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Comparative study of regression modeling methods for online coal calorific value prediction from flame radiation features

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HIGHLIGHTS

- Models for coal calorific value prediction from flame radiation were established.
- Comparison of linear and nonlinear regression models was made.
- Statistical approaches could not improve the performance of the linear model.
- Statistical approaches could effectively improve the performance of the nonlinear model.
- The PLSA-based SVR model shows the best performance with fewer feature components.

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ABSTRACT

In this paper, multiple regression methods are presented and compared for online coal calorific value prediction from multi-spectral flame radiation features. Several statistical approaches including principle component analysis (PCA), independent component analysis (ICA) and partial least squares analysis (PLSA) were used in linear and nonlinear regression analyses. Analyzing results show that nonlinear regression model can better approximate the relationship between the coal calorific value and the flame radiation features than linear regression model. In linear regression analysis, the performance of the linear coal calorific value prediction models was not improved by involving the statistical approaches. In nonlinear regression analysis, however, the performance of the prediction models was significantly improved when combined with the statistical approaches. The variation of coefficients of multiple regression showed that only the PLSA-based nonlinear regression model can discriminate useful feature components from useless feature components. The PLSA-based nonlinear regression model showed the best performance for coal calorific value prediction with the number of features reduced to about a third of that in the other models. With the PLSA-based nonlinear regression model, online coal calorific value prediction from the multi-band flame radiation features under the operating conditions used by the industrial boiler has the mean absolute error, standard deviation of the absolute errors, mean relative error and standard deviation of the relative errors of 148.76 kJ/kg, 291.86 kJ/kg, 0.76% and 1.53%, respectively.

1. Introduction

For centuries, study of combustion process has attracted extensive attentions of related researchers. Reported researches are mostly numerical simulation studies supplemented by experimental verification [1]. For large scale industrial boilers, the research works are more challenging for the harsh application environments.

Combustion process involves fuel/air chemistry reactions and complicated heat and mass transfers. Simulation of combustion inside a combustor needs to specify boundary parameters including fuel compositions, pressure and temperature, etc., and more importantly, special measurement technologies are needed to validate the simulation results. Although some energy-intrusive techniques, such as tunable diode laser absorption spectroscopy [2,3], laser induced breakdown spectroscopy [4] and X-ray fluorescence analysis [5], have been used to measure some interested parameters including temperature, gas concentration, etc., from attenuation or spectral variation of the penetrated rays in engine design,

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the techniques have limited applications in design and monitoring of large scale industrial boilers due to complicated industrial environments.

Industries involving coal fired energy conversion utilities are facing problems of low efficiency and tightened emission limitations. Industrial boilers are required to use fuels of designed ranges to keep high efficiency [6–8]. However, standard coal supply could not be assured because of the complexity of raw coal resources. Usually, coal mining has regional features, and coal resources at different layers under earth often have different ranks. The flame generated with one type of fuel will not be duplicated with another. Coal fired industries often have to use sub-quality or blended coals, and are often under off-design conditions, causing efficiency degrade and excess pollutant emissions [9].

On the other hand, lack of adequate auto-adjustment strategy is another factor that hinders the performance of modern industrial boiler system. As mentioned, it is hard to get knowledge of instant combustion conditions even on pilot rigs. There are scarcely in-situ approaches to directly get detailed knowledge of the combustion inside a boiler, from which automated control could be implemented to optimize the utility operations. In industrial applications, steam pressure, temperature and other parameters that can be conveniently obtained are normally used in the control of energy conversion process [10]. In routine procedure of utility operation adjustment, steam pressure is translated into the heat content of the fuel feed, which is used for the regulation of coal/air ratios. However, the signals like steam pressure are post-stage parameter of the coal/air combustion, and greatly lagged in phase than what happened in the boiler. This greatly inhibits the efficiency of modern boiler control systems. As a result, coal fired power generation plants suffer from economic loss and excess pollutant emissions.

Due to technique obstacles in industrial boilers, a lot of researches are trying to exploit in-situ methods to improve the energy conversion efficiency. Related literatures mostly adopt passive methods, which are safe and practical for industrial applications. In such technologies, combustion parameters are obtained from spectral analysis of optical radiation. Optical radiation carries rich information about combustion status and fuel properties [11]. Combined with artificial intelligence methods, some parameters on combustion conditions such as the fuel/air ratio, SO_x and NO_x emissions etc. can be evaluated [12,13]. 3D visualization of the flame profiles is also implemented by using several CCDs [14]. Some industry-oriented researches are also trying to accomplish in-situ measurement of combustion process parameters by using energy-intrusive technologies [15]. Related technologies can analyze flue gas in an online manner by using laser absorption detection sensors that are usually arranged in exhaust duct or near the exit of the boiler. Concentration of OH, CO, NHx and other gas components are measured, which is helpful to get knowledge of the combustion process and make optimization decisions to reduce pollutant emissions. Commercial products using laser technologies for in-situ applications also begin to appear in recent years. However, there is no consensus about the cost-benefit of in-situ flue gas analyzers using laser techniques. Flue gas analyzers have not been widely used in industrial applications.

Boiler performance is closely related with coal qualities [16,17]. In literatures, tracing of coal qualities used in coal fired power stations are studied through proximate or ultimate analyses using technologies of secondary ion mass spectrometry (SIMS), ion chromatography-inductively coupled plasma mass spectrometry (IC-ICPMS), X-ray power diffraction (XRD), etc. Through sampling and analysis of feed coal, fly and bottom ash of the boilers, concentrations of major and trace elements, especially toxic elements, as well as the modes of occurrence of trace elements can be obtained. Furthermore, the relationship between the content of trace elements and the ash yields is studied, from which the environmental impact of fly and bottom ash disposals from coal fired power stations could be accessed [18–20]. However, coal qualities are seldom measured for online boiler efficiency improvement. In the literature, some researches realized coal calorific value prediction using artificial intelligence techniques from ultimate or proximate analyzing data of coal samples [21,22]. Such researches need sampling of feed coal and analysis using SIMS, IC-ICPMS and XRD, etc. to get data for the prediction. However the method is off-line and long time is needed to get the result. In earlier publications of the research group of the authors, online fuel type identification and preliminary research on coal calorific value prediction have been reported [23–25]. Challenges of techniques for in-situ applications include tolerance of harsh environment in industrial boilers, fast sampling and interpretation of data. Operability, reliability, economic costs of installation and maintenance are necessarily considered and the cost-efficiency ratio should be low enough.

Fuel/air combustion inside a boiler can be characterized by flame radiation features that directly reflect fuel properties. Mass contents generated in coal combustion comprise hot soot, molecules, radicals, ash, atoms, etc., and flame radiation is the summation of optical radiations of all the components. Different ranks of coal will generate contents with different mass concentrations and different radiation spectra [26,27]. Given adequate interpretation scheme, important indexes of coal properties could be obtained from the radiation features. In this paper, multiple regression analysis-based methods for coal calorific value prediction are presented and compared. The measurement system used photoelectrical sensors to detect flame radiation of coal-fired boiler in visible, ultra violet and infrared bands. In system preparation stage, data base containing calorific values of coal samples and synchronous recordings of flame radiation signals was established, and used in regression analysis for linear and nonlinear modeling on the relationship between coal calorific value and flame radiation features. From the raw multi-band radiation signals, raw features were extracted. Linear and nonlinear regression analyses for coal calorific value prediction from monitoring of multi-band flame radiation signals were made based on the least squares method and support vector regression (SVR), and the performance of all linear and nonlinear regression models established were compared in this paper. Combined with statistic approaches including principle component analysis (PCA), independent component analysis (ICA) and partial least squares analysis (PLSA), correlations among raw features were eliminated and new components with different statistical properties were generated. Through comparison of the coefficients of multiple regression of the models, and the prediction accuracies of coal calorific value using different models, the best fitted model for coal calorific value prediction from the flame radiation features was obtained. Based on the best fitted regression model, online prediction of coal calorific value could be realized with low cost measurement system at high accuracy. As well known, fuel type is one of the important factors for boiler design, the knowledge of fuel properties could help operators to get insight into the combustion process and regulate fuel and air rates more accurately. Meanwhile, online measurement of calorific value of burning coal could supply verification for coal fired boiler designs.

2. Methodology

2.1. Experiment system

The experiment system used photoelectric sensors to detect flame radiation in visible, infrared and ultra violet bands. Hamamatsu Co. Ltd. produces various photo-electrical sensors. From the list of products commercially provided by Hamamatsu we selected