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Estimating the fuel moisture content to control the reciprocating grate furnace firing wet woody biomass

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A B S T R A C T

In small countries like Lithuania with a widespread district heating system, 5–10 MW moving grate biomass furnaces equipped with water boilers and condensing economisers are widely used. Such systems are designed for firing biomass fuels; however, varying fuel moisture, mostly in the range from 30% to 60%, complicates the automated operation. Without manual adjustment of the grate motion mode and other parameters, unstable operation or even extinction of the furnace is possible.

To ensure stable furnace operation with moist fuel, the indirect method to estimate the fuel moisture content was developed based on the heat balance of the flue gas condensing economiser. The developed method was implemented into the automatic control unit of the furnace to estimate the moisture content in the feedstock and predictively adjust the furnace parameters for optimal fuel combustion.

The indirect method based on the economiser heat balance was experimentally validated in a 6 MW grate-fired furnace fuelled by biomass with moisture contents of 37, 46, 50, 54 and 60%.

The analysis shows that the estimated and manually measured values of the fuel moisture content do not differ by more than 3%. This deviation indicates that the indirect fuel moisture calculation method is sufficiently precise and the calculated moisture content varies proportionally to changes in the thermal capacity of the economiser. By smoothing the data using sliding weighted averaging, the oscillations of the fuel moisture content were identified.

1. Introduction

As environmental regulations are becoming more stringent, renewable fuel sources that substitute fossil fuels and are more widely being used for electricity and heat production [1]. For heat production, woody biomass is mostly used in the form of chips, logs, chunks and coppice stems. However, freshly sawn wood contains over 50 wt.% of moisture. This makes direct combustion difficult due to the extra energy required to evaporate the moisture from the wet fuel. According to the literature [2], the harvested wood loses 1–2% of its moisture content per month in uncovered storage, and producers of biofuels are inclined to store the harvested wood to reduce the moisture content before supplying it to heating plants. Sometimes, when there is a high demand for heat production, freshly harvested biomass is delivered. During the cold season, biomass with 30–60% moisture content is delivered to heating plants, where it is combusted in a furnace. Depending on the heat demand, different types of furnaces, such as fixed bed combustors (up to 5 MW_{th}), moving grate (up to 100 MW_{th}), fluidised bed (up to 500 MW_{th}), and co-firing (up to 900 MW_{th}) are used [3]. Nowadays, the moving grate or fluidised bed combustors are the most popular. Fluidised bed combustors are designed for various forms of biomass with a moisture content up to 60% [4]. However, moving-grate furnaces have difficulty burning chips with moisture content higher than 55% [5]. Regardless, combustion on grates is the most widespread heat production method in small and medium-scale heating plants, where produced heat is used for district heating in small countries such as Lithuania. To meet the requirements of district heating systems, the modern moving-grate combustors are designed for high thermal efficiency with low emissions of gaseous pollutants (CO, NO_x, etc.) firing biomass with a 30–55% moisture content [6]. Even though the combustors are equipped with advanced parameter measuring instrumentation, significantly fluctuating biomass moisture levels can cause operational problems in biomass combustors, such as the lower burning stability and insufficient heat supply under conditions of elevated heat production [7]. These problems can be avoided by adjusting the boiler operating regime if the fuel properties or, at minimum, the moisture content is known. Typically, the moisture

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Nomenclature

Abbreviations

FGCE	flue gas condensing economiser
FT-IR	fourier transform infrared spectroscopy
MC	moisture content
NIR	near infrared spectroscopy
PLC	programmable logic controller
RH	relative humidity
SCADA	supervisory control and data acquisition

Notations

AF_E	flue gas blower reference capacity, m^3/h
c_{p1}	specific heat of the dry flue gas, kJ/kg K
c_{p2}	specific heat of water evaporation (latent heat of water vapour), kJ/kg K
$c_{p,wv}$	specific heat of water vapour, kJ/kg K
h_D	moisture content in the dry flue gas at FGCE inlet
h_{D1}	moisture content in the dry flue gas at FGCE outlet
LHV	lower heating value of the completely dry feedstock, kJ/kg
m_D	mass of combustion products, kg
m_F	reference mass of fuel, kg
m_{O2}	mass of consumed dry air, kg
m_{mfg}^{RH}	moisture content in flue gas obtained from the RH method, kg/h
m_{mfg}^{HB}	moisture content in flue gas obtained from the heat balance of the economizer, kg/h
P_{atm}	atmospheric pressure, Pa
Q_B	boiler capacity, kJ
Q_{fg}^{dry}	amount of heat extracted in the FGCE, kJ
Q_{FGCE}	thermal capacity of the economizer, kJ
T_{fg}	inlet flue gas temperature, °C
T_{fg1}	outlet flue gas temperature, °C
T_r	reference temperature, °C
Y^{RH}	fuel moisture content of fuel calculated from the RH method, %
Y^{HB}	fuel moisture content of fuel calculated from the FGCE heat balance method, %
Δt	time period of data recording in the SCADA system

Greek letters

φ	measured relative humidity in the flue gas, %
f_r	flue gas blower reference frequency, Hz
υ_E	flue gas blower frequency, Hz
ρss_T	density of superheated steam according to the flue gas temperature, kg/m^3
η	boiler efficiency

content of fuel supplied to the heating plant is measured manually by drying the sample in an oven [8], but this method takes from 4 h to 16 h to estimate the moisture content. Also, multiple samples must be taken to determine the bulk moisture content. Besides, fuel from various heaps is mixed before it enters a furnace and adjustments to the boiler operations for manually measured fuel moisture content could cause insufficient heat supply. To ensure stable furnace operation with moist fuel, automatic control of the furnace with continuous operation should respond to changing fuel parameters obtained by real-time measurements.

Fuel moisture content can be measured online before it enters the furnace or estimated from flue gas analysis. Methods of fuel analysis include nuclear magnetic resonance [9], microwave [10], near-infrared spectroscopy (NIR) [11], radio frequency [12] and X-ray spectroscopy [13]. Microwave and nuclear magnetic resonance methods are more adaptable to a laboratory than to industrial applications and are unreasonably expensive to use in a small or medium-scale heating plant [14]. Using the NIR method, the fuel surface is illuminated with wavelengths from 800 to 2500 nm and the three absorption maximums are associated with moisture in fuel [15]. According to Sweden scientists [16], NIR is a suitable method for measuring the moisture in moving bark and wood chips. However, variations of fuel characteristics such as density, composition and size requires re-calibrating the NIR. Daassi-Gnaba et al. [12] proposed a moisture estimation method based on radio frequency measurements with an antenna that is fully buried into the wood chips. The results showed that this method is suitable for real-time measurements of fuel moisture content in the heating plant, but an industrial prototype is still in the testing phase. Niedermayr et al. [17] presented an innovative fuel feeding system: a crane and a sensor-equipped gripper, featuring different sensors, such as ultrasound, moisture, and image recognition with a camera. The sensor-equipped gripper analyses the fuel in the hopper and feeds the fuel with the required moisture at the required feeding rate according the boiler operating regime. This approach helps to avoid fluctuations in the boiler operation regime due to differing moisture content, as well as to reduce CO_2 emissions, though the feeding system is only at a lab scale and has only been tested in a thermal power plant with a capacity below 500 kW [17].

The reviewed methods for measuring the fuel moisture content [9–17] are financially disadvantageous to use in small and medium size biofuel fired heating plants. Besides, these methods require adjustments and calibration of the instruments and handling skills for the measurements [18]. In this case, indirect methods that estimate the fuel moisture content from the flue gas analysis are more suitable and economically attractive. These methods include Fourier-transformed infrared spectroscopy (FT-IR) [19], tunable diode laser spectroscopy [20], relative humidity (RH) [21] and soft-sensor measurements [22]. Kortela and Jämsä-Jounela [23] analysed moisture-saturated gas using an FT-IR gas analyser. The results revealed that the measured moisture content differs from that present in the fuel by up to 4.1%, but this result was obtained by analysing clean gas. Measuring moisture content in a flue gas duct in a boiler house with this instrument produces imprecise results because of the presence of solid particles in the flue gas, as well as the effects of pressure and temperature. More precise results can be obtained from tunable diode laser spectroscopy, but the measuring instrumentation is more expensive than that of FT–IR, and continuous cleaning of diodes and handling skills for measurements are necessary [24]. Another indirect moisture measurement method is the relative moisture sensor [25]. Hermansson et al. [21] from Sweden performed analysis to improve the accuracy (<4% error) by reducing the signal delay and thereby expanding the application capabilities of the RH sensor to measure the moisture content in flue gas from biomass combustion to determine the moisture content of the fuel. Since the sensor can operate only at a temperature of up to 200 °C, the flue gas duct was cooled before performing the measurements. The method is able to detect variations in the moisture content within seconds; however, new devices, measurements, and calibration are needed to apply this method in wood fired boilers.

Kortela and Jämsä-Jounela [26] presented a soft-sensor for online monitoring of fuel moisture in a BioPower 5 CHP plant, where

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