Determination of kinetic parameters of pyrolysis of wheat straw using thermogravimetry and mathematical models

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Abstract. In many countries of the Central and Eastern Europe which have huge economic and energy potential of the straw, this agricultural waste becomes to be attractive material which can be utilized near to place of the production in the heating devices as well as in the gasifying facilities. Unfortunately straw is characterized by strongly various properties, which depends on type of straw, geographic location of growing as well as methods of the cultivation. Due to this fact, comprehensive approach to studies of the straw from given region is required to obtain information necessary to perform reliable simulations of its thermochemical conversion, what allows to carry out the optimisation of operation of the heating devices and the gasifiers. The paper presents methodology and results of the studies of the wheat straw from the southern Poland. The analysed properties were selected in order to use them for further development of the numerical simulation of the heterogeneous combustion of the considered fuel. Proximate and ultimate analysis as well as determination of the higher heating value (HHV) have been performed and compared with data presented in literature. Then thermogravimetry was carried out to determine content as well as dynamics of the decomposition of the pseudocomponents in the fuel. Selected approaches to model fitting and model-free methods described in this paper have been applied to find kinetic parameters of the straw pyrolysis.

1. Introduction
In the age of sustainable energy development, biomass is considered as a promising fuel that allows to reduce consumption of conventional fuels as well as to produce fuel directly in area of generation. Most of this type of fuels are still used in rural areas of developing countries [1], but today a number of advanced applications for the energy generation using this green energy source can be listed. Many technologies are based on utilization of agricultural waste, especially straw.

At present, gasification as well as combustion of straw are promising technologies for heat and power generation from biomass [2, 3]. However, in small scale heating devices, it is the direct combustion that is the most popular [4, 5]. The process of biomass combustion involves a number of physical/chemical aspects of high complexity. The combustion process in case of straw or generally – biomass, depends on the fuel properties as well as the combustion application [5]. The combustion process can be divided into given general stages: heating and drying, pyrolysis, gasification and combustion both in gas (pyrolysis and gasification products) and solid phase (char).

In case of solid biofuels drying and devolatilization are always the first stages. Release of the moisture occurs without any chemical processes. During pyrolysis, the fuel undergoes thermochemical
decomposition in the absence of reacting agents. Volatiles, tar and char are formed during the process in variable amounts. Contribution of gasification is various and depends on technology of the biomass combustion, process performance and properties of the fuel. Due to relatively high content of the volatiles, pyrolysis and formation of simple combustible gases in the gasification process are key issue from the point of view of the straw combustion.

Pyrolysis of each component of the biofuel occurs in a different temperature range. Incomplete thermal decomposition of hemicellulose begins in temperature higher than ~ 200 ℃ and it takes place to about 320 ℃, while for cellulose and lignin it is consequently ~ 300 – 400 ℃ and 300 – 500 ℃. Gas phase hydrocarbons, tar and char have to be listed as main products of the process [6]. In conditions of conventional pyrolysis, formation of relatively high amount of the char occurs, while in fast pyrolysis higher amount of liquid hydrocarbons in products can be observed.

Pyrolysis of lignin and cellulose is precursor for the gasification process, which involves presence of the oxidizer and leads to formation of gases characterized by low molecular weight, including carbon monoxide (CO), hydrogen (H₂) as well as carbon dioxide (CO₂). Stage of the gasification is referred to as series of oxidation - reduction processes occurring in gas and solid phase as well as between both of them. The char is of course not pure carbon but rather substance characterised by some content of solid hydrocarbons. Reactivity of the char and consequently gasification process are more intensive for solid biofuels comparing to coal due to higher porosity of the biomass. Detailed description of the gasification can be found in a number of references, i.e. [2, 5-7].

Due to dynamic increase of a number of biomass - fired heating devices, advanced methodology of studies of the combustion process has been developed. This includes the experimental investigation of the processes of thermal decomposition of solid fuels with various approaches.Thermogravimetric analysis (TGA) is a widely used method, which allows describing of the kinetics of pyrolysis and combustion of the biomass [8, 9].The method is based on precise measurement of the mass loss of the fuel sample in conditions of increasing temperature and inert atmosphere. Detailed description of methodology of the TG has been presented in further part of the paper. TGA can be combined with differential scanning calorimetry (DSC) to analyse the heat of reaction of thermochemical decomposition of biomass [10]. The combination of TGA and DSC in one experiment is called simultaneous thermal analysis (STA).

Additional methods can be used together with macroscopic thermogravimetric analysis to achieve more complex description of the pyrolysis and especially the composition of the volatile gases. Laser-induced fluorescence (LIF) and pyrolysis–gas chromatography/mass spectrometry (Py–GC/MS) have to be listed here. Both are used to analyse the volatiles leaving the pyrolysing biomass based on different technologies [11].

Due to more consistent properties of the composition of coal compared to the most popular types of the biomass and due to intensive research in the field of coal combustion, the pyrolysis of the first one is better known and described in detail [12, 13]. However, in case of the biomass different values of the kinetic parameters for the same types of the fuel are given in published results. Some studies demonstrate, that accurate description of the biomass pyrolysis requires a multi-scale consideration of pyrolysis on multiple levels – specifically, on molecular, particle and reaction levels [14]. The effect comes from variety of the biomass properties as well as approach to the methodology of the measurement and process control. Based on this fact it can be concluded that each specific case of detailed description of the kinetics of the thermal decomposition of the biomass has to be based on experimental TGA studies. Such approach is crucial when as a next stage of the studies kinetics of the reactions has to be applied in numerical models of the combustion process. Determination of the activation energy and preexponential factor for given heating rate is one of factors allowing to achieve satisfying level of agreement between results of simulation and studies of operation of given heating device.

Investigation of operation of straw - fired heating devices requires comprehensive approach to the kinetics of the combustion process, in which the pyrolysis plays key role. Therefore Authors of this paper performed TGA analyses of wheat straw used as a fuel in prototype 100 kW batch-boiler which currently is the subject of the research project. Kinetic parameters obtained as a result of TGA
measurements described in the paper will be input data for the CFD model allowing analyses of operation of the combustion in the boiler, what will be carried out as a next stage of studies.

2. Studies of the straw pyrolysis and combustion

It is required to consider individual stages of the straw pyrolysis to describe detailed scheme of the process, including kinetics of decomposition of pseudocomponents (cellulose, hemicellulose, lignin), determining char, tar and gas yield. Such approach has been clearly presented in [15], where authors were focused on investigation of the influence of wheat straw particle size, initial weight of the sample and heating rate on the devolatilization process and kinetics of reactions. In frames of described studies both proximate analysis and pyrolysis experiment were performed. However, proximate analyses were performed using thermogravimetric analyser (with combustion in oxygen atmosphere as a last step, while in case of the pyrolysis the analysis has been carried out in atmosphere of nitrogen). Estimation of the parameters of the wheat straw pyrolysis has been performed based on the assumption, that three stages of the process have to be considered as non-interacting mass loss events, described by 'n'th-order reactions. Mechanism of the pyrolysis in the mathematical model describing process has been based on standard Arrhenius equation. Based on their results, the authors [15] noted, that particle size and initial mass of the sample as well as the heating rate were directly related with the efficiency of the heat transfer. For a bigger particle size, initial mass and heating rate, lower efficiency of the heat transfer were observed. Slower heat transfer through the straw particle resulted in increase of the solid residue. The second significant factor was the surface area of the straw particle, which increased with reduction of the particle size and resulted in decrease of the biochar yield. The analyses of the global kinetic parameters using reformulated model with n-th - order reaction kinetics allowed to obtain the reactions orders for each individual step of the pyrolysis.

As it was mentioned in the previous section, results of the TGA are useful for numerical models of the biomass combustion including CFD simulations. In [16] possibilities of an optimisation of the straw bale burnout in the dedicated combustor and the minimisation of gaseous emissions (volatile organic carbons, carbon monoxide, nitrogen oxide) were investigated. Homogenous combustion in the gas phase was extended for characterisation of the solid phase (straw bale) and solid - fluid interactions. According to [15], solid phase representing fuel and char were treated as porous zones with defined flow resistance. While the kinetic parameters for the homogeneous gas phase reactions were taken from literature, parameters for the thermal degradation of the solid phases were determined by experiments. Therefore, TGA measurements were conducted to develop part of the model responsible for description of pyrolysis of cellulose, hemicellulose and lignin. Furthermore, TGA was applied to determine dynamics of the evaporation of the biomass moisture. The authors of the above mentioned paper stated that also biomass char combustion under chemical reaction control can be derived from TGA measurement. Model based on results of the thermogravimetric analyses allowed to determine a series of relations, like dependence between excess air and residential molar fraction of compounds such as volatile organic carbons, carbon monoxide and nitrogen oxide. It was concluded that the flue gas recirculation and the overall equivalence ratio can be varied in order to reduce gaseous emission of CO and NOx. The paper proves the importance of the TGA in studies of operation of the straw-fired heating devices.

In case of studies of the biomass pyrolysis it is the most difficult to describe in detail behaviour of lignin in the process. On the other hand pyrolysis of lignin is an important stage of the biomass decomposition due to role of the lignin in formation of the large molecules included in pyrolytic liquids. In [11] the thermal behaviour of wheat straw lignin during the pyrolysis process was studied by using TGA in order to find kinetic information necessary for the equation of the process and to characterize fast pyrolysis vapours of the examined fuel. In frames of analyses the wheat straw lignin was separated from the fuel using physical - chemical methods. According to previously discussed works [15, 16], wide range of the heating rates have been applied and again it was noted, that the char residue at high temperatures close to 1100 K varied significantly at different heating rates. Interestingly, the results presented in the paper show that the slower heating rates result in the lower degradation degree, what is explained as an effect of shortertime of attaining necessary temperature of pyrolysis by sample in case of faster heating rate. These observations are in opposition to data
presented in [15], although they not refer to pyrolysis of straw but just to the separated component. Therefore it can be concluded that impact of heating rate on the devolatilization dynamics is complex and strongly depends on the stage of the pyrolysis. It has to be noted that differential (Kissinger) and integral (Ozawa) methods of thermal analysis have been used to carry out estimation of the apparent activation energy in range of applied heating rates.

Model - free methods which include differential and integral approaches were also applied in work [17], where thermogravimetric analysis (in range of heating rates 10 - 40 K/min) of rape straw has been presented. Three approaches (Friedman, Kissinger-Akahira-Sunose KAS, Ozawa-Flynn-Wall OFW) based on results obtained from the TGA have been used to determine activation energy. Then master plot method was applied to analyse calculated kinetic parameters and a multicomponent parallel reactions scheme was incorporated into a global optimizer to estimate required model parameters. It was possible to achieve satisfying agreement between kinetic parameters obtained especially as a result of the KAS and OFW application. Moreover, it was found that the optimized model parameters are applicable not only to conditions of performed TGA (applied range of the heating rate), but also beyond them. Anca-Couce et al. [9] proposed to combine model fitting and model – free methods for the determination of kinetic parameters for pyrolysis of biomass to obtain the best results from TGA measurements.

Despite series of differences of approach and methods of measurement and modelling of the straw pyrolysis process, literature provides a number of useful tips allowing to determine kinetic parameters of the biomass thermal decomposition, some of which have been described in this section. Selected elements of the methodology were applied in experimental studies outlined in further part of the paper.

3. Methods and material
The biomass used in frames of described studies was wheat straw from farm located in the vicinity of Krakow (Malopolskie Voivodeship, Poland). Straw was harvested in 2015 and was stored for two years in a roofed shed.

Ultimate analysis of the straw has been carried out using CHS-580 Eltra analyzer. The Principle of measurement is incineration of the sample in temperature 1623 K in oxygen flux and subsequently determination of CO2, H2O and SO2 in post-reaction gas. Then calculation of C, H and S is performed. Additionally, it is required to introduce the correction to the hydrogen calculation due to moisture presence. The measurement was based on PN-G-04571:1998 and PN-G-04584:2001 standards. Applied method was positively examined using patterns:

- NJV 94-5 #655, provided by Swedish University of Agricultural Science;
- Eltra no 60824.

Determination of higher heating value has been performed using AC 350 LECO Calorimeter. Measurement was carried out based on PE-EN 14918 standard. Applied method has been positively verified using benzoic acid pattern.

Proximate analysis was performed using weight loss methods based on standards:

- PN-80-G-04511 for moisture content
- PN-G-04516 for volatiles content
- PN-G-04512 for ash content

Accuracy of the results obtained in proximate analysis was determined mainly by laboratory scale (0.1 mg).

Experiments for simultaneous thermal analysis (STA) were conducted with NETZSCH STA 449 F3 with balance resolution 25 ng resolution (at a weighing range of 5g), temperature resolution 0.001 K and balance drift less than 2 μm per hour, at laboratories of DBFZ. Nitrogen was used as purge gas to create an inert atmosphere in order to investigate the pyrolytic decomposition of the biomass. Prior to experiments the straw was grinded to a particle size below 0.5 mm. Samples of 5 to 10 µg of the milled biomass were filled into Al2O3 crucibles for the experiments. Biomass samples were heated with the heating rates 2 K/min, 5 K/min, 10 K/min and 20 K/min from 25°C to 900°C. Small amounts of biomass and low heating rates were used to avoid thermal lag. Each experiment was conducted three times. During heating, the mass loss of the samples was measured.
To obtain kinetic parameters from the measured mass loss, the results were analyzed with two different approaches. Fitting of the resulting DTG curves to model equations is a widely use method to determine kinetic parameters and was also used in the present study. By the method of least squares, the kinetic parameters for the best fit were determined. Additionally, Ozawa-Flynn-Wall (OFW) and Friedman analysis were conducted. These analytical methods are independent from kinetic models and help to avoid mistakes resulting from the wrong kinetic model. For the Friedman analysis, the logarithmic conversion rate is plotted over the reciprocal temperature for each measured heating rate. Based on the logarithmic Arrhenius equation a linear relation between points of the same degree of conversion at various heating rates can be found. The activation energy is connected to the slope of the line and the pre-exponential factor to the axis intersect [18]. The Ozawa-Flynn-Wall analysis is based on the same principle, but follows an integral approach [19].

4. Results and Discussion

4.1 Proximate/ultimate analysis and combustion heat

Data presented in a number of papers shows how significantly various are properties of the wheat straw from different regions. It is especially clear visible in case of [20], where selected parameters of the fuel have been compared for wheat straw from different countries (Turkey, India, UK, Mexico, Spain, Canada). Content of elemental carbon for most of results presented in Table 1 is around 40%, but in case of [21] it exceeds 50%. Higher percent of carbon corresponds with content of hydrogen and both chemical elements influence on the higher heating value (HHV). However, heat of combustion obtained in current study is slightly higher than in [20], although higher content of the carbon and hydrogen as well as lower ash content in wheat straw were determined in this work. It has to be noted, that content of carbon and hydrogen in the fuel results from characteristic of the hydrocarbons which build fibers of the straw. Variety is visible also in case of sulfur content, which in [20] and [22] achieves level normally obtained for coal, but the lowest percent determined in [22] for fuel from Canada is comparable with the results of current studies. Reduction of the sulfur content in straw is observed as a result of impact of atmospheric conditions (flushing by rain and subsequent drying), so presented differences can be partially explained by different treatment of the straw after harvests. Moreover, impact of type of fertilizers and time of fertilizing has to be taken into account [23].

| Ultimate analysis [%] | Proximate analysis [%] | HHV |
|-----------------------|------------------------|-----|
|                       | C  | H  | S  | M  | V  | A  |     |
| Current study         | 42.7 | 5.5 | 0.06 | 8.4 | 65.54 | 3.4 | 16.49 |
| Mani et. al. 2010 [15]| -  | -  | -  | -  | 5.4c | 78.3c | 6.77c |
| Dhyani, Bhaskar 2017 [21]| 53.9 | 7.0 | -  | 8.5 | 63.0 | 5.5- | 13.5 |
| Montero et al. 2016 [20]| 37.2- | 5.10- | 0.06- | 5.58- | 68.23- | 5.30- | 14.47- |
|                      | 45.5b | 6.10b | 0.20b | 7.70b | 84.04b | 17.04b | 15.74b |
| Biswas et. Al. 2017 [22]| 38.34 | 5.47 | 0.37 | 12.81 | 83.08 | 6.63 | 14.68 |

a Weight percent on dry biomass basis
b Depending on the straw origin
c Calculation based on TGA

Differentiation of the moisture content can be related with method and time of the straw storage, while higher amount of ash in many types of the biomass is often a result of way of harvesting. Content and type of mineral substance has influence on the dynamics and efficiency of the heat transfer through the biomass, however porosity and surface area are key factors here [15, 23].

Intensity of release of the volatiles depends on content of individual pseudocomponents, as in case of percent of elemental carbon and hydrogen in the fuel. However, it is not direct relation [5]. Amount of volatile matter determined in current studies is relatively low compared to literature but it is at the
same level as in [21] and [20]. Less volatile matter normally is related with bigger share of lignin in the thermochemical conversion of the straw. Application of the TGA for determination of moisture, volatiles and ash content in case of [15] has to be listed as one of possible reasons of quite high content of the volatile matter. However, such result are comparable with parameters presented in [20], which are characteristic for fuels from different regions.

4.2 TGA results

Normalized mass loss of the biomass samples during pyrolysis is presented in figure 1. Pyrolytic decomposition starts between 150 °C and 200 °C and continues until approximately 650 °C. In figure 2 the first derivate of the TGA results (DTG) are shown. The velocity of mass loss increases with the heating rate and reaches its maximum between 300°C and 340°C, depending on the heating rate. Decomposition slows down significantly around 370°C.

Figure 1. Normalized mass during pyrolysis of wheat straw at applied heating rates in inert atmosphere (nitrogen).

For increasing heating rates, the nominal temperature of the STA rises faster than the temperature in the biomass sample due to effect of heat transfer from the walls to the center of the sample. Therefore, thermal lag can be seen in the direct comparison of the normalized mass during pyrolysis process. Since thermal lag increases with heating rate, low heating rates are recommended for the determination of kinetic parameters.

4.3 Model fitting results

Results of the model fitting are presented in table 2. Four parallel reactions were chosen to describe pyrolysis of four pseudo-components of wheat straw. Four or five reactions can be used to increase the accuracy of the mathematical model. It is assumed that the additional reactions describe the decomposition of extractives in the biomass [23]. In figure 3 the results of the model fitting (lines) are compared to measured values of the TGA experiments (points). Good agreement of measurement and model can be found.
Table 2. Kinetic parameters for pyrolysis of wheat straw determined by model fitting

| Pseudo-component | c  | log A / s⁻¹ | Eₐ / kJ/mol | n  |
|------------------|----|-------------|-------------|----|
| Cellulose        | 0.3347 | 17.691    | 224.986     | 1.233 |
| Hemicellulose    | 0.431 | 16.653     | 202.639     | 3.765 |
| Lignin           | 0.114 | 12.668     | 197.339     | 6.467 |
| 4th component    | 0.12  | 9.825      | 117.102     | 2.081 |

Figure 4 shows the individual decomposition of each pseudo-component during pyrolysis at a heating rate of 10 K/min. Decomposition starts with the 4th pseudo-component, which relates to extractives and continues with hemicellulose and cellulose, which have the highest mass fractions in the biomass composition. The last step of pyrolysis is the slow decomposition of the lignin-rich fraction.

Figure 3. Results of model fitting.
4.4 Analysis of results with model free methods

The results of the model-free methods (Ozawa-Flynn-Wall (OFW) and Friedman analysis) are shown in Table 3. They propose relatively constant activation energy between 210 and 240 kJ/mol for the major part of the decomposition of wheat straw with tendency to increase in the end of pyrolysis. The consistency of activation energy during pyrolysis process can also be observed in the results of the model fitting. However, the increase of activation energy toward the end of the conversion, which correlates with the decomposition of lignin, is not observed in the model fitting results.

Table 3. Results of Ozawa-Flynn-Wall and Friedman analysis

| Mass loss | Ozawa-Flynn-Wall analysis | Friedman analysis |
|-----------|---------------------------|------------------|
|           | Ea / kJ/mol | log A / s⁻¹ | Ea / kJ/mol | log A / s⁻¹ |
| 0.02      | 186.18 ± 22.38 | 16.55         | 213.83 ± 17.81 | 19.00 |
| 0.05      | 198.62 ± 6.3  | 16.89         | 227.97 ± 13.48 | 19.61 |
| 0.10      | 213.9 ± 5.79 | 18.05         | 227.39 ± 10.07 | 18.96 |
| 0.20      | 217.96 ± 4.31 | 17.93         | 227.08 ± 7.67  | 18.39 |
| 0.30      | 224.91 ± 4.24 | 18.28         | 229.26 ± 5.77  | 18.27 |
| 0.40      | 227.67 ± 4.49 | 18.30         | 223.58 ± 5.56  | 17.54 |
| 0.50      | 226.99 ± 5.03 | 18.05         | 221.08 ± 4.71  | 17.15 |
| 0.60      | 229.96 ± 5.11 | 18.16         | 226.82 ± 4.28  | 17.50 |
| 0.70      | 235.24 ± 5.80 | 18.45         | 237.89 ± 4.78  | 18.22 |
| 0.80      | 262.90 ± 8.36 | 20.51         | 281.19 ± 8.99  | 21.23 |
| 0.90      | 345.72 ± 23.57 | 25.02       | 335.36 ± 22.18 | 22.88 |
| 0.95      | 377.78 ± 30.20 | 25.31       | 378.83 ± 33.00 | 24.10 |
| 0.98      | 441.33 ± 68.19 | 27.01       | 4.28.31 ± 65.36 | 24.78 |
Table 4. Comparison to kinetic parameters from literature

| Wheat straw; present studies | \(c\) | \(\log A / \text{s}^{-1}\) | \(E_a / \text{kJ/mol}\) | \(n\) |
|-----------------------------|------|-----------------|-----------------|-----|
| Cellulose                   | 0.3347 | 17.691 | 224.986 | 1.233 |
| Hemicellulose               | 0.431 | 16.653 | 202.639 | 3.765 |
| Lignin                      | 0.114 | 12.668 | 197.339 | 6.467 |
| 4th component               | 0.12 | 9.825 | 117.102 | 2.081 |

| Rape straw; Xu et al. 2017 [17] | \(c\) | \(\log A / \text{s}^{-1}\) | \(E_a / \text{kJ/mol}\) | \(n\) |
|----------------------------------|------|-----------------|-----------------|-----|
| Cellulose                        | 0.4637 | 16.707 | 211.26 | 1.21 |
| Hemicellulose                    | 0.2763 | 10.701 | 156.41 | 3.00 |
| Lignin                           | 0.26 | 11.674 | 57.84 | 2.87 |

| Wheat straw; Miltner et al. 2006 [16] | \(c\) | \(\log A / \text{s}^{-1}\) | \(E_a / \text{kJ/mol}\) | \(n\) |
|--------------------------------------|------|-----------------|-----------------|-----|
| Cellulose                            | 0.4083 | 11.95 | 128.5 | 1 |
| Hemicellulose                        | 0.3493 | 5.573 | 75.47 | 1 |
| Lignin                               | 0.2424 | -2.796 | 15.00 | 1 |

| Wheat straw lignin; Yang et al. 2010 [11] | \(c\) | \(\log A / \text{s}^{-1}\) | \(E_a / \text{kJ/mol}\) | \(n\) |
|------------------------------------------|------|-----------------|-----------------|-----|
| Lignin, Kissinger                       | -    | 10.12 | 103.92 | 1 |
| Lignin, Ozawa                           | -    | 10.72 | 107.69 | 1 |

| Wheat straw; Mani et al. 2010 [15] | \(c\) | \(\log A / \text{s}^{-1}\) | \(E_a / \text{kJ/mol}\) | \(n\) |
|-----------------------------------|------|-----------------|-----------------|-----|
| Stage 2                           | -    | 7.598 | 78 | 0.65 |
| Stage 3                           | -    | 6.501 | 80 | 2.7 |

\(c\) – mass fractions of given components, \(A\) – pre-exponential factor, \(E_a\) – activation energy, \(n\) – reaction order

Many studies about pyrolysis of straw have been conducted in the past. Investigations on the influence of inorganic salts, pre-treatment and other parameters on the pyrolysis process were investigated [24-27]. For a large number of numerical investigations of straw firings, pyrolysis was described with a single step reaction. Therefore, they are not comparable to the results of the presented experiments (for example [28]). More complex kinetic mechanisms were also investigated, as described above [11, 15-17]. They are compared to the results of the present study in table 4. There are essential differences in types of biomass and in the methodology of the analysis of experimental results, which reduces comparability. Results of Xu et al. [17] are in the same range as the results of this study, but in their case, rape straw was investigated. They used heating rates from 10 K/min to 40 K/min, even though low heating rates are recommended to avoid thermal lag. Miltner et al. [16] used equations with the reaction order \(n=1\) and very low values for pre-exponential factor and activation energy. Yang et al. [11] analysed only the lignin of wheat straw and obtained their results from analysis with model free methods. Mani et al [15] did not assign pseudo-components to the reaction stages they investigated, which reduces comparability to the results of this study.

5. Conclusions

Ultimate, proximate and thermogravimetric analysis of wheat straw were performed in order to obtain relevant information for further numerical study of straw combustion. Elemental composition, content of moisture, volatiles and ash, higher heating value and kinetic parameters for pyrolysis were determined. The results of this study were compared to literature. The comparison showed that the results of the various studies about the same type of biomass deviate from each other in a certain range. This is on one hand caused by variations in biomass origin, harvesting and storage resulting in differences in properties and composition. On the other hand, different approaches of experiment and analysis of the results can contribute to further variations. The results of this study emphasize the importance of individual determination of biomass properties for each experimental and numerical investigation of thermochemical conversion of biomass. It has to be noted, that due to variety of properties of the biomass even if one specific type is considered, only development of dedicated appliances for distributed heat and power generation guarantees operation in accordance to
environmental and energy efficiency legislation. Furthermore, comprehensive studies of the biomass fuel provides wide range of information necessary to design dynamic control systems which have to be implemented in such kind of installations. Kinetic parameters determined in presented analyses will be applied with further studies of authors of the paper as input parameters in the numerical CFD model of operation of the straw-fired batch boiler.

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