E3S Web of Conferences 10, 00136 (2016) DOI: 10.1051/e3sconf/20161000136
SEED 2016

The possibility of using flue gases as a medium for straw drying

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Abstract. The paper presents the possibility of drying straw in dedicated and innovative straw dryers with a modified drying system. The basic problem behind the use of bales of straw as a fuel is their moisture content. The moisture content is mostly dependent on the time of harvest and the conditions of storage. The humidity level of dry straw may be as low as 10%, however harvesting the straw during unfavourable weather conditions may cause the moisture level to increase up to 60-70% of the relative humidity, a value often observed for fresh biomass. Experimental studies were conducted to examine the effectiveness of drying and heat transfer in the straw bale. The studies have shown that the inner layers of the bale heat up much faster and achieve significantly higher temperatures than the outer ones. With the application of dedicated straw dryers, a homogenous field of moisture content in the straw bale is achieved in a very cost effective way.

1 Introduction

Since the great energy crisis in the 70s of the 20th century, society has been increasingly interested in alternative energy sources and possibilities of using them for the generation of power, heat production or powering vehicles. In recent years, we have observed a rapid and dynamic development in the field of renewable energy sources. More and more companies manufacturing elements for photovoltaic or wind farms as well as biomass boilers are being established. This is caused mainly by two factors. The first one is the uncertainty in terms of supply of fossil fuels, namely oil and natural gas, due to the current political crisis between Russia and the European Union, and the political situation in the Middle East. The second reason for the development of technologies based on renewable energy sources are the Directives of the European Union aiming at the limitation of the emissions of greenhouse gases to the atmosphere [1,2,3,4]. An additional impetus for the development of renewable energy-based technologies of all kinds is provided by various subsidies for low-emission devices and the introduction of feed-in-tariff or e.g. green certificates.

There are many studies confirming the fact that biomass is one of the most important sources of renewable energy in Poland. Its technical potential fluctuates within 800-900 PJ per year [5,6]. In the estimation prepared for the purposes of the GHG Reduction Strategy report, the number of 100 PJ [5] is given. Biomass exhibits the highest potential in relation to other renewable energy sources. Moreover, it is the most predictable energy source and – as opposed to solar energy or wind – it can be used throughout the year. In addition, biomass may be easily stored and used in the periods of increased demand and transported to locations with deficits.

Poland, as an agricultural country with a large woodland area, has considerable biomass resources which may be used for generating electricity or in heat production. One of the basic problems regarding the use of biomass for energy production is bulk density – as well as calorific value. In a given biomass volume, there is approx. 4-8 times less energy than in a similar volume of coal. This causes a number of problems including the issue of transportation – the costs related to biomass transportation over long distances and emissions associated with its transportation from the place of harvesting to the place of utilisation [7,8].

Large biomass resources in the form of straw are available in Poland. It is estimated that the annual production of straw is approx. 20 million tons [9], while the technical potential of obtaining straw for energy purposes is approx. 7 million tons [10]. This potential is going to increase each year due to a decrease in the number of breeding animals [11], which will result in a decreased demand for straw for animal and bedding purposes. Such large surpluses of straw will popularise the use of straw for heating purposes by farmers or in public buildings. This may be exemplified by the Municipality of Człuchów, where straw is used for the heating of four school buildings. Straw is also used in district heating in towns such as Lubań in Lower Silesia.

Dry straw humidity may reach a level of as low as or even less than 10%, harvesting straw during unfavourable weather conditions, however, causes the moisture level to increase up to 60-70% of the relative humidity [12], a value often observed for fresh biomass [13]. In the Polish climatic conditions, as well as in many European countries, the heating season is relatively long and lasts from October to May, while straw is only

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harvested in the summer period – in July and August. It is therefore necessary to store the straw that will subsequently be used in the heating period. It should be stored in closed barns or haystacks covered with foil, tarp or special waterproof materials. This allows to minimize the impact of weather conditions on the quality of the stored fuel. Excessive straw moisture level has a negative impact on the burning value of the fuel and results in problems related to the burning of wet straw in boilers [12, 14]. It is best for the straw used in batch boilers to exhibit humidity at a level of approx. 10-20%. This has a favourable effect on the combustion process due to the catalytic effect of water vapour on the combustion of the excessive amount of volatiles present in the biomass [12].

2 Experimental stand

The main elements of the dryer used in the study include the drying chamber, the transport table, the discharge fan, the fire prevention system, the regulation assembly and the system for the control of operational parameters, the system of pre-extraction and separation of sparks and the exhaust introduction system.

The heat used in the drying process comes from the process of biomass combustion in the boiler. Such utilised waste heat increases the efficiency of the entire system and helps to obtain a much more efficient fuel. The drying process involves the injection of waste gas characterized by a properly controlled temperature by the automatic system (Fig. 1) using a specially designed nozzle with a diameter of 80 cm into the bale of straw.

For safety reasons, the exhaust gases coming from the boiler are pre-dusted in the sedimentation chamber (cyclone) due to the presence of large, sometimes incandescent stalks of unburned straw. Subsequently, the gases are transported to a special mixer (Fig. 2), where, if necessary, the process of mixing of the exhaust gas with ambient air takes place in order to obtain the desired temperature of the drying medium. After the mixing process, the fan introduces the previously prepared mixture using the specially designed nozzle into the cylindrical bale of straw. The schematic diagram of the system has been presented in Figure 3.

The effectiveness of drying cylindrical straw bales (diameter: 160 cm, length: 140 cm) with exhaust gases was measured using a specially prepared recorder equipped with eight measuring probes. The probes were calibrated by the manufacturer using a sample of straw characterized by varying humidity. Capacitive relative humidity sensors and temperature sensors with the SHT11 device were installed.

The measuring probes varied in length (80 cm, 60 cm, 40 cm and 20 cm denoted respectively by lowercase “a”, “b”, “c” and “d”), so as to make it possible to measure the humidity and temperature in locations at a preset distance from the axis of the straw bale. Figure 4 presents the visualisation of the placement of the right probe in the bale during the measurement.

Figure 1. General view of the control system

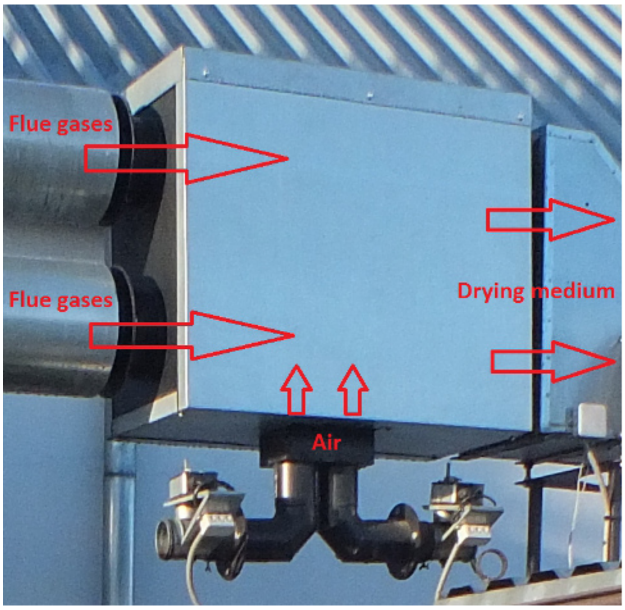

Figure 2. General view of the medium mixer

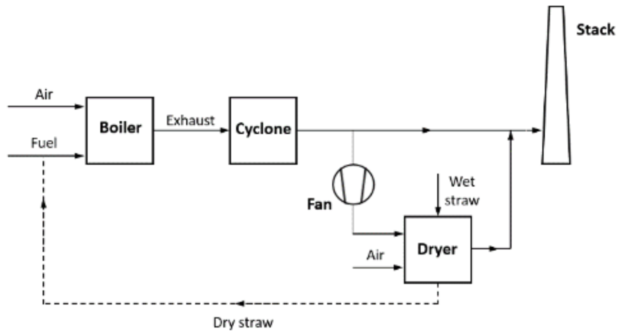

Figure 3. Schematic diagram of the installation used in the experiment

The measurements were always carried out in two planes. The measurement points were located at a distance (x=0 – the place where the drying mixture was pumped to the bale) of 40 cm (plane A, x=40) and 100 cm (plane B, x=100) from one end of the bale (Fig. 4).

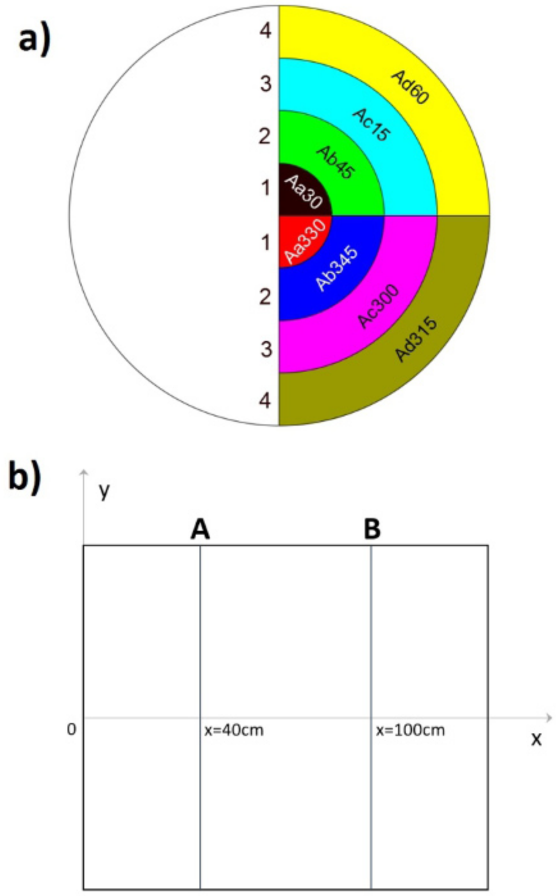

Figure 4. Visualisation of the locations of measurement probes: a) locations of individual probes, b) coordinates of the A and B planes.

The results of the experiment have been presented below. The curves show the change of temperature and humidity during the drying process. The prefixes "A" and "B" designating the probes refer to the measurement plane according to Figure 4b, while the prefixes "T" and "H" refer to the measurement of temperature and humidity, respectively.

This article presents the possibilities of drying straw using a basic and a modified drying process. After gaining some experience in the process of drying straw bales [15], some modifications of this process have been implemented, which involved preparing a duct along the bale axis with the diameter of 63mm and applying a metal plate with the diameter of 1,000 mm at the side opposite to the fitted drying medium. This modification was designed to allow for the highest radial propagation of the medium and to obtain a uniform temperature and humidity inside the bale.

3 Results and discussion

A study of changes in the humidity and temperature inside the bale of straw were conducted in the A plane (Fig. 4b). The measurements were carried out in two configurations (with and without three holes) to examine the effect of the presence of the holes inside the bale of straw on the dynamics of drying cylindrical straw bales and on the temperature changes inside. In addition, in each drying process the temperature of the drying medium injected into the bale was recorded. The exhaust gas temperature was presented in charts in the form of a dotted curve with the values given on the right axis. During the basic drying process, one bale of straw was dried in 280 min, and during the modified drying process one bale of straw was dried in 270 min.

3.1. The basic drying process

The first two graphs (Fig. 5 and 6) present the variation of humidity inside the bale of straw in the basic drying process (without the holes). Immediately after the completion of measurement no. 1, measurement no. 2 was performed. The initial humidity of the bale was in the range of 23-43%. The internal layers of the bale were drier, and the humidity increased along with the distance from the centre of the bale. This was caused by the fact that the bale had not been covered while storing.

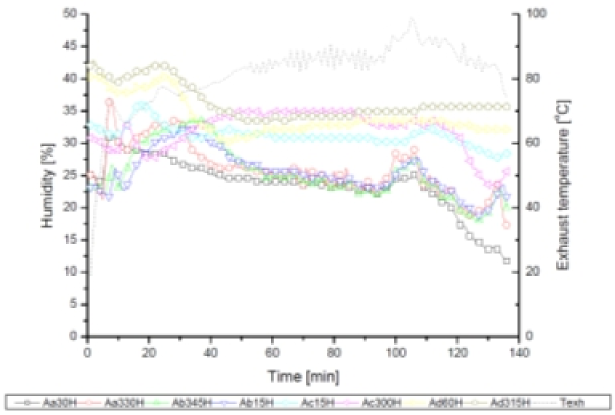

Figure 5. Basic drying process, humidity measurement No. 1

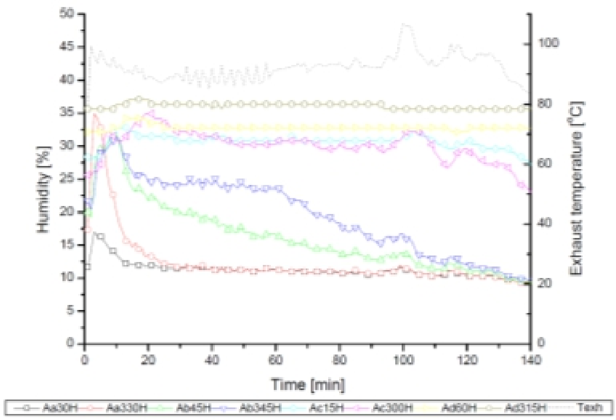

Figure 6. Basic drying process, humidity measurement No. 2

Measurement No. 1 was carried out for approx. 140 min. In the initial phase, one could note a sharp increase in the humidity at the inner portion of the bale represented by sensors Aa30H and Aa330H. This was due to the rapid temperature increase in this part of the bale, which contributed to the temporary increase in relative humidity. After the 30th minute of the measurement, a decrease in humidity in the first and second layer (the layers are presented in Fig. 4a) could be observed. This decrease continued until the end of the measurement. In case of planes 3 and 4, a stable humidity content oscillating in the range of 30-35% was observed. The final humidity value after the first measurement reached the value of 12-35%.

Measurement No. 2 was started 5 minutes after the completion of measurement No. 1. In this case, the drying time using the hot drying medium (the period of combustion in the boiler) was also approx. 140 min. In the initial drying phase, a similar increase of humidity as in the case of measurement No. 1 was observed. During the entire drying process, the humidity in planes 1 and 2 decreased until it reached 10%. No significant changes in humidity were observed in planes 3 and 4 and after approx. 280 minutes of drying, the humidity oscillated within the range similar to the initial humidity, reaching 30-35%.

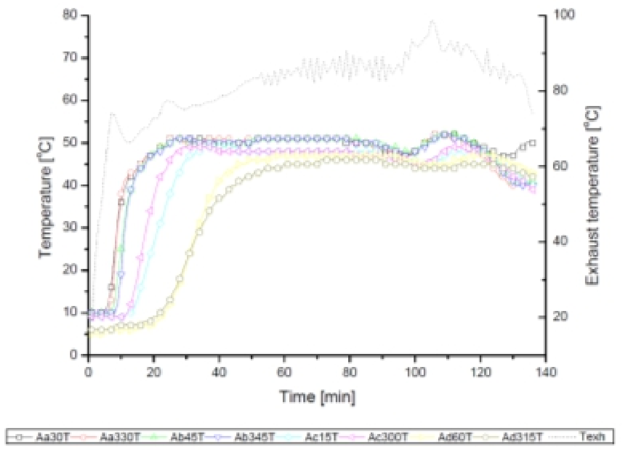

Figure 7. Basic drying process, temperature measurement No. 1

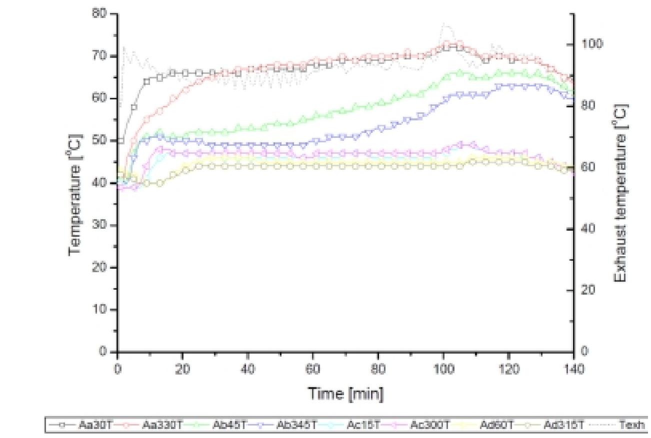

Figure 8. Basic drying process, temperature measurement No. 2

The two graphs above (Fig. 7 and 8) present the temperature variations inside the bale of straw in the respective measurement points during the basic drying process.

Figure 7 presents measurement No. 1 and the temperature changes inside the bale of straw in a period of approx. 140 minutes of the drying process. Five minutes after the drying process was started, a rapid temperature increase was observed in plane 1. Subsequently, after another 2 minutes have passed, rapid heating of plane 2 was observed. Planes 3 and 4, because of their distance from the centre of the bale, heated up much slower, and the beginning of the temperature increase in these places could be observed from the 15th and 20th minute, respectively. The maximum temperature for planes 1 and 2 was achieved in the 25th minute of the measurement and its value was approx. 52°C. In case of plane 3, the highest temperature of 50°C, was reached in the 35th minute. The extreme plane was heated at the lowest rate and reached the lowest temperature values, reaching the maximum of 46°C at approx. the 60th minute of the measurement. After reaching the temperature of 85°C, the flue gas temperature was maintained until the end of the combustion process.

Fig. 8 above presents the temperature changes during measurement No. 2. In this case, the highest temperatures were achieved only in plane 1, with values within the range of 65-73°C. These values were achieved after approx. 15 minutes from the start of the measurement. In plane 2, the maximum temperatures were achieved as late as 100 minutes from the beginning of the measurement and they reached approx. 60-65°C. During the entire drying process, no significant temperature changes were observed in planes 3 and 4 and the temperatures oscillated within the range of 44-48°C. In this case, the exhaust gas temperature was maintained at a relatively stable level within a range of 85-90°C.

3.2. The modified drying process

The following graphs (Fig. 9 and 10) present the changes in humidity for the bale with the application of the three holes and the metal plate.

The initial humidity of the bale which was subject to the measurement for the modified drying process oscillated within 30-45% and was comparable to the bale used in the basic drying process. The inner layers of the bale were drier, and the farther from the centre of the bale, the higher was the humidity. Measurement No. 1 was carried out for approx. 140 minutes. In this case, problems occurred with igniting the straw in the biomass boiler, and thus the drying mixture had a very low temperature. In the 18th minute of the measurement, it was possible to observe a sudden increase of the flue gas temperature, which proved that the fuel started burning in the combustion chamber. After a sudden increase in the drying mixture temperature, a sudden humidity increase was observed, and after approx. 5 minutes the humidity slowly declined. After 5 more minutes, the humidity in the whole bale was stabilised and reached 35%. Subsequently, until the 120th minute of the measurement, a sudden decrease of humidity was observed, and after another 20 minutes the humidity in planes 1 and 2 was stabilized at the level of 10%. Planes 3 and 4, just as in the previous measurements, were characterised by a similar humidity of approx. 35%.

Measurement No. 2 was carried out for 120 minutes and was initiated after approx. 5 minutes after the completion of measurement No. 1. In this case, a constant humidity value for planes 1 and 2 was observed during the entire period of the drying process, and the value reached approx. 10%. In addition, one of the sensors (Ac15H) in plane 3 recorded humidity values similar to planes 1 and 2. The second sensor located in plane 3 (Ac300H) showed a constant decline in humidity, until it reached a minimum (approx. 10%) in the 30th minute of the measurement. In plane 4, the humidity remained at a stable level until the 90th minute of the measurement, in which one of the sensors (Ad315H) started registering a decrease in the humidity value. At the end of the drying process, the bale of straw was characterised by a very low content of humidity of approx. 10%. Only one of the sensors (Ad60H) showed a higher value – 35%.

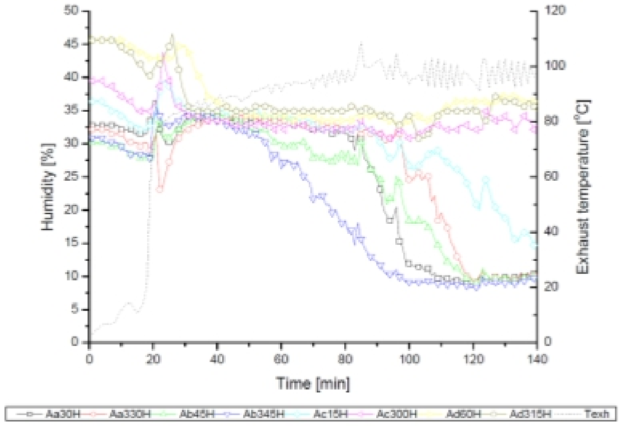

Figure 9. Modified drying process, humidity measurement No. 1

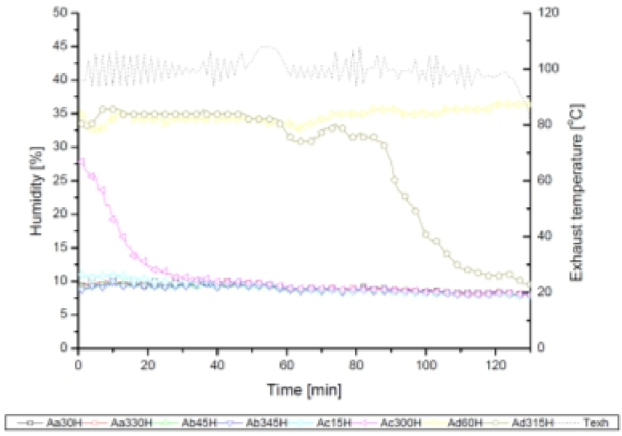

Figure 10. Modified drying process, humidity measurement no. 2.

The following two graphs (Fig. 11 and 12) present the temperature changes inside the bale of straw with the application of the three holes and the metal plate.

Figure 11 presents the temperature changes inside the bale of straw during measurement no. 1.

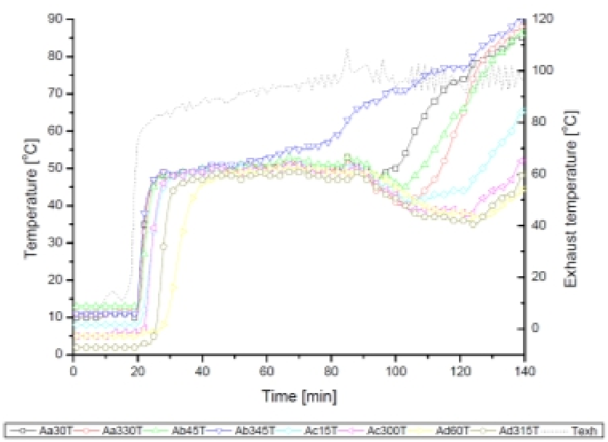

Figure 11. Modified drying process, temperature measurement No. 1

Until the ignition of the fuel in the combustion chamber, one may observe a similar temperature value throughout the entire bale of straw. In the 20th-25th minute of the drying process, a rapid rise in temperature in all measurement planes was observed, until the temperature reached 50°C. Subsequently, a stable temperature value may be observed in all planes, until the 90th minute. After this period, the temperature in planes 1 and 2 started to increase and it reached a maximum of 90°C. The maximum temperature reached at planes 3 and 4 was the range of 60°C. The flue gas temperature during the entire period of the drying process oscillated between 90 and 100°C.

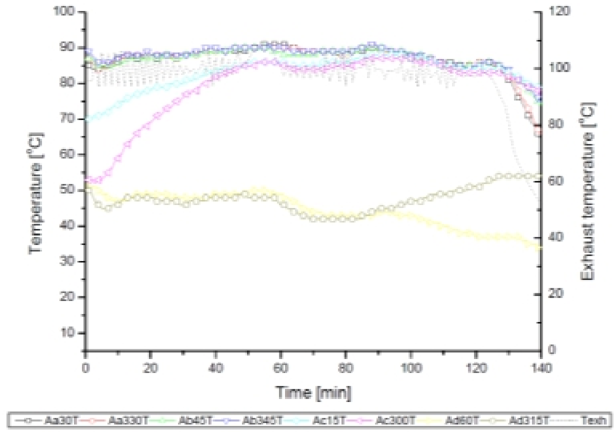

Figure 12. Modified drying process, temperature measurement No. 2

Fig. 12 above presents the temperature changes during measurement No. 2. During the entire drying process, the temperature in planes 1 and 2 remained at a constant level of approx. 90°C. In plane 3, the temperature was steadily growing until reaching approx. 85°C in the 50th minute of the measurement. At that point, it reached a stable level until the end of the measurement. The temperature in the outermost layer exhibited the lowest temperature values, which oscillated within the range of 40-60°C. The temperature of the exhaust gas was oscillating within the range of 95-100°C.

4 Conclusions

This article presents a study concerning the possibilities of drying cylindrical straw bales. Within the study, measurements were conducted for the basic and modified drying processes. In the modified drying process, the bale of straw had three holes made along the centre of the bale to achieve the best distribution of the drying medium. The measurement results confirm the validity of the implemented modifications. In this modified process, a satisfactory drying time was achieved. A bale with a relative humidity of 45% was dried to a level of 10% of moisture in 270 minutes. Within the basic drying process, however, a much worse coefficient of heat transfer was achieved, and thus the drying was insufficient.

Acknowledgments

This work was financially supported by the Statutory Grant of the Faculty of Energy and Fuels at AGH University of Science and Technology and it was carried out by BioORC Project within the KIC InnoEnergy Programme.

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