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On-line flame signal time series analysis for oil-fired burner optimization

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ABSTRACT

Flame monitoring and characterization have been recognized as an important aspect for burner combustion tuning. Flame flickering and its electromagnetic flame spectrum have been extensively demonstrated to provide characteristic information of flames in the combustion processes. This information can be used for combustion and emissions optimization and control. A system based on flame characterization would comprise of an on-line monitoring instrumentation, a time series processing algorithm and a control scheme. This paper reports the development of a smart software for flame data processing, to provide flame indexing and infer combustion stoichiometry under a range of combustion conditions. The software processes standard flame scanner data in the time and frequency domain, and employs standard statistical measures, shape factor, information entropy analysis and plant data for flame classification. Artificial probabilistic neural networks algorithms were used for clustering the flame spectral data. Probabilistic neural network is a supervised learning algorithm but includes no weights in its hidden layer. It is often an excellent pattern classifier that outperforms other classifiers, including back-propagation. Data from the scanner flame monitoring system, the plant data acquisition system and the stack emissions monitoring system are processed with proprietary algorithms to provide burner flame classification. Additionally, an expert system utilizes the flame classification information and interfaces with the plant operators for open-loop control of the burners and to achieve optimal scheduling of burner maintenance. The software was deployed at the Mexican Commission of Electricity's CTPALM Unit 1. This unit consists of a multi-burner unit that fires Bunker C oil. The results demonstrated the benefits of the software.

1. Introduction

Flame scanners are important instruments that are used in fossil fuel-fired utility boilers for the operation of burners and combustion systems. Most of large utility boilers are equipped with a firing system arrangement that includes a series of burners located at different elevations in the furnace. Flame scanners are traditionally used on each burner to monitor flame stability and the flame/no-flame condition. The data provides important input to the burner management system for the safe operation of the firing system. In the case of unexpected flame instability or blow-off from a particular burner, the flame scanner provides a signal to the burner management system to initiate a sequence involving fuel shut-off and a purging cycle, to prevent a particular burner or group of burners from operating unsafely.

As can be observed by the human eye, most combustion flames pulsate randomly in addition to emitting steady radiation. The pulsing characteristic or flicker frequency of a flame reflects its radiation oscillation and pressure. It can provide other characteristics related to the flame structure (like instability), energy efficiency and the formation of harmful pollutant emissions, such as particulate matter (or total suspended particulates, TSP) and nitrogen oxide (NOx). It is therefore important to monitor and measure the flicker of a flame in order to achieve a good understanding of the combustion conditions of a particular burner and its contribution to the overall fuel efficiency and stack emissions of the boiler. Additionally, this information could be used to provide an insight into the condition of burner maintenance process. Other combustion process measurements are also available for flame condition

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monitoring. For an oil-fired boiler, these measurements include the amount of combustion excess air measured at the furnace (or boiler outlet), fuel flow, fuel temperature, oil and atomization steam pressure, and other pertinent parameters, such as flue gas carbon monoxide (CO) concentration and particulate matter loading level. Typically, boiler operators use these process measurements to approximate and indirectly indicate combustion conditions and the level of burner nozzle cleanliness. However, these global parameters do not provide information for individual burners, nor provide timely information for combustion-related problems, such as the onset of burner coking. This prevents plant operations and plant maintenance personnel from being proactive in improving the operation and maintenance conditions of the burners.

Combustion is a non-linear dynamic multivariable process that has short time predictability. Therefore, is very difficult to model using conventional deterministic methods. Different approaches have been used to link optical signals from flame scanners to significant combustion parameters, including flame stoichiometry [1–5], pollution [2,5–9], stability [10], fuel properties [2,11–14], and different or abnormal operating conditions [5,7,15,16]. Optical data have been typically processed to extract select features, such as the mean intensity [1–6,8,9,15,16], standard deviation [2,15], the characteristic frequencies [8–11] or other related parameters [7,8,11,16], and temporal asymmetry [17]. Some research uses optical data for the following classifications: functional combustion regime [18], physical shape and appearance (for coal-fired utility burners using nonlinear dynamics), and laboratory gas-fired based combustion [19]. Due to the need to maintain a monitored combustion process, several techniques have been developed for process control using digital signal processing and soft computing techniques [20], fuzzy logic controller design for combustion control [21], multiple linear regression models and neural network [22,23], and coal-fired boiler optimization based on modified support vector machine models and genetic algorithms [24].

An on-line oil fuel multi-burner monitoring system is proposed. It would provide an early warning to the operators on combustion-related problems, and on an individual burner basis (i.e., identifying individual malfunctioning burners and accessing combustion conditions for each burner). It would also, considerably enhance combustion control and the maintenance and scheduling of burner maintenance. Additionally, this will improve in the thermal efficiency of the boiler, save fuel consumption costs, and reduce harmful pollutants emitted from the stack. The software was deployed at the Mexican Commission of Electricity's CTPALM Unit 1.

2. Technical approach

Combustion optimization for the burners of an oil-fired unit is a complex process that requires in-depth knowledge of the boiler, the operation of auxiliary systems, and factors that affect emissions and unit heat rate. The approach to combustion optimization in burners relies on an in-depth understanding of the underlying physics and significant experience in the operation of fossil fuel-fired boilers. The general approach used for combustion optimization in burners consists of five steps:

Step 1. Test preparations.
Step 2. Combustion tuning.
Step 3. Parametric testing.
Step 4. Optimal solution determination using PNN.
Step 5. Smart software implementation.

Since burner combustion depends on data-based models that describe the effect of boiler control settings on emissions and performance, issues related to creating a good database, and developing good correlation probabilistic neural network (PNN) models, are very important.

2.1. Unit and equipment description

CTPALM Unit 1 is a 350 MW opposed wall-fired unit, designed and manufactured by Babcock Hitachi. The unit has a balanced draft furnace and is of the subcritical, single reheat design. The maximum continuous rating (MCR) steam flow output at 170 kg/cm^2 and 538 °C is 1058 metric ton/h. Both main steam and hot reheat design temperatures are 538 °C. Steam temperature control is achieved at the CTPALM Unit 1 with flue gas recirculation (FGR) and steam attemperation. This unit fires Mexican and imported high-Sulfur ($\sim$3–4% Sulfur) heavy fuel oil (Bunker C). The firing system is composed of 24 conventional cell burners, (distributed in 12 cells with 6 cells per wall), with common secondary air registers per burner pair. Fig. 1 shows a diagram of the configuration and burner arrangement at CTPALM Unit 1. There is no individual control of the fuel flow to each burner. Fuel atomization is achieved with steam, with an expected atomizing viscosity at the nozzle in the range between 15 and 30 cSt. Each burner is equipped with one iScan flame scanner from COEN. These scanners work with a dual UV/IR spectral response, with a UV peak at 350 nm and an IR peak at 700 nm. The iScan scanners incorporate HART Communications, and can be read by the plant data archiving system. The major advantage of the scanner system at CTPALM Unit 1 is the detection of the enhanced flame and other distinct features, which produced a flame signal suited for this flame processing study. CTPALM must comply with a Mexican regulation (NOM-085-SEMARNAT-1994) for stationary sources that utilize fossil fuels. This regulation specifies the limits for total suspended particles, nitrogen oxides (NOx) and sulfur dioxide (SO_2) at 350 mg/Nm^3, 375 ppmv and 2200 ppmv, respectively – all at 5% reference oxygen (O_2) level.

Typically, CTPALM Unit 1 complies with its mandated emissions limits during periodic emissions verifications. However the level of pollutant emissions during the interim-period is of concern. It is believed that above-the-limit pollutant emissions are common during these interim periods and are due to abnormal combustion conditions at the individual burners. Additionally, it is known that some burners are operated at the particular combustion conditions that result in non-optimal flames, which reduce combustion efficiency and increase fuel consumptions. Therefore, the net thermal performance of the unit decreases, or the net unit heat rate increases.

2.2. Test preparation and combustion tuning

Some preparations were necessary prior to testing. These included Project planning, Instrumentation, Boiler inspection, Burner balancing and a Preliminary test. Using the "Flame Optimization in Burner Approach", the first step of the parametric test involved the installation of individual flow meters during a planned outage. The flow meters installed at CTPALM Unit 1 were the VersaFlow Coriolis1000 from Honeywell. These meters are true mass flow sensors working on the Coriolis principle, with an accuracy of ±0.1% of actual measured flow rate with repeatability better than 0.05%. The installation included temperature measurement and compensation. Additionally, Zirconium oxide excess O_2 probes were installed at the economizer outlet location together with infrared CO probes (one per duct) for flue gas monitoring. A boiler inspection was performed at the unit before the planned outage. During the outage, new burner tips and diffusers were installed on all the burners in preparation for combustion optimization. As part of Step 2, combustion tuning was performed to balance the combustion stoichiometric conditions at the burners, and to