Effect of Moisture Content of Solid Woody Biofuel on the Boilers Performance

Nerijus Striūgas
Nerijus.Striugas@lei.lt
* Lithuanian Energy Institute, Laboratory of Combustion Processes, Breslaujos str. 3, LT-44403 Kaunas, Lithuania

Abstract
The work presents the R&D experience of recent years in cooperation with local heat supply companies operating a solid woody biofuel boilers. Last decade, in Lithuania, most district heating supply companies have switched from liquid (heavy fuel oil) or gaseous fuels (natural gas) to solid biofuels, mainly burning forestry residues. The increase in demand for solid biofuels has not only increased the price, but has also reduced their quality. In particular, one of its main characteristics, moisture content, has changed or variated over the last decade. In most cases, solid biofuel boilers works well in the automated mode when their moisture content of wood chips varies between 40 and 55 %wt. However, once out of this range, there are constant operational and process control problems. This results in increased emissions of harmful pollutants and a reduction in the efficiency of the boiler itself, leading to significant economic losses.
The paper presents examples from several projects showing how the performance of the firebox varies with extremely dry or with wet solid biofuels. Proposed solutions and mechanisms to control the process are also presented.

Introduction
Lithuania is one of the few EU countries having a widespread district heating system (DHS). Currently most of the heat suppliers, with support from EU, essentially replaced the fossil fuels by biofuels in the DHS. The reciprocating (or moving) grate combustors are most popular. The furnaces with a typical capacity of 5–10 MW are equipped with water heating boilers and flue gas condensing economizers. Even though these moving grate furnaces is a common and well developed technology for burning biomass fuels and they are sufficiently robust to changes in the fuel quality, however, varying fuel moisture mostly in the range from 30 to 60% complicates their automated operation. Without manual adjustment of the grate motion mode and other parameters, unstable operation or even extinction of the furnace is possible. In order to adjust automatic control of the furnace with continuous operation to changing fuel parameters, it is necessary to measure the fuel moisture content or to establish dependencies between the fuel moisture and changes in the load of the condensing economizer and, based on this, keep adjusting automatically the boiler operation regime as the fuel moisture content changes.
Modern grate combustors are designed for high thermal efficiency with low emissions of gaseous pollutants (CO, NO_x, etc.) when firing biomass of 30–55% moisture [1]. Even though combustors are equipped with advanced parameter measuring instrumentation, but significantly fluctuating biomass moisture levels mainly cause operational problems in biomass combustors, lower stability of burning and insufficiency of the heat supply under conditions of elevated heat production [2]. These problems can be avoided by adjusting the boiler operating regime if the moisture content in biomass is known. However, direct methods for measuring the fuel moisture content in small to medium size biofuel fired heating plants are costly [3]. A soft-sensor for on-line monitoring of fuel moisture can be one of the optimal solution for such size power plants [4, 5].
This work was aimed at optimizing the performance of wood biofuel boilers, which revealed different performance characteristics when fired the fuel with different moisture contents, and exposed different necessary actions to ensure stable operation of the boilers with time-varying fuel moisture. A soft-sensor mechanism has also been proposed and tested, which showed that can be perfectly used to predict the moisture content of the biofuel and allows operators to take the necessary actions to avoid malfunctioning of the boilers and the generation of unwanted pollutant emissions.

Study Approach

The data presented in this paper is not typical information obtained in a conventional research study. Here we will present a summary of the experience gained over the years of work, showing the main problems occurred in solid biofuel combustion in practice and the solution methods adopted to optimize the process. In this paper, we will present two different cases with different problems occurred at the combustion of very wet fuel in a grate fired furnace and dry fuel in a fluidized bed type furnace.

Case1. Combustion of Wet Biofuel

Some time ago in Lithuania there was a problem that heat producers, in order to remain competitive on the heat market, chosen cheap extremely poor quality solid biofuels instead of good quality ones. Typically in winter time, such fuel come straight from forest preparation sites and has very high moisture content of up to 60% by weight. The boilers in operation are not designed to burn so wet biofuels, which can lead to unstable boiler operation and incomplete combustion. In addition, the drying process of the wet biofuel in the combustion chambers occupies most of the length of the grate, so that further optimization of the operation is required to burn the problematic fuel.

The tests were performed in a heat power plant fired solid biofuel installed by Axis Tech (Lithuania); Figure 1. Technical characteristics of the furnace are presented in Table 1. The solid biofuel is fed into the furnace and it moves along the grate, where the primary air is fed from below of it. The primary air also divided to three separate zones: the first one intensely dries the fuel affecting by high temperature and primary air fed from under the grate; in the second zone, feedstock gasification begins where the secondary air is supplied over the feedstock layer for volatiles combustion; and in the third zone, feedstock burns completely and ash are formed. The combustion is finished by supplying tertiary air into the duct connecting the furnace with the boiler. The temperature of flue gas flowing from the furnace to the boiler depends upon the load and fuels, and varies in the range 900–1100 ºC. Combustion of dry feedstock (less than 40% of moisture) results in higher temperature and thus can be reduced by flue gas recirculation. After the boiler flue gas gets into the multicyclone and cleaned is supplied into a direct contact flue gas condensing economizer. The flue gas with the temperature of 46 – 56 ºC is ejected from the economizer into the atmosphere by a flue gas blower.

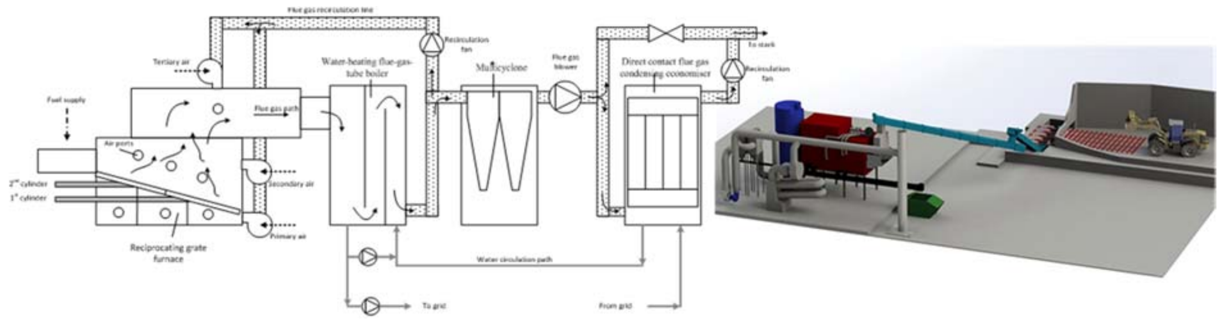

Figure 1. The scheme and photo of experimental combustion system

Table 1. Technical data of reciprocating grate furnace

Parameter	Value
Nominal power, MW	6
Operating power, MW	5.2
Capacity of feedstock hopper, m³	5
Maximum size of feedstock, mm	5x20x50
Load range, %	30...100
Air excess coefficient	1.4
Temperature of combustion products exiting the furnace, ºC	900...1100
Biofuel consumption, kg/h (m³/h) per MW	530 (1.74)
Boiler efficiency at biofuel moisture of 40 wt%, %	89
Ash content in feedstock, %	1.5...5.5

During experiments, the water heating boiler operated in the automatic regime according to the existing heat demand. The thermal performance of boiler was tested in accordance with standard EN 12952-15. In order to simulate the case when the fuels moisture changes, two types of biofuels with different moisture content were delivered at the site (Fig.2). The changes in feedstock moisture during plant operation were monitored using the indirect moisture determination method as presented in our previous work [5]. The main idea of this method was calculation of moisture from the heat balance of flue gas condensing economiser (FGCE). The mini soft was integrated into the SCADA system for predicting the changes in feedstock parameters. During this test were analysed how promptly this method would react to biofuel moisture changes. The experiments were carried out over the period of two days feeding feedstock of different moisture into the furnace. As well as all, the furnace operation was manually corrected in order to adjust the parameters of the selected regime to avoid pollution formation.

Figure 2. Two types of biofuels at the experimental site

The first run of experiments estimated automatic operation of the boiler with a furnace and its adjustment to feedstock with varying moisture content of 37, 46 and 50 wt.%. As the moisture content changes, so do the main technical parameters of the furnace. The highest biofuel consumption recalculated for dry fuel mass was in the case when the wettest feedstock was fired – 253 kg_{dry}/MWh, compared to 229 kg_{dry}/MWh for driest and 239.3 kg_{dry}/MWh for middle. One of the factors influencing increase in fuel consumption was inefficient combustion. Flow of primary, secondary and tertiary air for optimised process also changed. In order to combust 1 kg/h of biofuel was 4.3 m^3/kg for fuel with moisture content of 50%, slightly more at 4.8 m^3/kg for moisture content of 46%, and smallest at 4.1 m^3/kg for the driest one. As the fuel moisture content increases, water content in flue gas and flue gas volume increase as well, and the oxygen concentration decreases. As the oxygen concentration decreases, the boiler control circuit reacts and adjusts the air supply rate according to the pre-set oxygen content until the required value is reached, thereby increasing the real oxygen content recalculated for dry flue gas. Finally, the existing automatic control algorithm of the furnace might lead to insufficient air supply for moist feedstock at maximum loads, even though the air blowing equipment is selected with a certain excess capacity. Increasing the air increases the total volume of the flue gases, leading to higher heat losses with the outgoing flue gas. During combustion of wood chips with various moisture contents, the furnace operation regime was adjusted manually in order to avoid incomplete combustion or even extinction. This was done by changing the speed of two separate grates: for the driest one the ratio was 1:1 (this ratio shows that the feedstock motion velocity on the 1st grate is twice as high as that on the second grate) then 2:1 for middle and 6:1 for wettest. Performed experiments imply a few main conclusions. First, due to specific properties of the oxygen measuring instrument installed on the boiler, the measured excess oxygen rate changes only insignificantly in all the measured cases. Meanwhile, the readings of the flue gas analyser change, and the air excess ratio is lowest when operating with dry feedstock. This difference in instrument readings might appear due to different conditions of operation: the oxygen analyser installed in the boiler measures the oxygen concentration in wet gases, whereas the gas analyser measures it in dry flue gas. As the feedstock moisture content increases, the water content in flue gas and the flue gas volume increase, whereas the oxygen concentration decreases, therefore, the automated control supplies excessive amount of air. Second, in order to ensure the quality combustion of feedstock with increased moisture, not only the air flow distribution must be automatically adjusted, but the grate motion ratio as well.

The second run of experiments associated with predicting changes of biofuel moisture and how prompt is the reaction of the furnace to changes in the feedstock. Experiments were performed over a two-day period in feeding to the furnace biofuel prepared in advance with moisture content of 54 and 60 wt.%. In the SCADA system, these values are recorded every time period of Δt = 00:00:55. The scatter of values is very uneven, i.e., there is a rather large amplitude of oscillations. In order to eliminate the noise, signals were smoothed using a weighted sliding average. The window width of the averaging filter presented in data processing was 101 measuring point, meaning time slot of 46 min 17 sec to both sides from the current point. However, only by increasing the window width to 151 measuring point (1 hour 09 min. 12 sec) the minimum and maximum values of the fuel moisture revealed (Fig. 3). The presented figures thus show that the system is rather inert and changes of feedstock moisture from one value to another lead to transition period of up to 3 h. This is influenced by the feedstock feeding system and the furnace size: the feedstock supply hopper installed upstream of the boiler holds up to 1 t of wood chips and the full combustion cycle on the grate takes up to 30 min. Besides, changing the feedstock in the storage area and its supply to the furnace hopper also takes time.

For prediction of averaged feedstock moisture data in real system, we applied trail behind the real-time measurement by half the filter width. That means, that for the number of filter points n = 151, the total temporal width of the filter is 2 hours 18 min. 24 sec, and half the width is 1 hour 09 min. 12 sec. In this case, at every time moment we have the average (smoothed) value of moisture that was present 1 hour 09 min 12 sec ago. Consequently, the automated control circuit must follow the changes in moisture and predict from the moisture change rate the time when it attains the highest value for the selected regime. If the derivative decreases, it is possible to predict from its decrease rate (i.e., the acceleration of the moisture change rate) when will it become zero and the process will have stabilized, therefore, there will be no need for changes. Having determined the nature of smooth transition of the process parameters by observing the changes in moisture, the motion of the reciprocating grate could be changed gradually rather than stepwise.

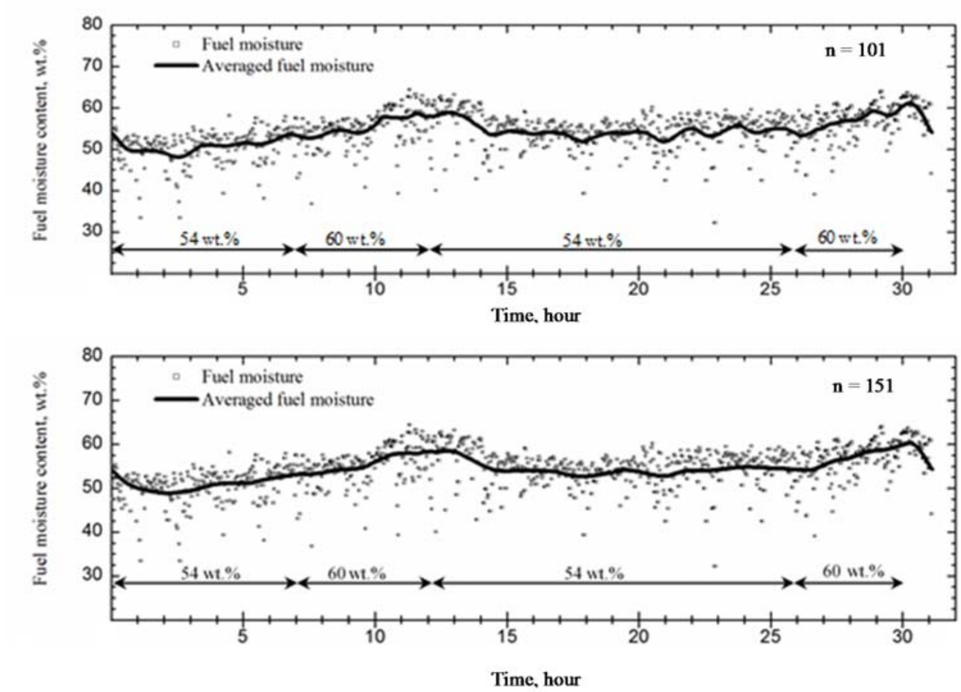

Figure 3. Temporal changes of calculated fuel moisture value and sliding weighted average calculated for n = 101 and 151 measuring point.

Case2. Combustion of Dry Biofuel

Case2 examined furnace performance working with dry solid biofuel, which are not in the range as designed for. The situation arose when fuel supplier started provide very dry fuel during the summer-autumn period, and thus fluidised bed boilers BFB 25-45-460 parameters became extremely dangerous for successful plant operation. When burning relatively dry fuel with a moisture content of less than 40%, the temperature of the fluidised bed in the furnace rises to the boiler shutdown threshold (950°C). The gas recirculation flue blower does not provide the necessary flue gas flow to maintain the calculated sand bed temperature when burning fuels (wood chips) with a moisture content below 40%. It was necessary to ensure a reliable operation of the biofuel boiler during the summer-autumn period, to maintain the estimated sand temperature between 840°C and 850°C and to prevent agglomeration of the bed when burning such type of wood chips. By default, the boiler temperature is controlled by increasing the amount of recirculated flue gas to the furnace. However, in this case, the flue gas recirculation fan is overloaded and its capacity is not sufficient to maintain the pre-set parameters. In this way, the plant operator started additional humidification of the feed biofuel. This method allowed the temperature of the fluidised bed to be lowered, but from an operational, combustion and cost efficiency point of view, it is not suitable.

In order to assess the quality of the bio-boiler operation, heat balance tests of the bio-boiler BFB 25-45-460 (Table 2) were carried out. The purpose of the tests was to carry test measurements with the dry biofuel in constant operation, to determine the actual boiler efficiency and to calculate the necessary flue gas flow to the boiler in order to avoid extra humidification of fuel. During these tests, samples of biofuel, bottom ash and fly ash were taken during the boiler's steady-state operation, and the main parameters of the air, flue gas leaving the boiler and the recirculated flue gas were measured (Figure 4).

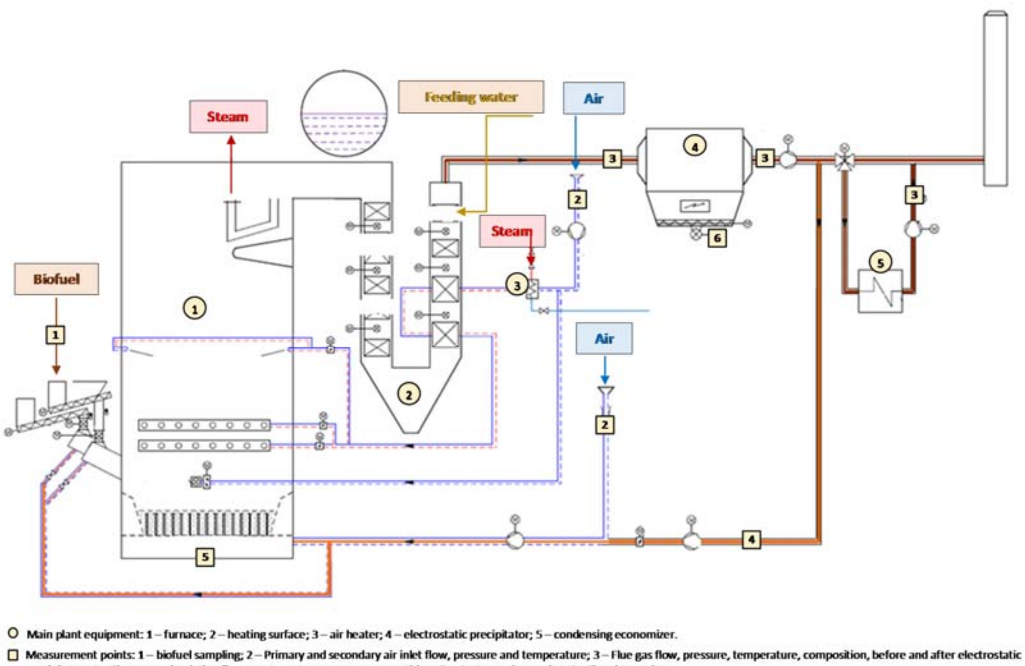

Figure 4. The scheme and photo of experimental combustion system

Table 2. Technical data of fluidized bed bio-boiler BFB 25-45-460

Parameter	Value
Nominal power, MW	20.2
Temperature of feeding water, ºC	110
Maximum temperature of superheated steam, ºC	460
Water volume, l	22000
Water flow through the boiler, m³/h	26,4
Maximum pressure of superheated steam, bar	56
Working pressure of superheated steam, bar	46

The composition and thus the energy value of the biofuels supplied during the tests varied only slightly throughout the test - a moisture content was of 37.9±1.6 wt%, an ash content of 0.84±0.05 wt% and a calorific value of 10343±363 kJ/kg. The amount of biofuel supplied to the furnace during the test was 8310±99 kg/h. The air velocity in the ducts was measured at three different points of the cross-section and averaged. The average primary air flow rate during the tests was found to be 2.1±0.1 Nm^3/s with the temperature of 30.6±0.1 °C and the averaged recirculated flue gas flow rate was found to be 2.7 Nm^3/s with the temperature of 182.5±0.5 °C. Both streams are mixed before entering the combustion chamber and the stream temperature reaches of 109.5±1.6 °C. Secondary air is fed into the furnace in two streams, one above the bed and one in the upper part of the furnace. The total measured secondary air flow during the test was 6.6±0.1 Nm^3/s. The secondary air is preheated in the air-flue gas heater at a temperature of 282.1±0.6 °C before entering the combustion chamber during the test. In order to recover a physical heat of flue gases and additional latent heat of condensed water vapour, a condensing economiser is used at the plant which operated continuously and stable during the thermal tests. The water temperatures upstream and downstream of the economiser were stable throughout the test, with mean values of 37.9±0.1°C and 46.7±0.1°C respectively. The flow rate of the thermal water through the economiser was 377.56±1.18 t/h. The flue gas temperatures before and after the economizer were 182.9±0.2°C and 48.9±0.2°C respectively. From these measurements can be seen how effectively is economizer which allowed to recover up to 4 MW (or increase of thermal efficiency from 88.4 to 90.2%) of heat from flue gases and condensation of water generation during combustion of biofuel and humidification of it. The thermal balance test revealed the efficiency operation of thermal power plant. However it does not explained the effect of fuel humidification on the operational parameters stability which leads to elevated temperatures of the bed and the entire furnace to an unacceptable limit and an emergency shutdowns of the boiler.

The temperature of the fluidised bed is controlled by varying the amount of flue gas recirculation. As the biofuel dries, the adiabatic combustion temperature rises, resulting in higher temperatures of the bed. The increase in temperature increases the amount of recirculated flue gas, which dilutes the combustion products with an additional flow, resulting in a lower adiabatic combustion temperature. However, trying increase the load of boiler obtained critical point when is not possible to increase the capacity of the flue gas recirculation blower to provide the required amount of flue gas and to reduce the temperature in the furnace. To avoid this situation, the dry biofuel is humidified, which in turn allows to increase the furnace output and not to raise the temperature above the critical stopping point. However, this solution increases operating costs, reduces the efficiency of the heat production process and makes the boiler more difficult to operate.

Additional humidification of biofuel increases the water content of the fuel and decreases its calorific value per unit mass (see Figure 5). For this reason, it is necessary to increase the amount of biofuel fed to the boiler in order to maintain a constant heat load of the furnace. Feeding wetted biofuel also introduces more water into the furnace, which needs to be heated and evaporated. This requires the combustion of additional fuel, which without wetting would provide an additional useful heat input. This wasted heat reduces the efficiency of the overall heat production process. In addition, as the moisture content increases, the volume of the flue gases increases as well and more heat is carried out with the outgoing smoke, which in turn reduces the efficiency of the boiler. By analysing the fuel parameters determined during the test, it is possible to estimate what the change in heat efficiency ($\Delta\eta$) would be if the fuel were not humidified. The average moisture content of the biofuel brought into storage during the test was 37.9±1.6 wt.% and after humidification was 40.2±0.6 wt.%. Thus, if we depict the points in Figure 5, we obtain that the $\Delta\eta$ at these two values is ~ 0.74 percentage points.

Figure 6 shows the variation of the average actual moisture content of the biofuel delivered to power plant in different months of the year, and the averaged moisture content of the humidified biofuel. As can be seen from the graph, the averaged moisture content of the biofuel supplied is ~37.7% and that of the biofuel humidified ~45.6%. Given these values and the amount of heat produced, the potential $\Delta\eta$ and its variation in different months of the year were also calculated and values plotted on the same graph (see Figure 6). The average annual $\Delta\eta$ was ~3.1 percentage points. However, it can be seen that in the summer months, supplied biofuel is extremely dry and its moisture content approaches ~30 %. In these cases, a significant amount of additional water is introduced to ensure the stable operation of the plant, which in turn increases the $\Delta\eta$ and reached a maximum of ~4.35 percentage points.

On the other hand, fuel humidification is good because it puts additional load on the flue gas condensing economizer, whose efficiency decreases significantly with decreasing biofuel moisture. In this way, part of the thermal energy can be recovered. However, during the summer when the highest fuel humidification and the highest $\Delta\eta$ the condensing economizer does not operate due to the absence of demand for heat consumption. For these reasons, once can be concluded, that it is necessary to optimize the combustion process in order to avoid the need for biofuel humidification and thus resulting heat losses.

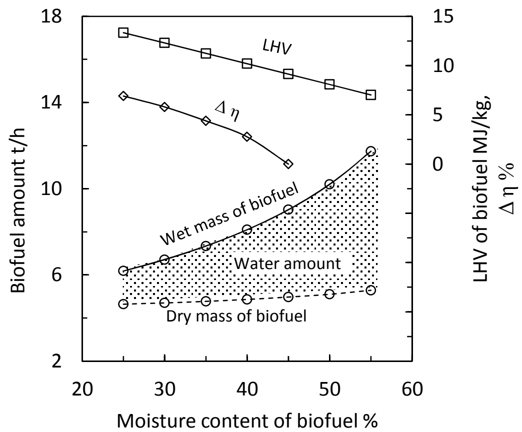

Figure 5. Dependence of biofuel LHV, the amount fed to the boiler and difference in thermal efficiency (Δη if the moisture content of biofuel is wetted to W^n=45 %) on the variation of the moisture content of biofuel, at a constant boiler thermal load of 22.91±0.23 MW and with the composition of the biofuel as determined in the tests

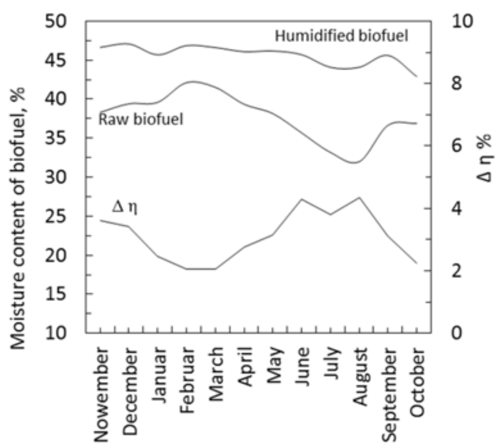

Figure 6. Variation of the average moisture content and calculated Δη of raw and humidified biofuels delivered during the year

For above purposes, additional calculations have been carried out to estimate the required air and flue gas recirculation flows to maintain the bed temperature within the target range of 740 - 840°C as the biofuel moisture content changes. The results of the calculation are summarised in Figures 7.

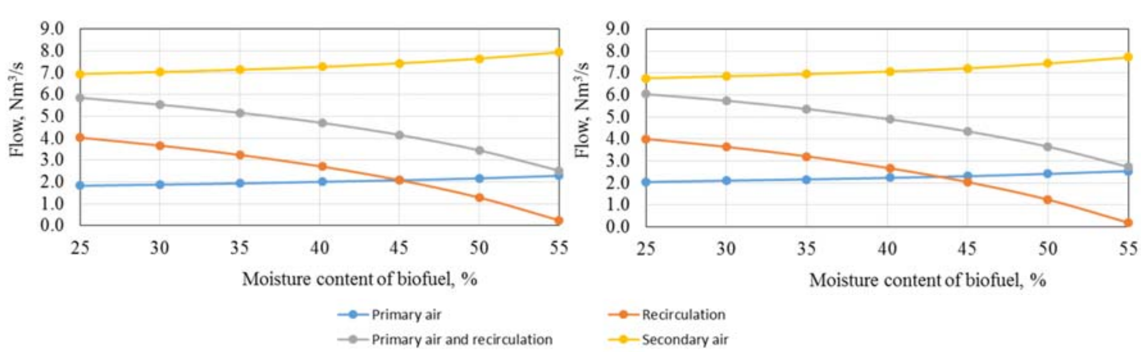

Figure 7. Combustion air and flue gas recirculation flows versus biofuel moisture content and at a bed temperature of 740 °C (a) and 840 °C (b)

As can be seen from the obtained results, in order to maintain a constant temperature of the fluidised bed, the primary and secondary air and flue gas recirculation ratios must be changed as the fuel moisture content changes: as the fuel dries, the primary air fed to the boiler must be reduced and the proportion of recirculated flue gas increased; while the secondary air feeding must be increased to compensate for the total amount of air required for combustion and to ensure full combustion. In the case of wet fuels, the flow distribution should be adjusted in reversed. Also it should be noted that, the total secondary air flow changes inversely to the case described above. However, this is only because the amount of fuel fed to the boiler changes as the moisture content of the fuel changes and the air amount changes accordingly to maintain the pre-set temperature. If the dependence were to be kept constant for a constant fuel amount regardless of temperature, the situation shown would be the same as that discussed above.

Conclusions

Research and experience with various solid biofuel boilers has led to the identification of a number of dependencies that are related to the raw biofuel properties. Biofuel boilers operated best within their design limits when the fuel moisture content is in the range 40-55 wt%. Outside these limits, continuous and usually manual adjustments to the process are required in order to maintain the target process parameters. This has been demonstrated in studies with extremely wet ~60wt% and dry solid biofuels ~35wt%. Combustion of wet fuels requires a longer biofuel residence time in the fuel bed, which requires the proper adjustment of the grate movement speeds, air distribution, and the reduction or elimination of flue gas recirculation below the fuel bed. In contrast, in case of dry biofuel requires the opposite, i.e. increased flue gas recirculation and also air supply readjustment. Thus, in order to successfully control the furnace automatically over a wide range of biofuel moisture content variations, it is recommended to use moisture measuring equipment. As these studies have shown, when operating a bio-power plant with a condensing economizer, very good humidity prediction is possible with the introduction of a soft sensor based heat balance calculation. Based on the experiments, an application of this method to predict moisture will lead to delay of data by half the filter width from the real-time measurement. In case of the presented research, half the width of the filter is 1 h 09 min 12 sec.

References

[1] Hermansson, S., Lind, F., Thunman, H., On-line monitoring of fuel moisture-content in biomass-fired furnaces by measuring relative humidity of the flue gases, *Chemical Engineering Research and Design*, Vol. 89, No. 11, pp. 2470-2476, 2011.

[2] Svoboda, K., Martinec, J., Pohořelý, M., Baxter, D., Integration of biomass drying with combustion/gasification technologies and minimization of emissions of organic compounds, *Chemical Papers*, Vol. 63, No. 1, pp. 15-25, 2009.

[3] Aulin, R., Karlsson, M., Standardisation of Moisture Measurement using NIR Spectroscopy for Delivery Control, *Värmeforsk rapport*, Värmeforsk, Stockholm, 2008.

[4] Kortela, J., Jämsä-Jounela, S.L., Fuel moisture soft-sensor and its validation for the industrial BioPower 5 CHP plant. *Applied Energy*, Vol. 105, pp. 66-74, 2013.

[5] N. Striūgas, L. Vorotinskienė, R. Paulauskas, R. Navakas, A. Džiugys, L. Narbutas, Estimating the fuel moisture content to control the reciprocating grate furnace firing wet woody biomass, *Energy Conversion and Management*, Volume 149, 2017, Pages 937-949.