KAUNAS UNIVERSITY OF TECHNOLOGY
LITHUANIAN ENERGY INSTITUTE

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ANALYSIS OF CHIPPED WOOD MOISTURE LOSS IN BIOFUEL FURNACES

Summary of Doctoral Dissertation
Technological Sciences, Energetics and Power Engineering (T 006)

2023, Kaunas

This doctoral dissertation was prepared at Lithuanian Energy Institute, Laboratory of combustion processes from 2015 through 2023.

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The official defence of the dissertation will be held at 10 p.m. on 1 June, 2023 at the public meeting of the Dissertation Defence Board of Energetics and Engineering Science Field in a Meeting Hall at Lithuanian Energy Institute.

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The doctoral dissertation was sent on 2 May 2023.
The doctoral dissertation is available on the internet http://ktu.edu and at the libraries of Kaunas University of Technology (K. Donelaičio 20, Kaunas, LT-444239, Lithuania) and Lithuanian Energy Institute (Breslaujos 3, Kaunas, LT-44403, Lithuania).

KAUNO TECHNOLOGIJOS UNIVERSITETAS

LIETUVOS ENERGETIKOS INSTITUTAS

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DRĖGMĖS IŠSISKYRIMO IŠ SMULKINTOS MEDIENOS BIOKURO PAKUROSE TYRIMAS

Daktaro disertacijos santrauka
Technologijos mokslai, energetika ir termoinžinerija (T 006)

Kaunas, 2023

Disertacija rengta 2015–2023 metais Lietuvos energetikos institute, Degimo procesų laboratorijoje.

Mokslinis vadovas:

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Redagavo: Lina Abraitienė (UAB „BELLA VERBA“)

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Disertacija bus ginama viešame Energetikos ir termoinžinerijos mokslo krypties disertacijos gynimo tarybos posėdyje 2023 m. birželio 1 d. 10 val. Lietuvos energetikos instituto AK-202 konferencijų salėje.

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Disertacija išsiųsta 2023 m. gegužės 2 d.
Su disertacija galima susipažinti interneto svetainėje http://ktu.edu ir Kauno technologijos universiteto bibliotekoje (K. Donelaičio g. 20, Kaunas, LT-44239, Lietuva) bei Lietuvos energetikos instituto bibliotekoje (Breslaujos g. 3, Kaunas, LT-44403, Lietuva).

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INTRODUCTION

According to new climate action plans, EU countries have pledged to reduce emissions by 2030 by at least 55%. The most polluting sectors in Lithuania that contribute the most considerable amounts of harmful pollutants that are regulated by "Euro" standards are transportation, energetics, and agriculture. Inasmuch as centralised heating is well-developed in Lithuania, the government can satisfy part of the regulations by waiving the usage of fossil fuels and focusing on energy production from renewable sources. Currently, 80% of energy dedicated to residence heating is produced from renewable sources, i. e. by burning wood-based biofuel.

The current geopolitical situation and the fact that energy production businesses want to stay competitive have caused lower quality biofuel to be supplied to the biofuel burning facilities. According to established technical specifications, SM3 quality class biofuel can contain water up to 60% by mass and 10% small fraction particulates. In most cases, this type of biofuel fails to meet the requirements of biofuel combustion systems.

High demand is not the only factor leading to the usage of low-quality biofuel – frequently, it is stored outside, susceptible to precipitation, and can lead to water content rising to 60% and above. In this case, the biofuel does not combust but instead continues to lose moisture, and this process occupies the majority of the combustion chamber. The negative impact of this process can be mitigated by increasing the drying intensity during the biofuel desiccation stage and by optimisation of the combustion process. In order to achieve this, it is necessary to know the dependencies that influence the intensity of biofuel drying in the combustion chamber. Despite the research in this field, little is known about the desiccation of damp biofuel in the combustion chamber and the drying stage parameters that significantly affect the elimination of humidity. In an effort to fill the missing gaps, an experimental setup was designed and assembled – its parameters match those of a typical 6MW combustion chamber, and the biofuel humidity elimination experiments were conducted. In said experiments, the injection of primary air, recirculated flue gas, radiation from internal chamber surfaces and stirring were simulated. Samples of low-quality biofuel that satisfy SM3 regulations, having a significant water content (60±5%) and containing chipped wood, were used. Initial test results showed that supplying primary air or recirculated flue gas heated to 200°C can reduce the chipped wood water content by up to 13% (in case of a smaller fraction – up to 23%) compared with initial water content. The application of complex solutions has yielded considerably less significant effects. It was determined that supplying 200°C temperature primary air from under the fire-grate and simulating internal radiation in the combustion chamber reduced the water content by 36% within 30 minutes. Analysis of obtained results has indicated that internal radiation speeds up the process 2-3 times. The experiments showed that the rate of desiccation is inversely proportional to the granulometry of the biofuel – a smaller fraction is dried more rapidly. Additional tests were performed in order to determine the stirring effect on biofuel drying. They showed that stirring increases the drying rate up to 1.6 times, resulting in a humidity content difference of up to 58%.

A review of related scientific publications reveals a shortage of in-depth research on chipped wood with high water content (60% by mass or more) drying on a moving fire-grate, hence the lack of information about the factors that affect the drying rate and combustion. From this follows the **study object** of this work – moisture loss rate of high moisture content chipped wood biofuel in a biofuel combustion furnace.

Aim of the research

It aims to analyse the drying process of high moisture content (60±5%) chipped wood biofuel of different properties and determine the effect of combustion-influencing factors on the drying process.

Tasks of the research

In order to imitate the processes occurring in the drying section of a furnace with a moving fire-grate, it is necessary to fulfil the following objectives:

1) By experimentally simulating different drying conditions to determine the drying rate of chipped wood biofuel with various fractional content:
   a) By supplying primary air in different temperatures through the bottom of the biofuel input;
   b) By supplying a mixture of different temperature primary air and recirculated flue gas through the bottom of the biofuel input;
   c) By supplying different temperature primary air through the bottom of the biofuel input combined with simulating internal radiation using infrared light sources.
2) To evaluate the chipped wood biofuel desiccation rate dependence on layer stirring frequency and establish optimal conditions for increasing the drying rate.
3) To determine the application possibilities of optimal parameters in actual combustion furnaces with the express purpose of controlling biofuel moisture content.

Relevance of the research

Biofuel combustion is one of biomass's most common heat and electrical energy production methods. However, it is a complicated process, and due to the constantly changing composition of supplied biofuel, various issues are faced, such as incomplete combustion and the formation of harmful byproducts. One of the most commonly variable properties of biofuel is its water content, varying in a wide range and occasionally reaching 60% by mass or more. High moisture content biofuel cannot undergo combustion in the furnace; instead, it takes much space on the fire-grate to dry. In order to improve the devices used for biofuel combustion, it is necessary, first, to determine the influence of drying factors and dependencies on drying agent temperature and stirring frequency. It is possible to design and integrate sensors to predict drying rate change based on obtained results and improve the efficiency of biofuel combustion equipment.

Novelty of the research

The dynamics of high moisture content (60±5%) biofuel drying were analysed, and their dependencies on combustion factors were determined.

Significance of research results

The results described in this dissertation allow to optimise high moisture content (60±5%) chipped wood biofuel combustion process and increase its effectiveness in currently used or newly designed moving fire-grate-based biofuel combustion furnaces. Virtual sensors can be designed and installed to predict the moisture content of input biofuel and its drying rate, thus, increasing the efficiency of biofuel combustion devices.

Statement presented for defence

1) Greatest drying rate is achieved when using the smallest fraction size biofuel, and increasing the temperature of supplied primary air results in an increased drying rate.

2) When using biofuel with 60±5% moisture content, supplying colder than 100 °C flue gas has a negative effect on the drying process.

3) Primary air supply and internal radiation prevent achieving optimal biofuel moisture content.

4) The combination of combustion-influencing factors allows achieving 2 times faster drying rates.

5) Moisture content calculation algorithm installed in the combustion controller allows predicting the moisture content change in the supplied biofuel.

Scientific approbation of dissertation

Research results presented in the dissertation have been published in 3 scientific articles, two of which have been published in journals with a citation index and are referenced in the “Clarivate Analytics” database “Web of Science Core Collection”, and the third has been published in a scientific journal that is registered in international databases of scientific information. Research results were presented at 11 conferences, 8 of them international.

1. LITERATURE REVIEW

Many countries, led by ecological initiatives, are replacing fossil fuels with biofuel. Today more than 40% of solid biofuel is consumed to provide residence heating; hence, wood still remains the most popular renewable resource. (European Biomass Association 2017) Pulverised wood is secondary material, remaining from educational and general-purpose forest clearcutting. Wood not directly used for the production industry is pulverised and burned to produce energy. Chipped wood is considered a sustainable energy source that does not contribute to greenhouse gas emissions (Wahlund, Yan, Westermark 2004) because the amount of CO2 emissions is the same as decomposing trees would emit it. During the plant's growth amidst photosynthesis, the plant absorbs as much carbon dioxide as it would release during combustion or decomposition, so the total net release of CO2 in the environment is zero (Wihersaari 2005).

The most common chipped wood biofuel combustion features are analysed in this literature review (Deboni et al. 2020; Merlan et al. 2016; Zhao et al. 2021).

Depending on the heating requirements, two different biofuel combustion technologies are used: boiling layer combustion furnaces (20-500 MW) and fire-grate combustion furnaces (up to 100 MW) (Williams et al. 2012). Boiling layer biofuel combustion furnaces can use various types of biofuel with moisture content up to and exceeding 60 % by mass (Zhang, Xu, Champagne 2010). However, fire-grate-based biofuel furnaces experience issues when combusting chipped wood biofuel with moisture content exceeding 55% (Sefidari, Razmjoo, Strand 2014). Despite the shortcomings of fire-grate-based biofuel furnaces, in small countries such as Lithuania, such devices are widely used in small and medium-sized facilities to produce energy for centralised heating. In order to satisfy the requirements for centralised residential heating, achieve high thermal efficiency and reduce gaseous emissions of combustion byproducts (CO, NO_x etc.), modern fire-grate-based combustion furnaces are designed for combusting high moisture content (30-55% by mass) biofuel (Razmjoo, Sefidari, Strand 2016). Even though such furnaces are equipped with advanced measurement devices, biofuel's changing moisture content may cause issues, such as low combustion stability and insufficient heat supply in cases of high demand (Svoboda et al. 2009). These problems can be easily avoided by adjusting the working regime of the combustion furnace, given that the properties or at least the moisture content of supplied biofuel are known. Hence, the structure, properties and effect of moisture content and its measurement methods were reviewed, as well as drying and combustion technology (Chan et al. 2018; Brandt et al. 2010; Mansfield et al. 2016; Kulasinski 2015; Anca-Couce 2016; Cserta 2012). The most significant focus was towards the research of factors affecting biofuel desiccation and combustion intensity in the combustion chamber drying stage(B. M van Kessel et al. 2004) (Rezaei et al. 2016; Huttunen, Holmberg, Stenström 2017; Liu et al. 2014; B. M van Kessel et al. 2004; Martinez-Garcia et al. 2015). This decision was made concerning the fact that highly damp (moisture content >60% by mass) chipped wood biofuel combustion frequently leads to incomplete burning and emissions of harmful pollutants.

The literature review has revealed that although many conclusive papers have been published on this topic, some data is still missing. For instance, it is still unknown whether there is information on chipped wood of various properties (containing bark, leaves, or coniferous foliage) sample desiccation depending on general factors relevant in combustion: primary air, recirculated flue gas, internal radiation, and movement speed of the fire-grate. Chipped wood biofuel of various properties, produced from forest clearcutting waste, will allow evaluating the effect of content and structure on the rate of desiccation in the combustion chamber drying stage. Based on scientific research, it has been decided to perform three distinct types of experiments:

- Chipped wood-based biofuel of various properties desiccation rate analysis using different (50-200°C) temperature air or air and steam mixture in an experimental stationary biofuel layer drying setup simulating the effect of primary air, recirculated flue gas and internal radiation.
- Analysis of a small fraction chipped wood desiccation rate dependence on the stirring intensity.
- Analysis of virtual sensor application eligibility for indirect measurement of biofuel moisture content in an actual combustion chamber.

Since the combustion of damp biofuel causes problems with emissions of pollutants and optimisation of the combustion process, performing a desiccation analysis of biofuel of various properties would yield results based on which certain conclusions could be formulated regarding speeding up biofuel drying based on factors that affect the desiccation process.

The author of this dissertation has analysed the scientific literature on the biofuel drying process and the possibility of speeding up the desiccation by simulating the working regime of the combustion chamber. An experimental setup was designed, assembled, and used for drying analysis by simulating the effects on drying rate in a combustion chamber rated for 6 MW power. The analysis of biofuel input content temperature variations was performed to determine the properties of biofuel drying and explain the processes and their reasons. Taking the results of the drying process analysis results, conclusions and recommendations were formulated regarding the rate of moisture elimination dependence from the factors that affect the drying process.

2. METHODS OF RESEARCH

2.1. Chemical and physical properties of the chipped wood samples

Considering that biofuel from various waste-related sources (from clearcutting, city maintenance or sawmills) is most frequently used for energy production, with its varying particle size and moisture content, samples of the different granulometric constitutions were selected for this experiment: chipped wood with bark (clearcutting waste No. 1), chipped wood with leaves (waste of city or park maintenance) and chipped wood with coniferous foliage remains (forest maintenance waste No. 3).

2.1.1. Analysis setup of chipped wood sample moisture loss

The drying of chipped wood was analysed with a designed experimental setup, the arrangement of which is displayed in figure 2.5. It is assembled from several main parts: a drying chamber, electric heaters, a steam generator and infrared lamps. Before performing tests in the biofuel drying chamber, the samples were prepared by simulating the supply of biofuel that had been exposed to the elements and not appropriately dried onto the fire-grate. To simulate damp and cold biofuel supply in a heated combustion chamber, the entire system is heated to the temperature of supplied drying agent. When the drying chamber (with dimensions 0.355×0.235×0.280 m) reaches the designated temperature, it is filled with a prepared sample of chipped wood. The layer thickness of chipped wood (0.23 m) was selected to match the layer thickness of supplied biofuel to the 6MW combustion chamber.

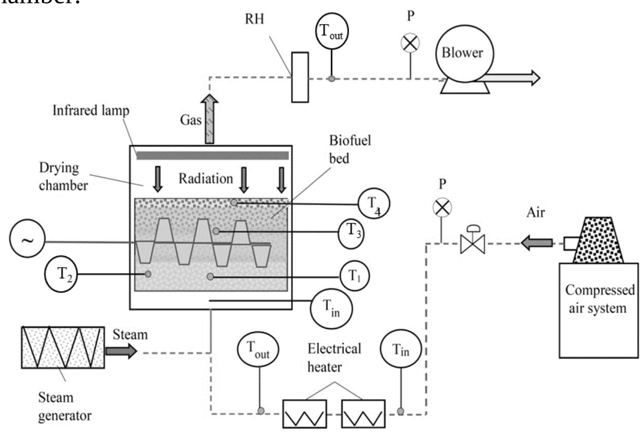

Fig. 2.1 Schematic diagram of the experimental rig for moisture loss of samples of chipped wood

Temperature sensors were installed at varying depths of the biofuel layer in order to determine the nature of warming up and desiccation of biofuel during the drying stage (see Fig. 2.1). The first, third and fourth sensors were installed at their respective heights concerning the vertical axis of the drying chamber: T_1 = 3 cm, T_3 = 12 cm, and T_4 = 22 cm above the fire-grate, respectively. The second sensor was attached to the side wall of the drying chamber at height T_2 = 10 cm. Data logger PICO TC-08 with respective software was used to collect sensor data. The average moisture content of biofuel input was evaluated by measuring flue gas humidity with a relative moisture sensor Testo 454.

The average time biofuel spends on the fire-grate until complete combustion is 30 min (Martinez-Garcia et al. 2015), and the drying stage takes up 1/3 of the chamber length; it is reasonable to state that the time biofuel spends on this stage is approx. 10 min. Based on these conditions, the maximum experiment duration was determined to be 30 min.

The experimental tests aimed to determine the effect of primary air, recirculated flue gas and internal radiation on biofuel desiccation rate in the drying stage. Various factors of drying rate were analysed during the experiments. During the primary air effect analysis, the gas was supplied from a pressurised system passing through two electrical heaters to heat the air to the desired temperatures of 50, 100, 150, and 200 °C. During the entire experiment, the gas flux was kept constant at 17.7 ± 0.5 m3/h. The heated air temperature was measured with K-type thermocouples attached prior to and after the electric heaters.

The effect of recirculated flue gas on the drying of chipped wood was analysed using a mixture of heated air and steam. By injecting a flux of steam into the air mixture, the absolute humidity of the drying agent was increased from 5 to 17 g/m3. The preheated air and steam mixture flux was kept at the same rate of 17.7 ± 0.5 m3/h.

Lastly, two infrared heaters were installed above the biofuel layer to simulate internal radiation. Selected 2 kW power heaters were sufficient to provide a 50 kW/m2 nominal rate of radiative power density in the chamber. The flux of drying air was kept at the same previous rate and supplied through the underside of the drying chamber.

Analysis of the stirring effect on the rate of drying was also performed. For this purpose, a special helical screw-type mixer simulating the movement of fire-grate in the 6 MW combustion chamber (fig. 2.1) was used. During the operation of this mixer, the bottom and middle biofuel layers were lifted to the top while the top layer was dispersed. Different stirring frequencies were analysed by mixing the samples every 150, 300, and 600 sec.

2.1.2. Processing of obtained data for comparison of results

During the experiments, the average chipped wood moisture content was evaluated indirectly, that is, by calculations after measuring the flue gas's

(1)

moisture content. The moisture content and flue gas temperature were measured using Testo 454 data logger. The flue gas moisture content difference at the time was determined by calculating the sample drying rate g_{H_2O} according to the following (1) equation:

$$g_{H_2O} = h_g \cdot \frac{V_{oro}+V_{H_2O_{(g)}}}{3600}\left(\frac{273+T_d}{273+T_{apl}}\right);$$

Where V_{oro} – flux of dry air (m^3/h); $V_{H_2O_{(g)}}$ – steam flux (m^3/h); h_g – moisture content of flue gas (g/m^3); T_d - temperature of flue gas (°C); T_{apl} – environment temperature (°C).

Steam flux is calculated according to the following (2) equation:

$$V_{H_2O_{(g)}} = V_{H_2O_{(kuro)}}+V_{H_2O_{(rec.pr.)}}; \quad (2)$$

Where $V_{H_2O_{(kuro)}}$ – humidity content in the flux during drying (m^3/h); $V_{H_2O_{(rec.pr.)}}$ – humidity content in the flux after injecting an additional 17g/m^3 of water vapour, simulating recirculation flue gas to the combustion chamber (m^3/h).

Due to the inconsistent composition of the samples, the mass of every sample was different to retain uniform layer thickness between samples. The initial moisture content of samples fluctuated in the range of 60 ± 3%. For this reason, in the processing of results, the moisture content in the biofuel was normalised according to the ratio of the largest ΔY_{max} and smallest ΔY_{min} (Holmberg et al. 2017) moisture content and dry sample mass throughout the entire experiment duration of 30min ((3) and (4) equations)

$$\Delta Y_{max} = \frac{m_i - m_s}{m_s}; \quad (3)$$

and

$$\Delta Y_{min} = \frac{m_i - m_s}{m_s}; \quad (4)$$

Where m_i – sample mass (g) at the time t_i, and m_s – the mass of dry sample (g), which is calculated according to equation (5)

$$m_i = m_{i-1} - m_{H_2O(i)}; \quad (5)$$

Where m_{i-1} – sample mass at the time t_{i-1} (g); $m_{H_2O(i)}$ – moisture content of flue gas (g), where the moisture content in the flue gas $m_{H_2O(1)}$, $m_{H_2O(2)}$, $m_{H_2O(3)}$… $m_{H_2O(i)}$ are each at times t_1, t_2, t_3… t_i, respectively, and are calculated according to equation (6) (6)

$$m_{H_2O(i)} = g_{H_2O(i)} \cdot \Delta t;$$

Where $\Delta t = t_i - t_{i-1}$ is the measurement period of moisture content in the flue gas. The period was chosen to be 5 seconds to account for the low drying rate.

In calculations with normalised moisture content Y_m (relative units), the maximum amount of moisture in wood pulp samples is equated to **1** and is calculated in relative units according to the equation (7):

$$Y_m = 1 - (\Delta Y_{max} - \Delta Y_{min}); \quad (7)$$

2.2. Analysis methods of virtual sensor application for combustion control based on determined moisture content in biofuel

The virtual sensor application is analysed at a biofuel combustion facility owned by Axis Technologies (Garliava). The system is equipped with a XILO SV water heater. The water heater of Danish manufacturing DANSTOKER VP-13 is paired with a recirculatory boiler circuit water pump, circulatory pump, mechanised biofuel (chipped wood) combustion chamber (DG-6), which consists of chamber hull, the foundation with 100-150 mm wide high-temperature insulating plates, biofuel hopper with a crane feeder, chamber fire-grate with moving grates, ash duct and ash removal system, air pipeline with valves and air supply ventilators (I, II, III inlet air), recirculation pipelines with recirculatory fan and hydraulic system.

During the duration of the experiments, the process was adjusted manually to ensure the parameters of the selected regimen.

2.2.1. Properties of test biofuel

During testing, chipped wood biofuel of various moisture content was supplied to the combustion chamber. Experiments were conducted for several days, varying the supplied biofuel moisture content in the 44 – 60% range. Biofuel was divided into two piles depending on its moisture content and manually supplied to the biofuel input system in designated periods.

2.2.2. Determining moisture content in chipped wood biofuel based on FGCE heat balance equations

Evaluation of moisture content in chipped wood pulp biofuel was based on FGCE (Flue gas condensing economiser) of heat balance. In order to calculate the heat balance, process parameters are extracted from the SCADA system: flue gas and water temperatures before and after condensational economiser, rate of gas flue ventilators and power output of the boiler. In order to evaluate the moisture content of flue gas, the heat power of FGCE is divided into two components: physical heat of dry flue gas and heat from condensation of water vapour in the flue gas.

Moisture content in flue gas formed by damp chipped wood biofuel combustion is determined by subtracting the calculated heat energy of dry flue gas from the heat energy of FGCE, displayed in the control panel, and dividing the obtained difference by specific heat of water vaporisation, as indicated in the (8) equation:

$$m_{mfg}^{HB} = \frac{3600}{c_{p2}}\left(Q_{FGCE} - Q_{fg}^{dry}\right); \tag{8}$$

Where m_{mfg}^{HB}– moisture content of the flue gas, calculated from the heat balance of the economiser, kg/h; QDKE – the heat power rating of the condensational economiser, kW; the coefficient 3600 serves to convert between hours and seconds to obtain the moisture content per hour figures.

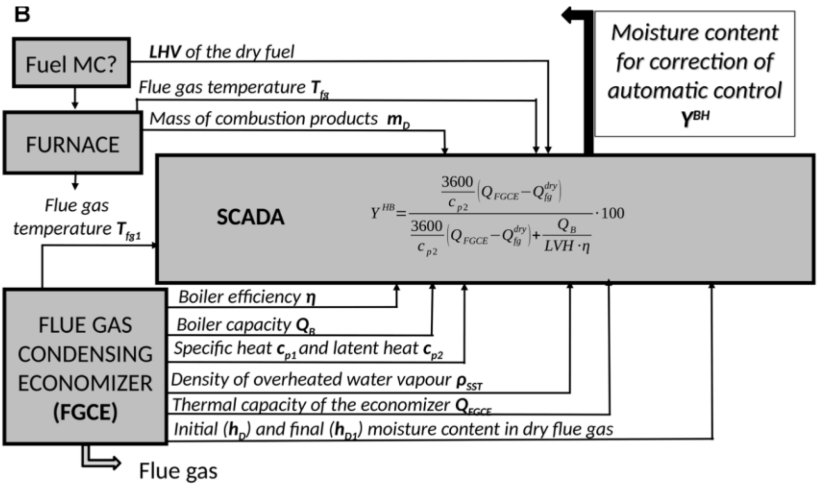

Fig. 2.2 Output and input measurement scheme to calculate the moisture content of biofuels using the FGCE heat balance method

Calculated flue gas moisture content is then converted to the moisture content of biofuel using the (9) equation:

$$Y^{HB} = \frac{m_{mfg}^{HB}}{m_{mfg}^{HB} + \frac{Q_B}{LVH \cdot \eta}} \cdot 100; \tag{9}$$

Where Y^{HB} is biofuel moisture content, calculated according to the FGCE heat balance method (%). The scheme for calculations using this method is displayed in Figure 2.2.

3. RESULTS AND DISCUSSION

3.1. Effect of primary air on temperature distribution in the chipped wood biofuel layer

In the conduction of initial experiments (Fig. 3.1), primary air of various temperatures was supplied. Observation of the temperature difference in chipped wood biofuel input allowed an understanding of the processes happening during biofuel dehydration and the drying agent's effect (primary air, recirculated flue gas and internal radiation) on the drying process. Obtained results allowed identifying the locations of the fastest rate of moisture loss within the biofuel samples and the stagnating locations.

By observing the temperature differences in various heights of the biofuel input layer, it was determined that supplying 50 °C temperature air causes sluggish rates of temperature increase, and after 30 min, the highest temperature across the entire biofuel layer was only 25 °C. Increasing the inlet air temperature to 100 °C caused a significant fraction of chipped wood with leaves and chipped wood with bark biofuel load-containing temperatures to reach 38 °C (T1) within 30 minutes.

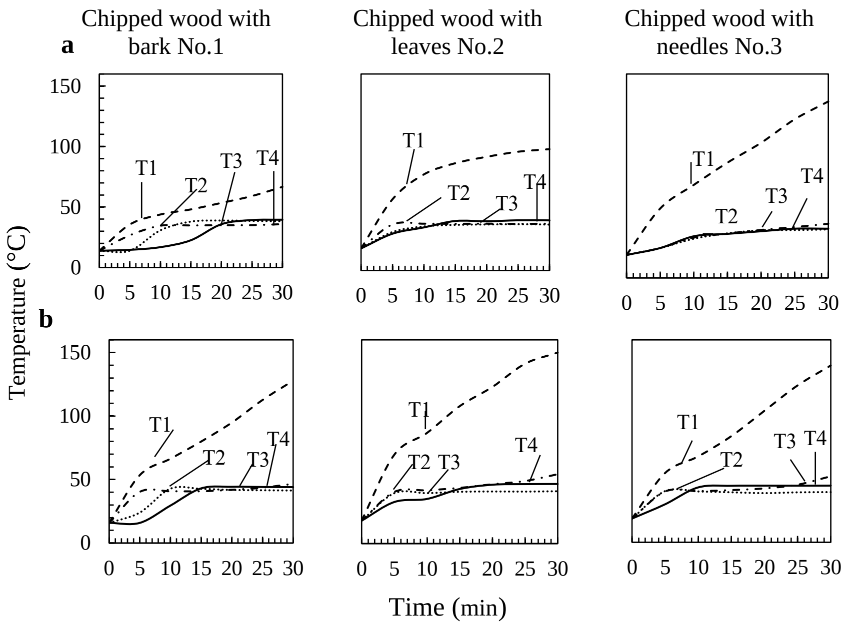

Fig. 3.1 Temperature variation at various heights of the chipped wood biofuel load from below supplying (a) 150 °C and (b) 200 °C preheated primary air

Drying small-fraction biofuel with primary air of 150 °C (Fig. 3.1a) and 200 °C (Fig 3.1b) temperature has caused an increase in the drying rate. Due to the particle size and delayed condensation more significant fraction of chipped wood input dehumidification is slowed down compared to a smaller fraction, which was also indicated by the results. When the temperature of supplied primary air was 200 °C, in the lower layer of the sample after 10 minutes, temperatures of T1 = 66 °C (127 °C after 30 min), T1 = 87 °C (150 °C after 30 min) and T1 = 68 °C (139 °C after 30 min) were registered for chipped wood with bark, chipped wood with leaves and chipped wood with needles. The highest temperature in the lower section T1 of the sample layer was achieved when drying chipped wood with leaves. As suggested by the experiment data, this type of biofuel has the ability to compress and set into layers, and due to increased layer resistance, airflow to the higher layers is restricted, resulting in more rapid drying of the lower layer.

In summary, the experiments using higher temperature air input revealed the nature of drying rates at different points of the samples. It was determined that the fastest drying layer of biofuel is the one closest to the fire-grate, the second location in terms of drying rate is near the side walls of the drying chamber, and the last is the remaining sections of the biofuel input.

3.2. Effect of recirculated flue gas on temperature distribution in the chipped wood biofuel layer

An air and steam mixture was selected for this experiment to recreate as accurate working conditions as possible and simulate combustion chamber processes. It is known that in the case of standard solid fuel combustion devices, recirculated flue gas is one of the methods to reduce NOx emissions. Supplying flue gas to the underside of the fire-grate helps to reduce the biofuel combustion temperature and, in turn, the formation of NOx. For this reason, additional tests were conducted with the aim of simulating the flue gas supply through the bottom of the fire-grate to the drying section of the chamber. The tests showed that biofuel sample desiccation rates were similar to instances of only using dry air, however the temperature differences in chipped wood biofuel layers were registered earlier. The fastest to heat was the bottom layer of the input; the second was near the side walls and the remaining layers of the input content.

Supplying 50 °C temperature air and steam mixture to the lower section of the chamber for 30 minutes (simulating recirculated flue gas), biofuel samples No. 1, No. 2, and No. 3 warmed up to 5 – 7 °C more rapidly and reached 30 °C, in comparison to tests performed with dry air only. The result was to be expected, considering the heat transfer coefficient of water condensation is considerably higher than that of air, and the heat transfer can occur more rapidly.

Identical temperature change characteristics were observed using a 100 °C temperature air and steam mixture; however, the process had slowed down slightly. Analysis of tests performed with different biofuel samples determined that the difference was due to the smaller particle size of biofuel taking less time to heat up. Results indicate the main difference in the drying process when using low temperature (50 °C and 100°C) air or air and steam mixture are that using air and steam mixture causes quicker heating-up of the biofuel layer during the initial 5 minutes. However, later condensation causes slower temperature increments, and the desiccation process proves more difficult within the entire input volume.

Increasing the temperature of the input air and steam mixture to 150 °C causes a more prominent earlier discussed effect; for instance, initially, temperature T1 increases in the first 5 minutes, then stabilises, and at the 15-minute mark, the lower layer temperature begins increasing (Fig. 3.2a).

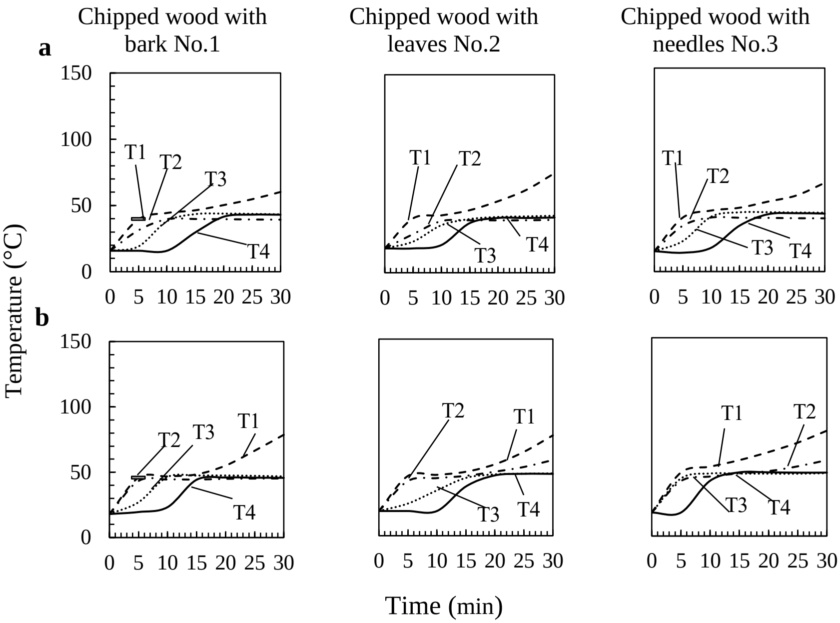

Fig. 3.2 Temperature variation at various heights of the chipped wood biofuel load from below supplying (a) 150 °C and (b) 200 °C preheated air and steam mixture

It was observed with all types of samples. The stabilisation of temperature mentioned above may be related to the condensation of initial moisture when the inlet steam condenses and later requires additional time and thermal energy to evaporate. It is why observing a stabilisation disposition suggests that the biofuel may begin heating up only when its moisture content decreases. The difference in sample heating rate is also related to the physical characteristics of the drying agents, where it is known that the steam-specific heat capacity cp = 2 kJ/kg·K (for comparison – the specific heat capacity of water is equal to 4.2 kJ/kg·K), and specific heat capacity of air is equal to 1 kJ/kg·K, and this determines the transferred energy quantity difference and its need for water evaporation. It is known that in order to evaporate water, it is necessary first to heat it to its evaporation temperature, and only then it may evaporate (specific evaporation heat r = 2256 kJ/kg·K).

During the experiment using a small fraction biofuel, increasing of supplied air and water vapour temperature to 200 °C it was determined that after 25 minutes from the beginning of the experiment, the bottom layer of the biofuel reaches 70 °C and begins rapid heat transfer to the biofuel located near the side walls of the drying chamber (Fig. 3.2b, T2 difference). During the desiccation of identical fraction and composition biofuel with dry air heated to 200 °C, once the bottom layer reaches the temperature of 140 °C, the biofuel at the sides begins to heat up and dry more rapidly (Fig. 3.2b). This effect can be explained by the fact that the specific heat capacity of steam is two times larger than that of air; hence the heat transfer in the same flux is two times higher, resulting in a 20 times higher thermal transfer coefficient compared to dry air. In drying experiments with heated air, most heat energy is consumed for evaporating the moisture of the bottom layer contents, leading to a slower rise of temperature of the higher layers of the input samples, compared to that in experiments using air and steam mixture.

3.3. Effect of radiation and primary air on temperature distribution in the chipped wood biofuel layer

They conducted experiments with recirculated flue gas, and the primary air mixture injected through the bottom of the fire-grate only considered heat exchange via convection. In a real setting, during biofuel combustion and having heated surfaces present, conditions are made to permit heat transfer via radiation, hence the reason for conducting experimental tests to simulate the effect of radiation from hot surfaces in the combustion chamber. Infrared heaters were installed to simulate the radiation in the combustion chamber; their power output per unit area matches the radiation intensity observed in real settings.

Having noticed that recirculated flue gas reduces the desiccation rate, only dry air was used as a drying agent for the experiments involving IR heaters. During biofuel sample drying with the dry air of various temperatures and radiating 50 kW/m2 of thermal energy into the surface of the sample, temperature differences were registered in various heights of the input layer (Fig. 3.3).

Analysis of sample temperature differences has determined that internal radiation only positively affects the drying rate of the top layer of the biofuel sample. The T4 temperature sensor, installed at the top layer of the stationary biofuel sample (approx. 1 cm from the surface), does not register a steep temperature increase within the first few minutes of the experiment. The input samples’ temperature change characteristics were very similar to using only heated air.

Drying small fraction biomass containing a lot of essential oils separation of volatile compounds occurs at lower temperatures, increasing the possibility of ignition (Johansson, Rasmuson 2017). Such random ignitions were also recorded during the experiments involving drying a small fraction biofuel (No. 3) containing a lot of coniferous foliage. This effect can be observed based on the T4 temperature difference, representing all the rapid changes happening while irradiating the surface with infrared. Biofuel samples are all but homogenous, and particle distribution is different every time, so the ignition of the surface occurs randomly without the possibility of prediction. Although the heat transferred by infrared radiation noticeably increases the drying rate in the top layers of the biofuel input, ignited particles are unable to transfer thermal energy to the lower layers of the biofuel.

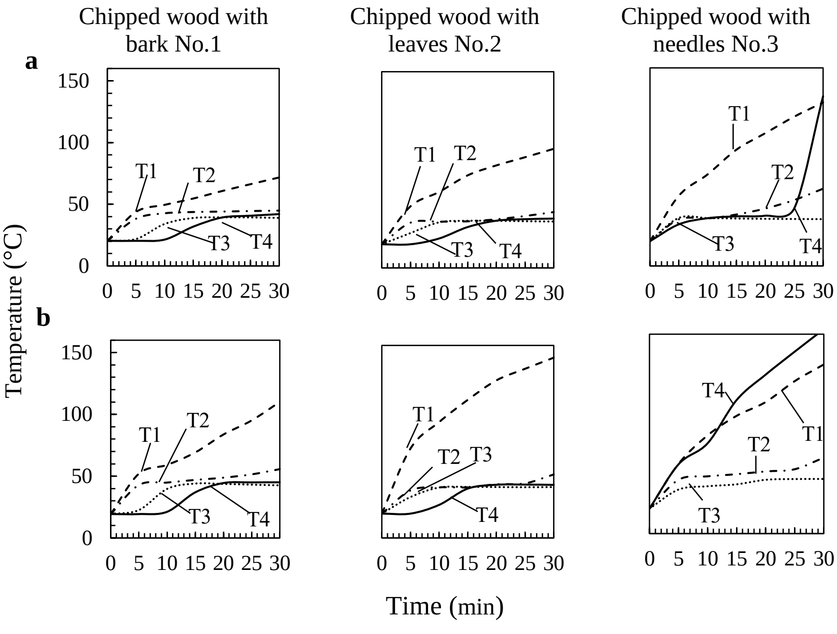

Fig. 3.3 Temperature variation at various heights of the chipped wood biofuel load from below supplying (a) 150 °C and (b) 200 °C preheated primary air and radiating

Additionally, the T2 temperature difference (Fig. 3.3) was registered at the side of the chamber near the side wall. During the operation of the infrared heaters, said biofuel layer temperature was approx. 10 °C greater, regardless of the primary air temperature. Such an increase in T2 temperature can be explained by the heating-up of the side walls of the chamber from the infrared radiation. Despite the insulation of the side walls to prevent heat transfer to the biofuel, insulation was likely insufficient or did not ensure proper heat resistance from the hot chamber walls.

3.4. Chipped wood biofuel particle size effect on the rate of moisture loss

Installation of temperature sensors at various heights of the biofuel layer may assist in predicting the characteristics of moisture loss intensity on the fire-grate, but it does not permit precise evaluation of the exact value of the moisture loss rate. For this reason, the average moisture loss rate of biofuel samples during the experiments was calculated based on the moisture content of flue gas.

Experiments with different biofuel particle sizes suggest similar moisture loss rates between the tests. The most significant differences in moisture loss rates were registered when injecting 200 °C temperature air and steam mixture through the bottom of the fire-grate; Figure 3.4 shows the comparison with this temperature of drying agents.

Fig. 3.4 displays the effect of the biofuel particle size on the drying rate at 10-, 20-, and 30-minute marks. Comparing chipped wood biofuel sample moisture loss rates based on the contents of the drying agent (either air or air and steam mixture) has indicated similar results. After 10 minutes, the smallest fraction (No. 3) biofuel moisture loss rate was 0.006 g/s, whereas the moisture loss rate for the largest fraction (No. 1) biofuel was only 0.003 g/s.

At a particular moment, the moisture loss rate fluctuated regardless of the particle size of the sample (Fig. 3.4). Installation of radiation measures as a means to stimulate the drying rate leads to a considerable moisture loss rate difference based on particle size. A decrement in particle size was observed to cause increments in the moisture loss rates, which is evident after the 30-minute-long drying. The smallest particle size biofuel (No. 3) moisture loss rate was approx. 2.3 times greater than only using air and steam mixture to dry the larger fraction samples (No. 1) when their fraction size difference was approximately equal to 1.9. The middle fraction sample (No. 2) moisture loss rate was around 1.5 times greater than that of the more significant fraction (No. 1) when their fraction size difference was approximately equal to 1.4.

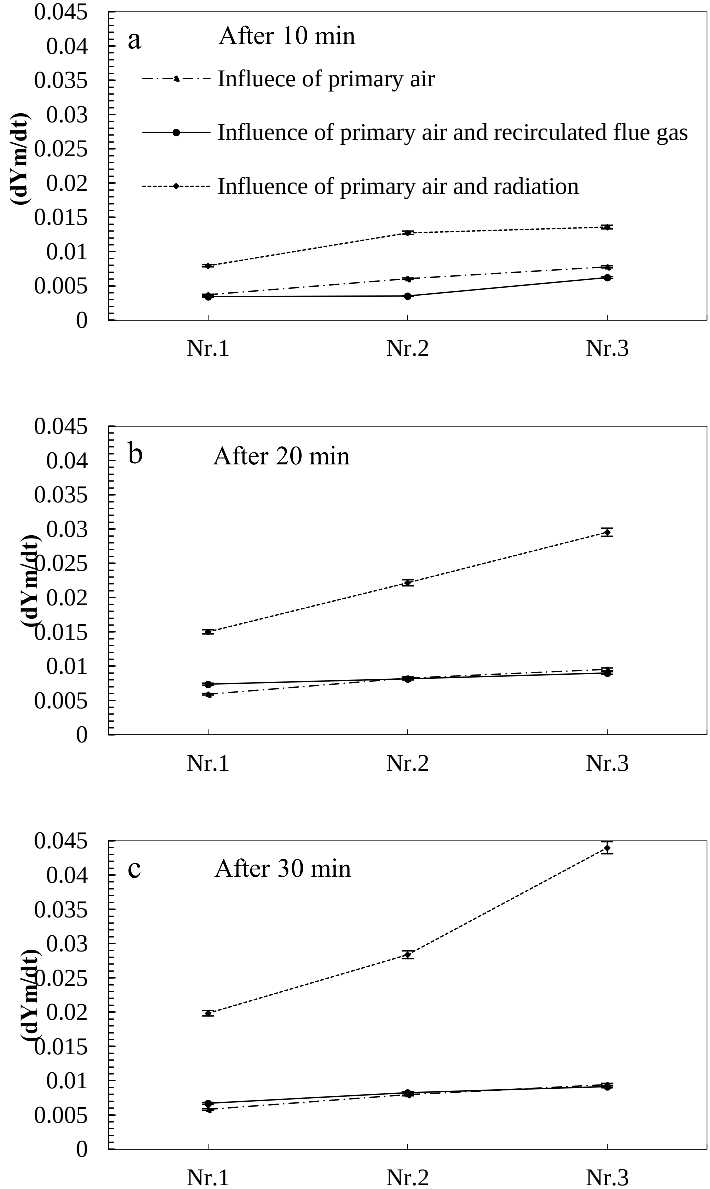

Fig. 3.4 Influence of residence time on moisture loss rate of chipped wood samples No. 1, No. 2 and No. 3

3.5. Effect of chipped wood biofuel layer stirring/mixing on the moisture loss rate

The chipped wood biofuel mixing intensity effect on the variation in moisture content rate when drying with various air temperatures is displayed in Figure 3.5. Increasing the air temperature to 200 °C caused the mixing period to become significant after 10 minutes from the start of the experiment. Mixing every 150 seconds led to a 3% decrease in normalised moisture content. Analysis of results obtained when drying chipped wood with bark content and evaluating the effect of mixing frequency on the rate of moisture loss has indicated that after 20 minutes from the start of the experiment, when supplied primary air heated to 100–150°C increases the rate of moisture loss and increasing the primary air temperature to 200 °C the influence of mixing on the intensity of moisture loss of biofuels is reduced, but the influence of the frequency of the mixing period is increased (up to 4,5 %). The effect of stirring intensity is more prominent in the results obtained after 30 minutes of sample drying.

Tests conducted in a stationary biofuel sample layer showed that supplied high temperature (200 °C) primary air results in the most significant moisture loss rate, hence the reduced magnitude of mixing effect on the speed of moisture loss, in comparison with results obtained when using 100–150 °C temperature primary air. During the experiments using 200 °C temperature primary air for drying, it was determined that increasing the mixing intensity causes the increased difference of normalised moisture content. This drying rate dependence on the mixing frequency indicates that when the primary air temperature is high (200 °C), it bolsters radiation’s effect on the moisture loss rate.

The most efficient mixing of the layer is when the chipped wood biofuel is dried at a drying air temperature of 150 °C for 30 minutes, and the mixing of the biofuel layer is repeated every 150 seconds.

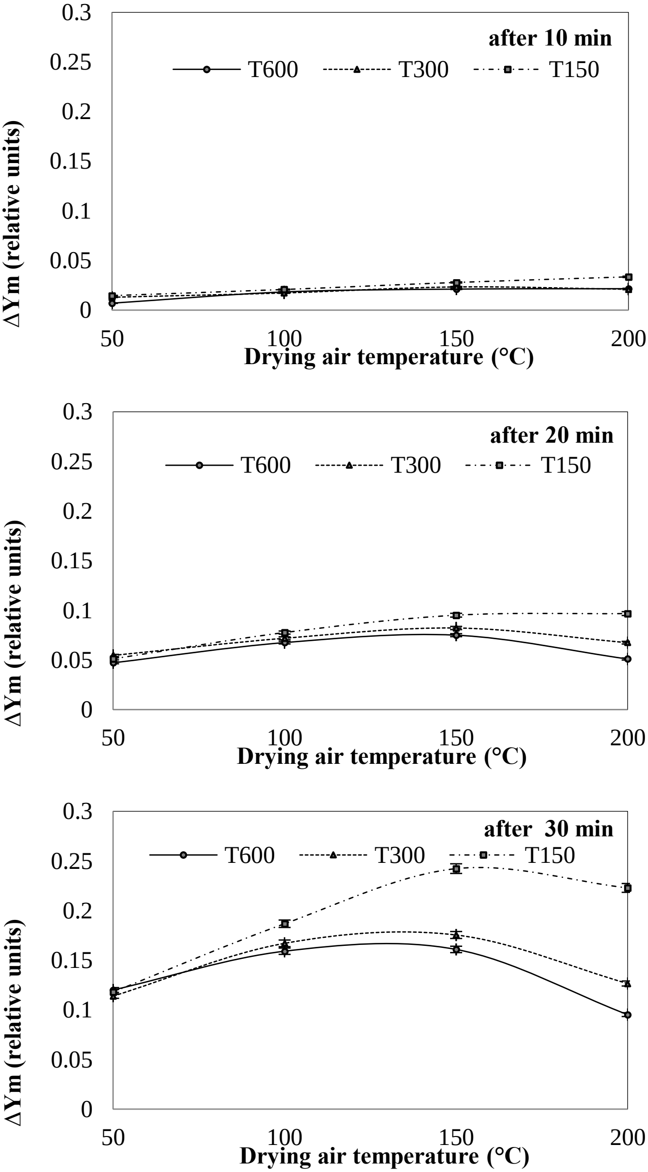

Fig. 3.5 Effect of chipped wood biofuel layer mixing on the variation in moisture content rate

4. APPLICATION OF VIRTUAL SENSOR FOR COMBUSTION CHAMBER CONTROL ACCORDING TO DETERMINED MOISTURE CONTENT OF BIOFUEL

Conduction of laboratory experiments allowed the identification of tools that have the highest effect on the process of moisture loss. Applying a combination of said tools permits adjusting the combustion rate to both directions based on the moisture content of the combusted biofuel. Although even if means of increasing the moisture loss intensity are known, the industry still lacks measurement devices that would allow it to monitor the moisture content of supplied biofuel in real-time and then apply the most suitable measures. As indicated in the literature review section, moisture content measurement devices currently on the market are very difficult to apply in real biofuel combustion systems for various reasons, hence the conduction of virtual sensor analysis in a real middle power range biofuel combustion device. With the aim of evaluating the precision of the designed method during fully automated biofuel combustion control, fuel moisture content was also measured. The designed algorithm was integrated into the data collection and processing system (further referred to as SCADA). The measurement of biofuel samples and registration of data was performed within several days (Table 4.1).

After collecting and analysing the data, the biofuel moisture content was calculated to be close to the figures obtained when measuring directly in a laboratory environment. Performing heat balance calculations determined that the maximum deviation compared to values obtained from direct measurement did not exceed 2.4% by mass (Table 4.1). During the experiments, simultaneous to heat balance calculations, moisture content measurements in the flue gas were measured using a relative humidity (RH) sensor. However, in this case, more significant errors were observed in the results, and the deviation exceeded 6% by mass. The reason for such an error is the relative humidity dependence on the temperature. In cases of high temperature measurements, the sensor reaches predefined limits of measurement, which are in the range of 2–98%. Hermansson S. et al. (Hermansson, Lind, Thunman 2011) have received similar results in their work and also observed low accuracy of the relative humidity measurement method.

Table 4.1 Moisture content measurements during the operation of the biofuel boiler

Parameter	T_21	T_22	T_23	T_24	T_25	T_26
Day month	07 11	15 11	22 11	29 11	30 11	05 12
Chipped wood moisture content, wt.%	52.1	54.2	49.1	44.3	47.2	53.0
Parameters of the boiler:						
Boiler capacity, MW	3.32	3.34	3.35	4.09	4.16	3.96
FGCE capacity, MW	0.70	0.75	0.68	0.79	0.80	0.81
Flue gas temperature °C	137.3	141.0	144.1	153.1	152.6	151.2
Flue gas blower motor frequency, Hz	24	27	30	32	32	33
Calculate fuel (daf) amount, kg/h	720	736	749	863	889	790
Estimation of fuel moisture from FGCE heat balance:						
Calculated moisture content in the flue gas, kg/h	724	846	655	715	785	831
Calculated fuel moisture wt., %	50.2	53.5	46.7	45.3	46.9	51.3
Deviation from the measured moisture wt., %	1.9	0.7	2.4	1	0.3	1.7

4.1. Prediction of biofuel moisture content for automated combustion process control

The connection between moisture content difference and FCGE heat load was determined by conducting tests of chipped wood biofuel combustion in an actual 6 MW power-rated combustion system. However, it is necessary to evaluate the operation of the system and its sensitivity to automated control concerning the changing moisture content of the supplied biofuel.

An experiment spanning two days was conducted to evaluate the designed method for predicting biofuel moisture content. Using the SCADA system, the data were collected continuously. Figure 4.1 displays the calculated (moisture content in biofuel, water content in biofuel and the mass of dry biofuel) and measured (FCGE and the efficiency of the boiler) parameter changes within the experiment duration. Additionally, Fig. 4.1 displays the frequency of biofuel feeding. The experiments were initiated, beginning to supply biofuel with 54% moisture content (by mass) during the first 7 hours. For the next period, from 7h to 12h, biofuel with 60% moisture content was supplied. For the night (12–24h period), the system was supplied with drier biofuel, the moisture content of which did not exceed 54% by mass. Finally, in the 26-30h period of the experiment, biofuel with a more significant moisture content (~60%) was used. It is necessary to note that at the 30.5h mark, the flue gas economiser water circulation pump experienced a critical malfunction and had to be switched off. For this reason, it was impossible to evaluate the stabilisation of the curves.

SCADA system displayed values at period Δt = 00:00:55. The distribution of the values is highly inconsistent, which indicates the possibility of a vast amplitude of fluctuations. In order to eliminate the noise, the signals were processed (smoothed) using a weighted average.

Selecting the measurement range of up to 151 measurement points (the equivalent of 1h 09min 12sec) provided maximum and minimum biofuel moisture content values (Fig. 4.1). The system was determined to be relatively inert, and the biofuel moisture content changes from one value to the other determine a transit period of 3 hours. It is affected by the fuel supply system and the size of the combustion chamber: the fuel supply hopper, located before the combustion chamber, contains up to 1 ton of chipped wood biofuel, and the entire combustion cycle in fire-grate-based combustion chambers runs its course in 30 minutes. Additional time is required to swap out the biofuel and supply it into the combustion chamber.

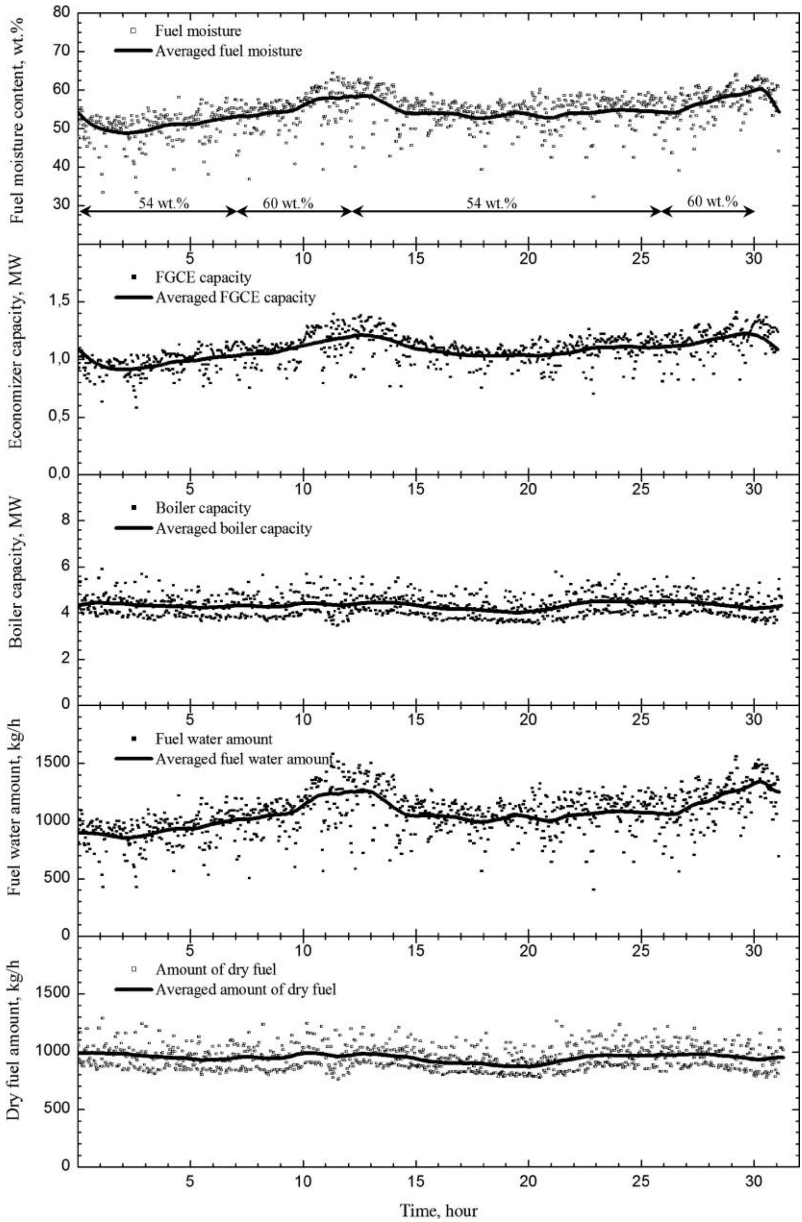

Fig. 4.1 Calculated (fuel moisture, fuel water and dry fuel amount) and measured (FGCE and boiler capacity) temporal changes. The sliding weighted average is calculated for n = 151 measuring

In order to introduce the correction coefficient for automated combustion control concerning the moisture content of the biofuel, it is necessary to analyse the moisture content changes with respect to time. A temporary magnitude of moisture content increment and decrement was observed by considering the average biofuel moisture content derivative for time $\frac{d\overline{Y^{HB}}}{dt}$ (Fig. 4.2).

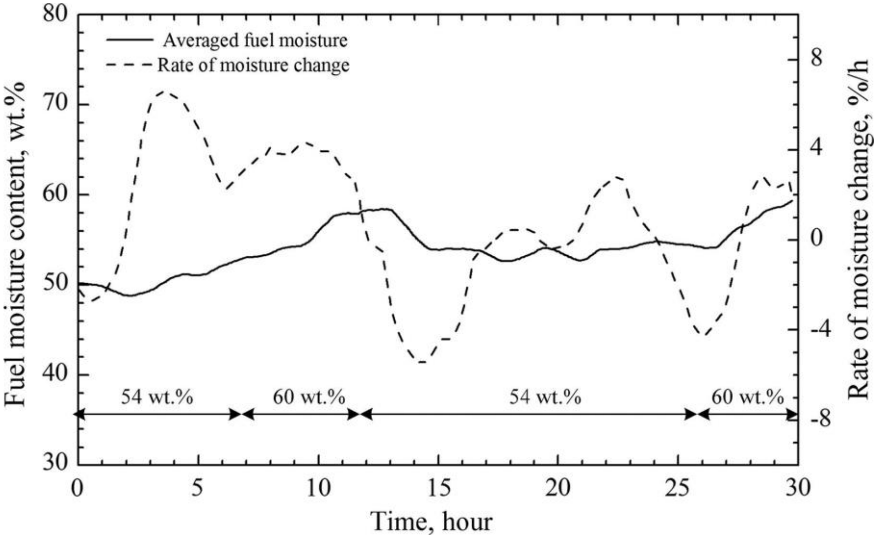

Fig. 4.2. Fuel moisture content (straight line) and the rate of moisture change (dashed line) during the boiler operation. The sliding weighted average is calculated for n = 151 measuring points

The positive value of the average moisture content derivative against time indicates moisture content increase in the flue gas, the negative value indicates decrement, and equity to zero indicates no change in the moisture content. This curve also indicates the moments of reaching maximum and minimum values of biofuel moisture content, i. e. when the fuel types in the combustion system are switched. The first peak of moisture content difference was registered at the 3-hour mark from the moment when biofuel of 54% moisture content began being supplied. Afterwards, the derivative started approaching zero, and if there were no changes in biofuel type for some time, this indicates stabilisation of moisture content within the biofuel. After 7 hours from the experiment's beginning, supplying 60%, moisture content biofuel was initiated. This switching of biofuel type affected the next peak of moisture content difference (moisture content rate increment of 4%/h) at hour 10. At night the system was using lower moisture content of 54% by mass, which led to the moisture content difference rate decreasing at hour 12 and reaching lower values at the 14-hour mark. Similar moisture content change rate characteristics were observed during the second day of the experiment when the high moisture content (60% by mass) biofuel supply was resumed at hour 26. Based on the analysis of these results, the most effective method of combustion process control is the usage of the average biofuel moisture content change against time, meaning when $\frac{d\overline{Y^{HB}}}{dt} \neq 0$, the system must respond by changing the parameters of the combustion process control: fire-grate movement settings, supplying of recirculated flue gas, parameters and amounts of primary air, etc.

Measurement of combustion chamber output data in real-time is smoothed according to the following (10) equation:

$$\bar{x}_j = \frac{\sum_{i=0}^{n-1} \omega_i x_{j-i}}{\sum_{i=0}^{n-1} \omega_i}, j = [0, N-1], x_j = x(t_j), t_j = t_0 + j\Delta t, \Delta t = 55 \text{ s}; \qquad (10)$$

Moisture content values smoothed using equation (10) will be delayed from real-time measurements by a margin of half-filter width. If the total amount of measurement points $n = 151$, the total filter temporal width equals 2 hours, 18 minutes, and 24 seconds, so the half-width equals 1 hour, 9 minutes, and 12 seconds. In this case, at each moment in time, there exists an average (levelled out) value of biofuel moisture content equal to the value for 1 hour, 9 minutes, and 12 seconds ago.

It can be assumed that at hour 27.5 of the experiment average moisture content difference becomes positive ($\frac{d\overline{Y^{HB}}}{dt}>0$). It means that the properties of the supplied biofuel are changing, and the moisture content in the biofuel began increasing 1 hour, 9 minutes, and 12 seconds ago. Using this method, the automated control circuit traces the change of moisture content in the biofuel and, according to this rate of change, anticipates when the greatest allowable value of the selected regimen is reached. If the moisture content derivative against time is decreasing, it is possible to predict based on the rate of acceleration of decrement when it will reach zero, i. e. when the process will stabilise, rendering any changes unnecessary. Determining the characteristics of smooth change of process parameters by observation of moisture content differences, biofuel drying- and combustion-affecting factors (primary air, flue gas parameters, movement of the fire-grate) allows making corrections gradually instead of in intervals.

For the application of the previously described indirect biofuel moisture content prediction method, a combustion control algorithm was designed (Fig. 4.3). It is necessary to install correction measures into the automated system of the combustion process control based on obtained values that depend on increasing or decreasing biofuel moisture content level. The control algorithm is a constituent of the biofuel moisture content prediction method, described in Section 2.2. Using the FCGE heat balance, described in detail in Section 2.2.2 and the equation (9) to calculate the biofuel moisture content Y^{HB} allows calculating the average moisture content Y_j^{HB} with the use of a real-time smoothening function (11):

$$\overline{Y_j^{HB}} = \frac{\sum_{i=0}^{n-1} Y_i^{HB} x_{j-i}}{\sum_{i=0}^{n-1} Y_i^{HB}}, j = [0, N-1], x_j = x(t_j), t_j = t_0 + j\Delta t, \Delta t = 55 \text{ s};$$

In order to perform these calculations in the algorithm, it is necessary to designate a period *dt*. In *d/dt* cycle, the time derivative $d\overline{Y_j^{HB}}$ at a time t is calculated as follows:

(11)

$$\frac{d}{dt} = \frac{d\overline{Y^{HB}}}{dt} = \frac{m_{mfg}^{HB}}{m_{mfg}^{HB} + \frac{Q_B}{LVH \cdot \eta}} 100/dt; \quad (12)$$

The relative humidity of biofuel supply d_K (%) is calculated as follows:

$$d_k = Y_j^{HB} = \frac{m_{mfg}^{HB}}{m_{mfg}^{HB} + \frac{Q_B}{LVH \cdot \eta}} 100; \quad (13)$$

If the derivative is equal to zero ($\frac{d\overline{Y^{HB}}}{dt} = 0$), the cycle starts anew; if the derivative is greater than zero, the cycle continues. Automated combustion control objectives are corrected using the condition d/dt>0 ($\frac{d\overline{Y^{HB}}}{dt} > 0$). If the value $d\overline{Y_j^{HB}}$ satisfies the condition 65>$\overline{Y_j^{HB}}$>54 (65>d_k>54),

The automated control system adapts to the parameters that match the moisture content of 60% (by mass). Otherwise, the control system adapts to the parameters matching the moisture content of 54% (by mass).

The moisture content prediction algorithm provides an advanced control strategy design for an effective and stable chipped wood biofuel combustion regarding the changing moisture content within the combustion duration. Such a control strategy ensures a stable and constant supply of biofuel to the combustion chamber by adjusting the movement rate of the fire-grate. Additionally, calculating flue gas moisture content allows introducing a correction coefficient for measuring the oxygen amount in the flue gas and reducing the excess air. The latter reduces heat loss and increases biofuel powerplants' overall effectiveness.

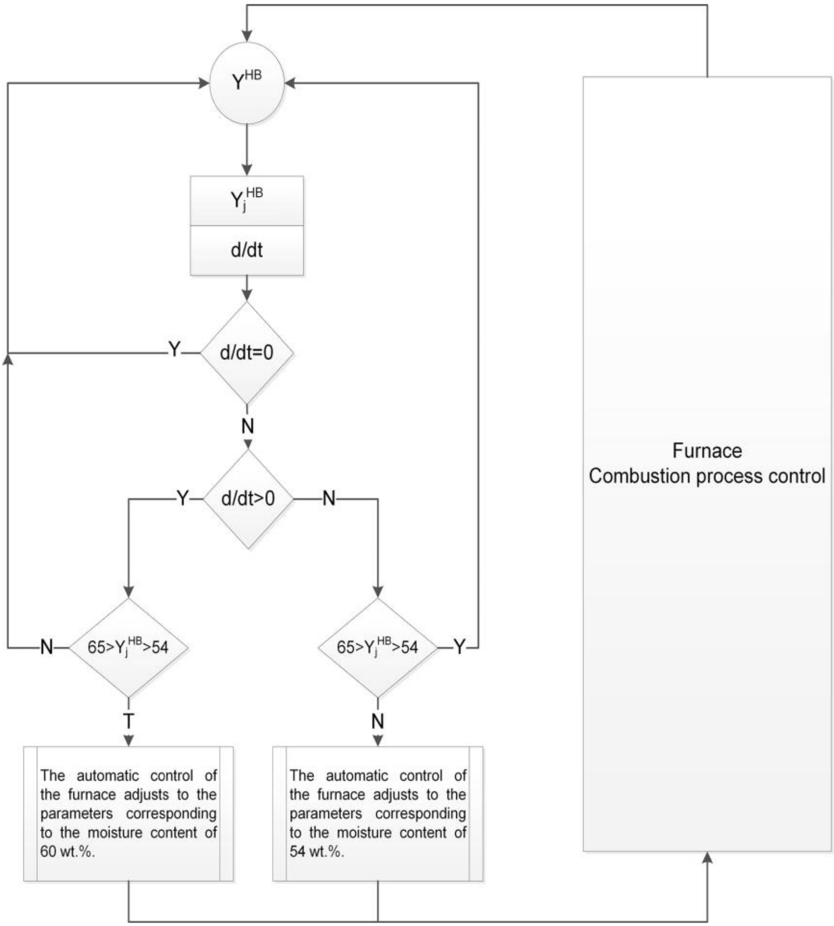

Fig. 4.3 Fuel moisture prediction algorithm to correct the automatic control of the furnace

5. RECOMMENDATIONS

Application of a virtual sensor for automation of the combustion process, based on the established measures of chipped wood biofuel moisture loss rate and its dependence on the type of drying agent (air or air and steam mixture), the temperature of the air and steam drying mixture, and the movement frequency of the fire-grate allow forwarding some recommendations for future research.

- ✓ A review of relevant research and comparison of test results determined that the biofuel moisture loss rate depends not only on the supplied air temperature but also its flow velocity. In order to stimulate the rate of moisture loss, it is recommended to increase the airflow speed in the drying stage of the combustion chamber. However, it is necessary to consider the airflow rates in other sections of the combustion chamber when increasing the airflow rate in order not to create an excess of air during combustion.

- ✓ During testing of chipped wood biofuel moisture loss intensity, it was determined that the air temperature supplied through the bottom of the fire-grate has a considerable effect. In order to speed up the spontaneous spread of combustion in the biofuel, its moisture content must be decreased to under 45% by mass (H. Thunman et al., 2001). It can be achieved by recirculating hot combustion products from the combustion section of the chamber towards the drying stage. This method allows achieving temperatures of primary air as high as 900 ºC.
- ✓ The chipped wood biofuel moisture loss rate results when the input was treated with a 50–200 ºC temperature mixture of air and steam indicated that recirculated flue gas for temperature reduction in the biofuel layer and combustion zone in a furnace reduces the rate of moisture loss. The return of humidity gases to the furnace causes a more intense water condensation onto the wood particles in all load layers. Hence if using highly damp biofuel (60% or more by mass), it is recommended that recirculated flue gas be heated no less than 200 ºC or their supply be discontinued.
- ✓ When conducting a literature review (Martinez-Garcia et al. 2015; Sheikholeslami, Watkinson 1992) and summarising the results of conducted experiments that were performed to analyse the effect of radiation from the inside furnace surfaces to the biofuel layer allowed to evaluate its effect on the moisture loss rate of biofuel (Section 3.3). It was determined that thermal radiation considerably affects the intensity of moisture loss in biofuel. Consequently, designers of new ‘smart’ combustion devices are recommended to design the internal dome of the combustion chamber, separating the gas combustion sections, slanted at a 195° – 205° angle (additional research in a real setting is required), in order to cause the side walls of the chamber to absorb as much heat as possible in the combustion section and to cause the majority of the thermal radiation to be directed towards the biofuel drying section.
- ✓ Biofuel takes about 30 minutes from the moment it enters the combustion chamber until the complete elimination of ash, and the drying section takes about 10 minutes. In order to determine the effect of time spent on the fire-grate on the rate of moisture loss, the duration of the experimental tests was selected to be 30 minutes. Conducting tests with both stationary and non-stationary chipped wood biofuel layers has determined that the biofuels with high moisture content (60% moisture content by mass) 10 minutes is insufficient for the drying stage and does not permit reaching conditions that favour spontaneous ignition. Reviewing of related research allows suggesting

changing the movement direction or slant angle of the grates in the combustion chamber, i. e. altering the direction of the grates so that they move opposite to the fire-grate. Scientists at the University of Luxembourg (Samiei et al., 2013) have determined that in the case of opposite grate movement, biofuel particles spend approximately 2 times longer in the drying section compared to unidirectional movement.

- ✓ Conducting analysis of chipped wood biofuel moisture loss involving agitation of the biofuel layers has determined that mechanical mixing of the biofuel layers increases the rate of moisture loss by 7–17 %, regardless of the temperature of drying air or the frequency of mixing, hence the recommendation to increase the mixing intensity in the combustion chamber. Based on research conducted by K. Samiei in 2013 (Samiei et al., 2013), it can be indicated that opposite grate movement concerning the main fire-grate in the combustion chamber induces better mixing of the biofuel content. Said researchers have also determined that increasing the biofuel layer thickness reduces the effect of the difference between types of fire-grates; hence the need to select optimal biofuel layer thickness, as in cases of very thick layers, the upper part of the layer does not mix but instead slides along the surface.

CONCLUSIONS

Having analysed the combustion factor influence on drying high moisture content (60±5%) chipped wood biofuel of various properties by simulating processes that generally occur in the drying section of the furnace, the following was determined:

1) Increasing the primary air temperature from 50 °C to 200 °C increases a chipped wood biofuel drying rate by 4.75 times. The highest rate of drying (23.2% in 30 min) is observed when drying the smallest particle size biofuel with 200 °C temperature primary air.
2) Recirculated flue gas of various temperatures (50 – 200 °C) supplied through the bottom of the fire-grate causes stagnation, and its duration ranges from 2.5 to 12 min. Due to this phenomenon, the steam in flue gas causes the drying rate to become insignificant, and most heat transferred is used to warm up the biofuel particles instead of drying them.
3) In cases of supplying 200 °C temperature primary air and using 50kW/m^2 power density infrared heaters simulate internal radiation, the maximum observed water content difference in smallest particle size chipped wood biofuel after 30 min of drying was 65%, in cases of only using primary air – 19.5% and in cases of using primary air and recirculated flue gas – 23.2%. A shorter drying period (10 min) has resulted in smaller moisture content changes (2 – 7%) using various affecting factors.
4) The highest stirring influence on the drying rate was observed when using 150 °C primary air and under 50kW/m^2 simulated internal radiation. Stirring every 150 s, the drying rate increases 2.1 times, every 300 s – 1.8 times and every 600 s – 1.7 times. Increasing the primary air temperature to 200 °C has caused the drying rate to decrease from 1.25 to 1.6 times with varying stirring frequencies.
5) Based on obtained results, an algorithm was proposed and installed for calculating moisture content in 6 MW power rating biofuel combustion furnace controller. During testing, it was determined that the calculated moisture content figures differ by less than 2,4% compared to directly measured moisture content. However, due to input inertness, the obtained data would be delayed by up to 1h 09 min 12s when using changing weighted average method.

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Padėka

Disertacijos darbo autorė dėkoja moksliniam vadovui dr. Nerijui Striūgui už kantrybę ir Lietuvos energetikos instituto Degimo procesų laboratorijos kolegoms už naudingus patarimus, paramą ir pagalbą, disertacijos rengimo metu.

Darbo tikslas

Ištirti skirtingų savybių drėgnos (60±5 %) smulkintos medienos sluoksnio džiūvimą ir nustatyti degimo procesą lemiančių veiksnių įtaką drėgmės išsiskyrimui.

Darbo uždaviniai

Imituojant judančios ardyninės pakuros džiovinimo zonoje vykstančius procesus, būtina atlikti šiuos pagrindinius uždavinius:

1) Naudojant skirtingos frakcinės sudėties drėgną smulkintą medieną ir eksperimentiškai imituojant skirtingas džiūvimo sąlygas, nustatyti drėgmės išsiskyrimo greitį:
   a) į sluoksnio apačią tiekiant skirtingos temperatūros pirminį orą,
   b) į sluoksnio apačią tiekiant skirtingos temperatūros pirminio oro ir recirkuliacijos dūmų mišinį,
   c) į sluoksnio apačią tiekiant skirtingos temperatūros pirminį orą ir infraraudonųjų spindulių šilumos šaltinį, siekiant imituoti šilumos spinduliavimą nuo įkaitusių vidinių pakuros paviršių.
2) Nustatyti smulkintos medienos drėgmės išsiskyrimo greitį keičiant kuro sluoksnio maišymo dažnį ir naudojant didžiausią įtaką džiūvimui turinčius veiksnius.
3) Išnagrinėti didžiausią įtaką džiūvimui turinčių veiksnių keitimo galimybes, siekiant kontroliuoti drėgmės išsiskyrimo procesą realiose biokuro pakurose.

Darbo aktualumas

Biokuro deginimas – tai vienas dažniausiai naudojamų būdų šilumos ir elektros energijos gamybai iš biomasės. Tačiau biokuro deginimas yra sudėtingas procesas, o dėl nuolat kintančios jo sudėties susiduriama su įvairiomis problemomis, tokiomis kaip nevisiškas kuro sudegimas ar pavojingų teršalų susidarymas. Viena iš dažniausiai kintamų biokuro savybių yra kuro drėgnis, kuris kinta plačiose ribose ir gali siekti daugiau nei 60 % patenkančio kuro masės. Labai drėgna smulkinta mediena pakuroje ant ardyno nedega, o džiūva, užimdama didžiąją dalį ardyno. Siekiant tobulinti biokuro deginimo įrenginius, pirmiausiai reikia nustatyti biokuro drėgmės išsiskyrimui ant ardyno turinčių veiksnių įtaką, priežastis ir priklausomumus nuo džiovinimo agento temperatūros ar įkrovos maišymo periodo. Pagal gautus rezultatus biokuro katiluose galima sukurti ir integruoti virtualius drėgmės kitimo prognozavimo jutiklius, leidžiančius efektyviau eksploatuoti biokuro deginimo įrenginius.

Mokslinis naujumas

Ištirta drėgnos (60±5 %) smulkintos medienos drėgmės išsiskyrimo biokuro sluoksnyje dinamika ir nustatytas jos priklausomumas nuo degimo procesui įtaką turinčių veiksnių.

Rezultatų praktinė reikšmė

Disertacijoje gauti rezultatai leidžia optimizuoti drėgnos (60±5 %) smulkintos medienos biokuro degimo procesą, padidinti jo efektyvumą esamose ar naujai kuriamose judančiose ardyninėse pakurose. Biokuro drėgnio patenkančio į pakurą prognozavimui ir džiūvimo proceso intensyvinimui galima sukurti ir įdiegti virtualius jutiklius leidžiančius efektyviau eksploatuoti biokuro deginimo įrenginius.

Ginamieji disertacijos teiginiai

1) Didžiausias drėgmės išsiskyrimo greitis pasiekiamas džiovinant smulkiausios frakcijos biokurą, o didinant pirminio oro temperatūrą, drėgnos smulkintos medienos drėgmės išsiskyrimas didėja.

2) Deginant 60±5 % drėgmės biokurą, mažesnė nei 100 ºC recirkuliuojamų dūmų temperatūra drėgmės išsiskyrimo procesą veikia neigiamai.

3) Pirminis oras ir šilumos spinduliavimas nuo įkaitusių vidinių pakuros paviršių neleidžia pasiekti optimalaus drėgmės kiekio biokuro sluoksnyje.

4) Degimo procesui įtaką turinčių veiksnių visuma leidžia pasiekti 2 kartus intensyvesnį drėgmės išsiskyrimą.

5) Pakuros valdyme įdiegtas drėgmės kiekio dūmuose skaičiavimo algoritmas leidžia prognozuoti tiekiamo į pakurą biokuro drėgmės kitimą.

IŠVADOS

Ištyrus degimo procesą lemiančių veiksnių įtaką drėgmės išsiskyrimui iš skirtingų savybių drėgnos (60±5 %) smulkintos medienos sluoksnio imituojant judančios ardyninės pakuros džiovinimo zonoje vykstančius procesus, nustatyta:

1. Didinant pirminio oro temperatūrą nuo 50 °C iki 200 °C, smulkintos medienos bandinių drėgmės išsiskyrimo greitis padidėja iki 4,75 karto. Intensyviausias drėgmės išsiskyrimas (23,2 % per 30 min) stebėtas džiovinant smulkiausios frakcijos medienos biokuro bandinį su 200 °C temperatūros pirminiu oru.
2. Pro ardyno apačią tiekiant skirtingos temperatūros (50–200 °C) recirkuliacijos dūmus, biokuro sluoksnyje pasireiškia džiūvimo stagnacijos reiškinys, trunkantis nuo 2,5 iki 12 min. Šio reiškinio metu dėl vandens garų esančių dūmuose kondensacijos drėgmės išsiskyrimo greitis tampa minimalus, o tuo metu išsiskyrusi kondensacijos šiluma yra sunaudojama šaltoms biokuro dalelėms šildyti, o ne vandeniui išgarinti.

3. Tiekiant 200 °C temperatūros pirminį orą ir imituojant biokuro sluoksnio paviršiui tenkantį 50 kW/m^2 šiluminį spinduliavimą nuo pakuros įkaitusių paviršių, maksimalus drėgmės kiekio pokytis smulkiausios frakcijos tirtame smulkintos medienos bandinyje po 30 min siekė apie 65 %, kai atitinkamai veikiant tik pirminiu oru – 19,5 %, pirminiu oru ir dūmų recirkuliacijos produktais – 23,2 %. Trumpesniu (10 min) džiūvimo laikotarpiu drėgmės pokytis siekė tik 2–7% veikiant medienos sluoksnį skirtingais, įtaką darančiais veiksniais.
4. Didžiausia maišymo įtaka drėgmės išsiskyrimui buvo džiovinant bandinius 150 °C temperatūros pirminiu oru ir esant šiluminiam 50 kW/m^2 spinduliavimui. Maišant smulkintos medienos biokuro įkrovą kas 150 s, drėgmės išsiskyrimo greitis padidėja net 2,1 karto, atitinkamai kas 300 s – 1,8 karto ir kas 600 s – 1,7 karto. Didinant oro temperatūrą iki 200 °C, drėgmės išsiskyrimo greitis sumažėjo ir kito nuo 1,25 iki 1,6 karto priklausomai nuo maišymo dažnio 600 s, 300 s ir 150 s.
5. Pagal gautus tyrimo rezultatus pasiūlytas ir įdiegtas drėgmės kiekio dūmuose skaičiavimo algoritmas 6 MW šiluminės galios pakuros valdyme. Pakuros bandymų metu nustatyta, kad pasitelkus šį algoritmą apskaičiuotos biokuro drėgnio vertės neviršija 2,4 %, lyginant su tiesioginiu metodu išmatuotu biokuro drėgmės kiekiu. Tačiau dėl pakuros inertiškumo, taikant kintamo svertinio vidurkio metodą kuro drėgmės kiekiui prognozuoti, gaunami duomenys vėluotų iki 1 h 9 min 12 s.

UDK 662.63+620.92](043.3)

SL 344. 2023-__-__, ___* leidyb. apsk. l. Tiražas 36 egz.
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