Development of an Intelligent Monitoring System with High Temperature Distributed Fiber-optic Sensor for Fossil-Fuel Power Plants

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Abstract—This paper presents the current research activities into the development of an intelligent monitoring system utilizing distributed fiber optical sensors for real-time monitoring of high temperatures in a boiler furnace in power plants. Of particular interest is the estimation of spatial and temporal distributions of high temperatures within a gas, coal or oil-fired boiler, which will be essential in assessing and controlling the mechanisms that form and remove pollutants at the source, such as NOx. Intelligent distributed parameter estimation coupled with the proposed fiberoptic sensor system is to be used to better estimate the temperature distribution within the boiler that can be used for feedback control for improved combustion.

Index Terms—pollution prevention, fossil-fuel power plants, boiler control, furnace control, high temperature measurement, distributed fiber-optic sensor, intelligent monitoring system, neural networks.

I. INTRODUCTION

The electric utility industry is charged to deliver power as inexpensively and as reliably as possible. Meeting these dual obligations has become increasingly difficult over the past 30 years. Environmental and economic concerns pressed the utility industry to develop clean and efficient ways of burning coal and oil. This has required major improvements in instrument, data management, and control of electric power plant components such as boilers. To control a boiler for both efficiency and low pollution, one needs information on each of many flames and on steam and water flows. However, it has become a challenge to measure high temperature distributions of high-pressure liquids, steam, combustion gases, and heat transfer components in extremely adverse power plant environments. Traditional sensors have not exhibited sufficient stability and long-term accuracy without requiring expensive maintenance and recalibration. The purpose of this research is to develop a distributed sensor system, which is a non-model-based, intelligent, and robust measurement system that uses the latest innovative optical sensing technology. This unique optical sensing technology is not only highly accurate but also very robust against elevated pressure, abrasive streams and corrosive atmospheres. By providing three-dimensional flame temperature mapping from measurements made with distributed optical fiber sensors, the system will greatly enhance the control of power plants to increase economy and reliability and to decrease environmental pollutants at the source. This project focuses research into the development of an intelligent distributed fiber optical sensor system for real-time monitoring of high temperature distributions in a boiler furnace in power plants. Of particular interest is the estimation of spatial and temporal distributions of high temperatures within a boiler furnace, which will be essential in assessing and controlling the mechanisms that form and remove pollutants at the source, such as NOx. Intelligent distributed parameter estimation coupled with the proposed fiberoptic sensor system is to be used to better estimate the temperature distribution of a boiler furnace and for improved combustion. The basic approach in developing the proposed sensor system is three fold: (1) development of high temperature distributed fiber optical sensors capable of measuring temperatures greater than 2000 C degree with spatial resolution of less than 1 cm; (2) development of distributed parameter system (DPS) models to map the three-dimensional (3D) temperature distribution for the furnace; and (3) development of an intelligent monitoring system for real-time monitoring of the 3D boiler temperature distribution. In section II, we describe recent theoretical and experimental research on the distributed fiber-optic sensor, boiler research facility. In section III, the development of a high temperature distribution fiber-optic sensor is described. In section IV, the development of boiler furnace monitoring models and intelligent temperature estimation approaches are described. Finally, we make some conclusions in section V.

II. CURRENT TREND AND FACILITY

A. Emissions and Air Quality

Emissions from coal burning power plants are a major source of air pollution. Although power generation is not the only source of pollution, it is a major contributor to sulfur...
dioxide and nitrogen oxide emissions. Consequently, utility and non-utility power generation facilities are major contributors to acid rain and ambient ozone levels. The driving force behind reducing the adverse impacts of power generation facilities has been the Clean Air Act and the Clean Air Act Amendments. Environmental regulations have helped to substantially reduce the emissions of primary pollutants and have begun to improve air quality across the nation. The EPA has documented the improvements in air quality and the remaining areas of concern [1],[2].

B. Fiberoptic Sensor for High Temperature Distribution Measurement

As aforementioned, to effectively reduce NOx emissions, it is critical to measure the in-situ temperature distribution in the high temperature regions of the coal flames. Since fiber-optic sensors can be used to monitor not only the magnitude of a physical parameter or measurand, but also its variation along the length of a continuous uninterrupted optical fiber [3], they are excellent candidates for measuring the temperature distribution. In recent years, many types of distributed fiber-optic sensors were developed. Basically, they can be divided into the following three categories. The first category is the so called Optical Time Domain Reflectometry (OTDR) [3], which was first developed based on the optical radar (LIDAR) concept. When a short pulse of light is launched into a fiber waveguide, a measurement of the back scattering against time is recorded, with which the external perturbations along the fiber can be determined. Due to the fast speed of light, the spatial resolution of this type of sensor is very limited, which, in general, is only in the order of a meter. Obviously, it may not have enough spatial resolution for the distributed furnace temperature measurement, which requires a spatial resolution in the order of cm. The second type is based on fiber optic Bragg grating [4]. A set of gratings with different wavelength response is fabricated in different locations along the fiber. By scanning the illumination wavelength, both the magnitudes and locations of the perturbations can be obtained. The third type is based on the coupling between propagation modes within the fiber [5],[6]. A special fiber capable of supporting two propagation modes is used as the sensing fiber. One of the major advantages of the last two techniques is the high spatial resolution, which can be in the order of cm. However, these techniques are basically based on single mode silica fibers. To measure the high temperatures, regular silica fibers cannot be used. The best candidate is the optical grade sapphire fiber, which can withstand more than 2000 °C [7]. Unfortunately, the current sapphire fibers are multiple mode fibers, which make it difficult to use the third technique. In addition, it is also difficult to use the second technique due to the following two reasons: (1) no permanent gratings have been fabricated in sapphire fibers; (2) the performance of the system will be severely degraded due to the nature of multimode fiber even if gratings could be fabricated in sapphire fibers.

To overcome the limitations of current fiber Bragg grating and mode coupling based fiber optic temperature sensors, we develop a novel robust, distributed fiber-optic high temperature sensor and corresponding detection algorithms, by which both high spatial resolution and good high temperature performance can be achieved simultaneously.

C. Boiler Research Facility

Four types of research boilers are available at the Penn State Energy Institute (EI). First, the drop-tube reactor (DTR) is an electrically heated furnace. The furnace is vertically mounted with a split-tube casing and elements for easy access to the muffle tube. A programmable temperature controller is used to maintain furnace temperature and has temperature ramp and soak features. This allows for complete automation of the furnace heat-up procedure. Second, the down-fired combuster (DFC) as shown in Fig. 1 is an advanced pilot-scale furnace designed to evaluate the combustion performance of various fuels (natural gas, coal, coal-water slurry fuel) including emissions monitoring. Wall temperatures are monitored with type-S thermocouples at six locations along the combuster. The temperature of the flue gas entering and leaving the heat exchanger is monitored with type-K thermocouple. The cooling water temperature entering and leaving the heat exchanger is also measured to perform heat balances across the heat exchanger. The data on gas and air flows, blower speed, flame signal, wall temperature profile along the combuster (6 locations), flue gas composition (O2, CO2, CO, SO2, NOx) entering and leaving the FGD (Flue Gas Desulphurization) Unit, water flow rates and temperatures in the three zones will be recorded. Third, the 1,000 lb. steam/h Watertube Research Boiler is a standard Cleaver Brooks "A-frame" watertube boiler with a maximum thermal input of 2 million Btu/h.

![Fig. 1. Schematic Diagram of the 500,000 Btu/h Down-Fired Combustor.](image-url)
III. HIGH TEMPERATURE DISTRIBUTED FIBER-OPTIC SENSOR DEVELOPMENT

In this research effort, a novel high temperature distributed fiber-optic sensor is developed, which can be used to monitor the boiler’s temperature distribution in real time. Since there are no sapphire fibers with in-fiber gratings, it is difficult to develop traditional grating based distributed fiber sensor. To solve this problem, a novel sapphire fiber with LPG (Long Period Grating) is developed. The period of LPG is designed to match the difference between the fundamental mode and the selected excitation mode. Note that most of the light energy stays in the single crystal sapphire fiber (i.e., the core of the fiber). Thus, the scattering effect of polycrystalline alumina cladding is not a major problem for the sensor [8].

A. High temperature Distributed Sensing with Sapphire Fiber

In the sensing system, a set of grating-based mode converters (e.g., 10) with different grating periods are fabricated in the same sapphire fiber as shown in Fig. 2. An infrared tunable laser diode (such as the one manufactured by HP) is used as the light source of the system. The incident direction of the light beam launched into the sapphire fiber is carefully controlled so that only the needed excitation mode is excited [9],[10].

Fig. 2. System diagram of high temperature distributed fiber sensor.

A photodetector with a pinhole in the center is used to detect the output light intensity of the fundamental mode as shown in Fig 2. Then, by scanning wavelengths of the light source, a sensing spectrum can be obtained as shown in Fig. 3. The first peak corresponds to the first mode converter; the second peak corresponds to the second mode converter, etc. When there is a temperature distribution along the fiber, the effective periods of mode converters will be changed due to the thermal expansion and the change of the refractive index of the material so that the center locations of the peaks will be shifted, as shown in the dotted lines in Fig. 3. Therefore, reliable distributed high temperature sensing can be realized with a single sapphire fiber.

The temperature resolution of the system will be less than 1 °C, which can be justified by the following estimation: Since the refractive index change, $\Delta n$, induced by the temperature variation for sapphire is about $10^{-6}$°C, to achieve 1 °C temperature resolution, we need to sense the refractive index change with resolution $10^{-6}$. Since $\lambda$ is about $10^3$ nm for the infrared and $\Delta \lambda = 10^3$ nm can be detected by the commercial wavelength meter, thus, a relative wavelength change $10^{-6}$ can be achieved. Thus, a 1 °C temperature resolution can be achieved by this fiber sensor system, which is high enough for monitoring the boiler temperature distribution. In most practical cases, 10 °C temperature resolution is good enough within the high temperature region. Since this mode coupling is wavelength sensitive, the distributed fiber sensing can be achieved by scanning wavelengths of the light source, so called WDM (wavelength division multiplexing).

B. Testing the Performance of the Sensor

The above sensor will be tested in a set of boilers at the Penn State Energy Institute (EI). To minimize the flame disturbance on the temperature measurement, instead of directly mounting the fiber into the furnace, the sapphire fiber is first embedded into a thick alumina tube. Due to the strong mechanical property of the thick alumina tube, the external mechanical disturbance (e.g., the pressure) can be isolated. Therefore, our distributed sensor is very robust against elevated pressure, abrasive streams and corrosive atmospheres because it uses highly reliable materials (i.e., sapphire and alumina) and is properly protected. This measured temperature distribution will provide crucial information for effectively controlling the burning in the boilers so that the pollution can be reduced at the source.

IV. INTELLIGENT MONITORING SYSTEM DEVELOPMENT

The proposed boiler furnace-monitoring model discussed in the previous section addresses the estimation of spatial temperature distribution continuously for any operating condition. The three-dimensional (3D) distributed parameter systems (DPS) model, however, is highly nonlinear and time varying with significant uncertainties in model parameters. Therefore, an efficient state estimation methodology needs to be developed for this class of DPS models. A three-dimensional DPS model is described by a set of partial differential equations for temperature distribution in 3D spatial domain. State estimation technique has matured for lumped parameter systems, that is, for the systems described...
by ordinary differential equations, primarily due to the Kalman filtering theory. Parallel attempts have been made for DPS [11]-[16]; however, its application has been limited due to the complexity of the model. Consequently, real-time computation is not feasible for on-line distributed parameter estimation.

As an alternative to the above model-based estimation techniques, such as infinite dimensional extended Kalman filtering, an intelligent monitoring scheme will be developed for 3D temperature estimation using computing intelligence methods such as artificial neural networks, fuzzy logic, and evolutionary computation. In the initial phase of the project, the 3D-temperature distribution will be simulated off-line and the resulting 3D-temperature data will be used to train neural networks. The generalization property of these intelligent system techniques will result in the mapping of the 1D sensor data into the three-dimensional temperature distribution. Finally, an intelligent algorithm will be developed to adaptively tune the monitoring system in real-time to operate in the experimental boilers.

A. Temperature Extrapolation

The following presents one possible method of extending 1D spatial data into 3D space, using neural networks. The method can be applied to time-dependent data, but for purposes of illustration, it will be applied to time-independent data. Refer to the Down Fired Combustor shown in Fig. 1 and assume that at one fixed instant in time, a set of \( N \) readings are available at \( N \) discrete locations along the vertical \( z \)-axis of the furnace, where at each \( z \)-location, there are, say, \( R \) values along the \( r \)-axis. The method hinges on two premises. The first is that an acceptable approximation to the "exact" solution \( T(x, y, z) \) can be obtained by using the following form:

\[
T(x, y, z) \equiv T(r, z) \equiv \sum_{i=1}^{n} C_i(z)E_i(r),
\]

where \( n \) is the number of linearly independent orthonormal basis functions \( E_i(r) \), and \( C_i(z) \) is a coefficient. The justification for the first replacement lies in the assumed radial symmetry of the problem, and the justification for the second replacement lies in the denseness of a given set of functions within a given vector set of functions, which is a generalization of Weierstrass’ Theorem which ensures that any continuous function can be approximated by a polynomial. The second is that the coefficients \( C_i \) of this expansion have a regularity to them, which reflects the physical regularity along the \( z \)-axis.

The mapping will be achieved with a system type (as opposed to component type) neural network [17]. Essentially, each channel is realizing one of the 2 premises listed above. The inspiration for this architecture stems partly from the failure of component-type neural networks to successfully achieve multi-dimensional mappings and partly from the need to implement a Semigroup type behavior.

The first (Implementation or Function) channel will consist of a set of \( n \) Radial Basis Function neural networks, each of which is trained to function as one element of an \( n \)-dimensional orthonormal basis set of functions, so that, when linearly combined, they realize an \( n \)-dimensional function space. The second (Observation or Semigroup) channel will consist of a recurrent neural network (e.g., an Elman network) which will be trained to possess a regularity feature similar to a Semigroup property. Specifically, they will be trained to produce a set of coefficients which have the property that \( C(z) = \Phi(z)C(0), \) where \( \Phi(z_1 + z_2) = \Phi(z_1)\Phi(z_2), \) i.e., the Semigroup property. The recurrent network must have the configuration that the input consists of the variable \( z \) and the constant \( C(0) \).

The Fig. 4 shows the system basic architecture.

![Fig. 4. System architecture.](image)

There are roughly three parts to the technique. In the first, referred to as algebraic decomposition, only the Function Channel is used. The basis set of vectors is defined and a preliminary coefficient vector is formed. In the second, referred to as smoothing, only the Semigroup Channel is used. The objective is to smooth the preliminary coefficient vector into a final coefficient vector. Finally, the (continuum) model is obtained by performing the vector expansion indicated in the expression: \( T(z, r) = C(z)E(r) \).

B. Simulation and Estimation Results

For simulation purposes, the temperature data is simulated as follows. It is assumed that the furnace is cylindrical in shape, with a height of 10 meters and a radius of 2 meters [18]. The internal dynamic behavior consists of a fluid-flow field, combined with a temperature field, which take place in laminar tube flow. There is an inlet section in which the velocity profile first forms and in which the complex thermodynamic phenomena associated with the jet flames take place and the boundary layer equations have their most dominant effect. This is coupled directly to the main section in which the (parabolic) velocity profile is fully developed and remains constant and in which the temperature profile develops and eventually remains constant. The following assumptions are made: constant wall temperature; forced convection – body forces are negligible; 2D flow; steady-state conditions. Furthermore, the following assumptions are made: there are 25 probes, each one at a fixed vertical position.
(given by \( z_i \)), and each one supplying 11 temperature readings which span the distance from the axis of the cylinder to the wall of the cylinder. To evaluate the performance of the proposed intelligent estimation technique, we consider a noisy environment in which white Gaussian noise (WGN) is added directly to the temperature field, which then produces an unsmooth coefficient vector. In this case, we need to use the Semigroup Channel (Elman network) to smoothen the coefficient vector. Once the coefficient vector is smoothened, analytic expressions are obtained for each component of the basis vector set and for each component of the coefficient vector. Finally, the continuum temperature model is obtained by expanding the product: 

\[ T(r, z) = C_1(z)E_1(r) + C_2(z)E_2(r) \]

using the derived component expressions. Figs. 5 and 6 show the smoothened coefficient vector \( C_1 \) and \( C_2 \), resulting from part 2 of the proposed intelligent technique.

Fig. 5. Smoothened \( C_1 \).

Fig. 6. Smoothened \( C_2 \).

Fig. 7 shows the empirical data and Fig. 8 shows the computed data, which means the data from part 1 of the proposed intelligent technique.

From the smoothened coefficient vector, we can get numerical expressions of each coefficient vector. Equations (2) and (3) are the coefficient vector expressions and equations (4) and (5) are the basis vector expressions.

\[
C_1(z) = -9.1e^{-0.05 z^3} + 0.0077z^2 - 0.019z + 0.24
\]

\[
C_2(z) = -1.9e^{-0.05 z^3} + 0.00083z^2 - 0.016z + 0.032
\]

\[
E_1(r) = 0.0078* r^6 - 0.045* r^4 + 0.03 * r^2 - 0.065* r^3 - 0.093* r^2 + 0.033* r + 0.32
\]

\[
E_2(r) = 0.0092* r^6 - 0.056* r^4 + 0.13 * r^2 - 0.15* r^3 + 0.079* r^2 - 0.021* r - 0.29
\]

Fig. 9 shows the result of this estimation using the above equations. We notice that the noise has been removed and, more importantly, that the estimation applies to the entire continuum defined by the interior of the furnace.
A preliminary development of an intelligent monitoring system using high temperature distributed fiber-optic sensors is presented. A new estimation method is developed using an intelligent system technique based on the neural network implementation of the Semigroup property. From the results, it has been shown that the proposed estimation method works well even in the presence of noise. Although this procedure was used only for estimation (interpolation), it lends itself to the related problems of extrapolation and parameter estimation. The potential impact of the proposed research is broad and significant. Combustion control of NOx is critically important to precisely control the 3-dimensional (3D) temperature distribution inside a furnace.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES


VIII. BIOGRAPHIES

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