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Gaussian process regression based optimal design of combustion systems using flame images

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HIGHLIGHTS

- The digital color images of flames are applied to combustion design.
- The combustion with modeling stochastic nature is developed using GP.
- GP based uncertainty design is made and evaluated through a real combustion system.

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ABSTRACT

With the advanced methods of digital image processing and optical sensing, it is possible to have continuous imaging carried out on-line in combustion processes. In this paper, a method that extracts characteristics from the flame images is presented to immediately predict the outlet content of the flue gas. First, from the large number of flame image data, principal component analysis is used to discover the principal components or combinational variables, which describe the important trends and variations in the operation data. Then stochastic modeling of the combustion process is done by a Gaussian process with the aim to capture the stochastic nature of the flame associated with the oxygen content. The designed oxygen combustion content considers the uncertainty presented in the combustion. A reference image can be designed for the actual combustion process to provide an easy and straightforward maintenance of the combustion process.

1. Introduction

The heat transfer process from the combustion gas to the boiling water is complex as processes like combustion, convection and radiation are involved. Recently, limited fuel availability and the rising cost of fuel made it necessary for engineers to improve boiler efficiency. The excess air will not be at its optimal value if the combustion is not at its optimum operation, causing a decrease in the thermal performance. Also, environmental directives require conformity with strict pollution and safety standards. Therefore, the effectiveness of combustion is an important issue. Electrical power is produced by combustion of different fuels in the industrial furnaces [1]. However, the use of low-quality fuels and fuel blends causes problems, like poor flame stability and high pollutant emissions. Studies have been carried out to improve the combustor [2]. Bitenc et al. have developed a micro-computer based controller and continued with the realization of the control of combustion in the steam boiler PK-401 in Cinkama Celje's chemical work [3]. So far, it is still useful when one designs the combustion process operation to ensure the stability of combustion processes and decrease the extent of pollution emissions [4–6].

Traditionally combustion processes are monitored by experienced operators. However, there are a few shortcomings, including difficulty in quantifying the combustion performance by human experience and the poor environment at the work place [7]. The index used to measure combustion is temperature. In the monitoring of combustion processes, the conventional temperature measurement equipment, like thermocouples, provides only measurement at a single point instead of the temperature distribution of the flame. The flame detector is important to some modern combustion systems for prevention of accidents [8]. However, detectors based on ultraviolet or infra-red sensing does not provide enough measurements of flame as the flame area is limited. On the other hand, the distribution of flame temperatures can be obtained from optical-fiber based detectors, but the detectors are often limited to laboratories usage. Laser based detectors have also been developed to diagnose combustion systems through quantitative measurements, like temperatures, pollutant emission and rates of heat release. Their deployment in industry, however, is

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limited due to the higher price and complexity [5,9]. The continuous observation of flame on-line has become possible with the advancement of digital image processing and optical sensing as spatial observation can be obtained cost-effectively [5]. To get the flame image, the only required devices are traditional CCD cameras and flame-grabbers. Draper et al. have developed a broadband, RGB (Red, Green and Blue channels), two-color pyrometer technique to measure the flame temperature and the total emissivity of a two-dimensional image of a coal flame [10]. Yan et al. have proposed the visualization of the temperature distributions of the flame sections in a bench-scale opposed multi-burner gasifier [11]. Gonzalez-Cencerrado et al. have presented an image processing for the characterization of a given combustion state through flame visualization. The 2D distribution of statistical and oscillatory parameters of the flame condition is obtained. It allows the identification of areas with different luminous and oscillation patterns [12].

With the abundance of digital image data, there has been a vast increase in research related to the image analysis. Extensive overview of the subject has been done by Burkardt and Decquier and Candel [13,14]. Experimental study was conducted by Iion et al. to investigate the dynamics of flame and the variation with time of high-luminous region in flames [15]. The characteristics of flame contain important and rich knowledge of its measurement quality in the combustion performance [16]. Flame monitoring has been done by Yan et al. They used an advanced flame monitoring system to investigate the geometrical and luminous properties of pulverized coal flames [1]. The flames in various burning conditions have also been characterized using RGB and HSV (hue, saturation, and value) color models [17]. Some CCD based methods are more popular than laser based methods in the construction of flame temperature distribution because of its simplicity and low costs. They were also applied to experimental investigations of H_2 and H_2-enriched syngas flame radiation properties, and the useful image-based parameters related to the H_2-based combustion were obtained [18]. The usage of video in imaging has the advantage of observing large and open areas, but the difficulty lies in the ways to perform statistical analysis from large quantity of data and change them into applicable knowledge [19].

The presence of uncertainty in the combustion process implies the flame distribution is inherently stochastic in nature. It should be considered in the modeling process. To this end, a Gaussian process (GP) method is used to model the combustion system. Gregorcic and Ligthbody introduced the Bayesian GP to model a stochastic process [20]. Chen and Zhang used GP modeling in the multi-variate monitoring of batch processes [21]. GP has the capability of large scale sampling. It has found its application in the biological field as well as voice recognition. Herzallah and Lowe have applied GP to control of nonlinear processes [22]. Specifically in combustion control, Grancharova et al. applied a nonlinear model predictive control method to the design of a reference tracking controller based on a GP model [23]. The variance prediction control method has been shown to be capable of controlling the process with stochastic disturbance.

In view of the ability of GP to model the stochastic nature of the process, this work is the first-ever attempt to develop GP to tackle modeling and design of the combustion process in the practical operating condition. From the extracted flame data through PCA, the model is constructed to facilitate the design of a combustion operation. The model relates the PCA features to the outlet content of the flue gas, like oxygen, because of significant delay in measuring exhaust gas. The PCA features, on the other hand, are characterized by the combustion condition, so the GP model indirectly relates the oxygen content to the operating condition. It also provides an optimal operation condition to ensure the efficiency of combustion and meet the requirements of the environmental regulations. The image can be used in the application of the control scheme presented in Chen et al. [24]. The next section describes the combustion in our experimental setup. Section 3 presents GP modeling of the combustion process which makes use of the extracted data from the flame image. Section 4 details the design procedure with an experimental study. The concluding remarks are made in Section 5.

2. Combustion system description

It is essential for efficient combustion to have a fuel–air metering system in large heating processes that are fuel fired. The combustion efficiency is a measure of the effectiveness of conversion of fuel to heat for usage. In this study, an experiment is set up to collect the image data from the combustion which can then be used for the design of combustion.

Fig. 1 shows a schematic of the experiment. It consists of a furnace and a system for capturing flame images. The characteristics of the image are extracted through PCA and used as the input vector for modeling while the oxygen content is used as the output vector of the GP model. Based on this model, the image of combustion for particular oxygen content requirements can then be designed. It can be used in an imaging control system. The system then controls the air flow through a flow controller.

The fuel in the experimental furnace is industrial heavy oil. The opening of the air valve is adjusted by an industrial servomotor. The source of air comes from a direct-driven air compressor coupled with variable frequency drives. The temperature controller (TIC) is used to design the required flow of the fuel. During the operation, the pressure and temperature measurement in the furnace, the flue gas information, the air and fuel flow rates are automatically recorded. The oxygen content is measured by the exhaust gas analyzer to maintain energy consumption and complete combustion. Although the majority of combustion parameters, such as CO, NOx, and oxygen, in the exhaust gas can be easily measured by gas analyzers, the measurement results obtained in this way are significantly delayed. Because of these lags, the feedback control loop based on the simple oxygen content tends to overcompensate, resulting in sluggishness and slow control. On the contrary, the flame images can immediately reflect the current status of the combustors, making it possible for implementation to on-line continuous control of the flame. A digital camera with 658×492 pixels is used to capture images in the furnace. The 24 bits per pixel resolution can capture images up to one frame per 5 s, depending on the computer loading. Fig. 2 shows five images of the combustion operated normally. By cooling equipment, the CCD camera is safeguarded against damage from the extreme temperature so that the image quality can be maintained. In order to collect robust images, the camera front is connected with a set of optical filters which prevents saturation in the camera, and the detected signal is sent through the usage of IEEE-1394a interface to a field computer. A graphical system is used for data acquisition and it can correctly adjust the air flow rate of the compressor.

3. Modeling of combustion systems using GP

Rich information on combustion can be gathered from flame images thanks to the advancement in digital image process techniques and optical sensing. For example, a single image (658×492 pixels) contains up to 971,208 observed variables at each time point. However, the physical relationship between the flame images and oxygen contents is still not clear. In case of such data, it is unrealistic to use parametric models or nonparametric linear models. This research aims to consider the output as a stochastic process as in traditional Shewhart–Deming statistical model. Then the mean and the covariance structure are estimated simultaneously,