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Image-based deep neural network prediction of the heat output of a step-grate biomass boiler

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HIGHLIGHTS

- A deep learning-based system was developed for the monitoring of biomass combustion.
- The system can predict the heat output of a step-grate boiler up to 30 min ahead.
- The water temperature predictions are accurate up to ±1 °C.
- The system has great potential in optimizing step-grate biomass combustion.

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ABSTRACT

This work investigates the usage of deep neural networks for predicting the thermal output of a 3 MW, grate-fired biomass boiler, based on routinely measured operating parameters and real-time flame imaging. It is hypothesized that flame imaging can provide information regarding the quasi-instantaneous state of combustion, therefore supplementing conventional measurements that generally produce lagging feedback. A deep neural network-based, continuous multistep-ahead prediction scheme was proposed and evaluated by using operational and image data collected through extensive campaigns. It was found that flame imaging increases the accuracy of predictions compared to those obtained by only using operational data. The complexity of biomass combustion was well captured by the proposed deep neural network; furthermore, the deep architecture produced better predictions than shallower ones. The proposed system can reliably predict output water temperatures with errors up to ±1 °C, up to approximately 30 min ahead of the current time.

1. Introduction

Biomass is the oldest energy source in the history of mankind. Due to global climate change and depleting fossil fuel reserves, the incentive to move towards sustainable energy production has defined the last decade. Biomass is considered to be the only viable option for renewable energy generation that can meet global demand in the short-term—the annual availability of biomass is believed to be approximately equal to that of coal [1]. Considering forestry alone, the annually harvested 530 billion m^3 biomass has the potential to cover 10% of the world's power demand [2]. In the EU27 in 2010, of the approximately 3000 PJ of renewable energy generation for heating and cooling, biomass had a dominating share of approximately 91%—this decisive role is projected to remain in and after 2020 [3]. For heat and electricity generation from biomass, combustion is by far the most widespread technology, holding a share of over 90% [4].

Grate firing is the most widely used method for biomass combustion. When used for heat generation, grate-fired systems are normally limited to an output power of approximately 150 MWth, which is not a disadvantage in certain decentralized industry segments. Flexibility in terms of fuel type and granularity further popularize the technology in smaller scale applications [5]. Grate-fired boilers are known to have lower efficiency compared to e.g., fluidized bed combustors [2], therefore, given the share of the technology in global renewable energy production, it is important to optimize their operation.

In this work, the feasibility and potential benefits of a deep neural network-based prediction system are investigated. Trained on synchronized image and operational data, the neural network is set up to predict the output water temperature of the system, therefore the heat output of the boiler. The motivation behind

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the prediction system is the desire to eliminate or reduce uncertainty caused by heterogeneous fuel quality and highly complex combustion process in systems operated under varying loads. Such a prediction system is meaningful in boiler systems that operate without installed on-line fuel analysis systems (e.g., on-line moisture analyzers), as it is hypothesized that flame images contain quasi-instantaneous information about the combustion process and fuel properties [6]. If this hypothesis is valid, flame imaging can become an inexpensive and reliable tool for the optimization of boiler operation, offering additional benefits, i.e., from the point of process safety [7]. To the best of the authors' knowledge, no reports are available on the on-line monitoring and prediction of grate-fired biomass combustion using imaging and machine learning.

Nowadays, machine learning and artificial neural networks (ANN) are widely used in the combustion industry. Complex processes in the field are routinely modeled using ANN's [8]. Artificial neural networks are used to interpret data collected by optical, acoustic or other sensors for monitoring and quantifying combustion processes [9]. One of the most promising uses of machine learning methods is in the prediction of power plant emissions to ensure meeting limits. Neural networks have been used to predict NO_x emissions in coal- [10,11] and gas-fired boilers [12] and as the algorithmic engines behind soft sensors, e.g., for estimating the O_2-content of the flue gas or air flow rate [13,14]. The emission levels of pollutants are known to be difficult to predict, but ANN-based systems can achieve remarkable accuracy (less than 5% error) and respond well to system non-linearities [11].

Thermochemical conversion processes of biomass are known to be complex, due to the heterogeneous and uncertain fuel composition and multitude of chemical species involved in the reactions. Machine learning is a promising tool for the modeling of thermochemical processes of uncertain and heterogeneous fuels [15]. Machine learning techniques for the on-line estimation of biomass composition and moisture content have been successfully demonstrated in small-scale systems [16,17]. Similar soft approaches have been studied as parts of model-predictive controllers targeting output water temperature in medium-scale systems [18]. Liukkonen et al. demonstrated soft sensors realized by using machine learning techniques for the prediction of NO_x emissions during biomass combustion in a large-scale circulating fluidized bed boiler [19]—it was found that non-linear ANN models outperform linear models and can potentially predict emissions over several hours long time horizons.

The use of machine vision and image processing have gained considerable attention in the combustion industry since the early nineties [20,21]. Industrial combustion is a complex process that depends on many variables. While systems can be equipped with monitoring cameras, human operators may not interpret the visuals of the flame reliably due to the complexities of the underlying process and monotonity of the task. Flame monitoring is therefore a type of task that can be efficiently outsourced to machine learning algorithms. Image data, in conjunction with advanced data processing can provide information on the current state of the combustion system. Several past studies have demonstrated that combustion processes can be classified [21–28], quantified [29–32], predicted [6,20,33–39] and even controlled [40,41] by using on-line imaging and machine learning. Researchers have recently started to adopt deep learning methods (e.g., convolutional neural networks [42]) to detect combustion instabilities in gas turbines [43]. Imaging and ANN's have been shown to be particularly successful in predicting pollutant emissions in different industrial or semi-industrial systems [20,33,37,44], which suggests the applicability of ANN's and imaging to highly non-linear and complex prediction problems. Lu et al. used a two hidden layer ANN to classify laboratory-scale butane/air flame images into 10 different groups based on the air/fuel equivalence ratio and achieved high classification accuracy. The same group demonstrated the use of single hidden layer ANN's and multi-spectral imaging of chemiluminescence to estimate the air/fuel ratio and NO_x emission from laboratory-scale gas flames [36,39].

Biomass combustors have been studied by using on-line image processing [45–48,48–50]. Some of these studies only described image-based quantification methods without machine learning or advanced data processing [45–47]. Previous work that did include machine learning mostly focused on laboratory-scale biomass burners [48,50]. Li et al. used shallow radial basis function ANN's to predict pollutant emissions from a laboratory-scale biomass flame and reported errors between 7 and 20% [48]. The same group found that the errors are higher when using support vector machines instead of ANN's [50] and that applying deep ANN's and automatic feature learning reduces the errors to a remarkable 2–3% [51]. Kotyra et al. used image processing to extract geometric and radiometric image features from the acquired images and applied k-NN regression modeling to predict boiler thermal power and excess air when co-firing coal and biomass, but found that the method does not produce acceptable predictions of excess air [49].

Although one can find several studies that focused on the application of flame imaging and ANN's to monitor, predict of quantify industrial combustion systems, the method has not been applied to biomass grate combustors before. The novelty of this work therefore lies in the studied system (a 3 MW, step-grate biomass combustor) and in the applied analysis technique (deep neural network prediction based on image and operational data). The current study aims to demonstrate that:

1. flame imaging improves the response time of predictive systems by providing near-instantaneous information as opposed to conventional, lagging sensor feedback,
2. flame imaging supplements conventional measurements in predicting the thermal output of the system, by improving the accuracy of the predictions and
3. using deep ANN's increase the accuracy of predictions and handle the complex and non-linear prediction problem better than shallow ANN's.

2. Materials and methods

In this section, the boiler used for the experiments, the instrumentation and imaging system and the details of the data processing algorithms are discussed.

2.1. Boiler

Fig. 1 shows a schematic drawing of the boiler used for the experiments. The boiler was a 3 MW nominal capacity, counter-current, inclined, stepping grate type combustor. The boiler was integrated into a sawmill process, producing heat for steaming timber products. Wood chips, by-products of the sawing process were used as fuel. The fuel was fed onto the grate by a hydraulic ram. The step-grate was operated periodically by a hydraulic system. The boiler had two main chambers—a primary chamber encompassing the grate and a secondary chamber between the primary chamber and the heat exchanger zone. The two chambers were separated by a refractory vault. Combustion air was supplied by two primary and two secondary fans. Primary air was blown in from under the grate, while secondary air was introduced at the beginning of the secondary flue gas pass. A flue gas recirculation system was used to feed back to the primary air stream in order to optimize chamber temperature, burnout and NO_x emissions. The movement of the grate ensured the mixing and transport of the fuel. Ash and solid combustion residues were transported by