispatching when only limited experimental data was available. Various neural networks were also developed for the modeling and control of the nitrogen oxide emissions from coal-fired boilers (Reinschmidt and Ling, 1994; David and Samuelsen, 1995; Chan and Huang, 2003). A BPNN-based NO_x emissions model was incorporated in several combustion optimization software packages and showed good operation experiences (Radl, 2000; Booth and Roland, 1998; Jia, 2007). A time delay ANN model was designed for the dynamic prediction of nitrogen oxides and carbon monoxide emissions from a fossil fuel power plant (Adali et al., 1999). Neural network-based black box model and a genetic algorithm-based gray-box model were employed to predict the NO_x emissions in a 500 MWe coal-fired power plant (Li et al., 2003). A neural network model consisting of 41 input parameters of the boiler, 6–10 neurons in the hidden layer and 1 output neuron was developed to model the NO_x emissions and other performances of a 540 MW capacity generator (Frenken et al., 1996). A cascading neural network was used to model the NO_x emissions in a dual fired drum type boiler with full load 300 MWe with oil firing or 200 MWe with coal firing (Dong et al., 1995). Later, a genetic algorithm-based neural network was developed for the identical power plant (Li et al., 2002). Estimation of NO_x emissions in thermal power plants using a combination of neural network and computational fluid dynamics (CFD) was also performed by Ferretti and Piroddi (2001). NO_x emissions from a combined-cycle natural gas power plant have been investigated using artificial neural networks (Azid et al., 2000), and the deviation of the predicted NO_x emissions is less than 5% of the measured values by the CEMS system. A MLP was presented to model the gaseous emissions emanating from the combustion of coal on a chain-grate stoker-fired boiler (Chong et al., 2001). Zhou et al. (2001, 2004) have proposed an approach to predict the nitrogen oxides (NO_x) emissions characteristics of a large capacity pulverized coal fired boiler with artificial neural networks (ANNs). In summary, various variants of artificial neural networks for NO_x emissions modeling have attracted much attention in last ten years, as reviewed by Kalogirou (2003).

Despite neural networks (NNs) having been used widely in modeling NO_x emissions from coal fired utility boiler, the neural network suffers from a number of weaknesses (Vong et al., 2006), which include the need for numerous controlling parameters such as the number of hidden neurons and the learning rate, difficulty in obtaining a stable solution and the danger of over-fitting. Moreover, the selection of network architecture is still problematic and time consuming task when developing a model for practical situation (Niska et al., 2004; Benardos and Vosniakos, 2007). Some improvements to basic neural network have attracted much attention of many researchers. A parallel genetic algorithm (GA) is proposed to selecting the inputs and designing the high-level architecture of a multi-layer perceptron model (Niska et al., 2004; Benardos and Vosniakos, 2007). The results show that the GA is a capable tool for tackling the practical problems of neural network design. However, the process remains to be computationally expensive and time demanding (Niska et al., 2004).

In recent years, SVR has been successful in mapping the complex and highly nonlinear relationship between system input and output, such as the daily meteorological pollution prediction (Osowski and Garanty, 2007), automatic signature recognition (Frias-Martinez et al., 2006), bearing fault detection (Samanta et al., 2003). It would appear that it also learns the relationship between the NO_x emissions and the boiler operational conditions.

Compared with the MLP (for BPNN instance) models, the SVR model has certain advantages. Firstly, training for the SVR results in a global minimum (Frias-Martinez et al., 2006). On the other hand, the training of BPNN may become trapped at a local minimum (Vong et al., 2006). The second advantage is that the model parameters of SVR are fewer than those of BPNN. With the Gaussian kernel function, there are only two design parameters that need to be tuned, i.e. the generalization parameter C and the width parameter γ in the kernel function. The third advantage is that it is relatively easier to achieve good generalization because structural risk minimization principle is applied by minimizing an upper bound on the expected risk whereas the traditional empirical risk minimization is used in BPNN minimizing the error on the training data (Frias-Martinez et al., 2006).

Nevertheless, to the authors' knowledge, SVR has never been applied to model NO_x emissions from coal fired utility boiler in the references. It is meaningful to investigate the applicability of SVR for NO_x emissions modeling, which will be favorable to develop the on-line and real-time NO_x emissions monitoring system and combustion optimization software package. This study will extend the use of SVR in NO_x emissions modeling in two ways: (1) unlike former studies that implemented NN model on very small samples (Zhou et al., 2001, 2004), this study applied SVR in more realistic conditions characteristic of an actual power plant. Indeed, once NO_x emissions model has been built, it must be able to accurately validate a new dataset, which contains in practice a large number of cases. This study contributes to the existing literature using a sufficient sample size for training and validating the SVR models in a NO_x emissions framework. (2) Before the SVR can be implemented, two parameters, i.e., the generalization parameters C and Gaussian kernel parameter γ, have to be optimized in order to construct an efficient prediction model. Extracting the optimal parameters is crucial when implementing SVR. Consequently, an ACO-based technique was proposed to perform the selection procedure. ACO has been applied to optimize the weights and bias of BPNN by several researchers (Liu et al., 2007; Socha and Blum, 2007). Theoretically, ACO can also be suitable for the selection of SVR model parameters. The technique is also compared to commonly used grid search method (Hsu et al., 2003).

The paper is organized as follows. Section 2 presents an introduction of SVR model fundamentals and the model parameters