Fragmentation of biomass particles in fixed and fluidized bed combustion and gasification

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Abstract. It is shown that when burning (gasifying) biomass in the fixed (fluidized) bed, it is important to take into account the change in particle size due to their fragmentation. The analysis of the current state of research of fragmentation processes is carried out. It is shown that considerable contribution to the grinding of fuel particles is made by primary fragmentation, and the main factors affecting primary fragmentation are particle size, heating rate, bed temperature, and fuel characteristics. The first results of studies of primary fragmentation of wood biomass particles in an inert medium at different temperatures are presented. The influence of bed temperature, particle size and shape on the quantitative characteristics and criteria of particle fragmentation, causes and nature of wood particle cracking are considered and analyzed.

1. Introduction
Studies of fuel particle fragmentation and its effect on the entrainment and mechanical burn out in the fluidized bed boilers during combustion of various fuels were mainly carried out by foreign researchers, and in most cases are the data of laboratory studies of different types of coal. Experimental studies of the fragmentation and attrition of particles during combustion in a fluidized bed [1], performed for a wide range of coals, showed that considerable contribution to the grinding of particles is made by primary fragmentation (at the stage of heating, moisture evaporation and devolatilization). The factors increasing the degree of primary fragmentation of solid fuel particles in the fluidized bed are particle size, temperature in the bed and fuel properties, (volatile yield) [2-7]. The nature of the particle size and volatiles yield influence on the degree of its fragmentation is known – the larger the particle size and volatiles yield, the more it is subject to fragmentation. These studies suggest that the effect of fragmentation in the fluidized bed combustion of biomass is greater than, for example, in coal combustion due to the larger size of the fuel particles and the high yield of volatiles. A number of studies have attempted to determine the critical diameter of the particles below which there is no fragmentation [4] – [7]. In [5] it is established that the critical diameter correlates with the ratio of volatile yield to fuel moisture. In a later study [8], the same authors found that the critical diameter is strongly dependent on the pore resistance number (PRN), decreases sharply with its growth to a value of about 3 mm at a value of PRN 15 %, and then remains almost constant. In [3] it is shown that the porosity of fuels is linearly dependent on the carbon content in the fuel decreasing with its growth by dry mass Cd. Research in relation to coal is most often focused on the study of changes in particle grinding during heat treatment in a laboratory installation with a fluidized bed. The obvious disadvantage of such work is that the data obtained are not the result of the study of the particles heating process and the process of chemical-physical interaction between the components of the ash and the bed material exactly, since they are superimposed by the influence of mass transfer and attrition. Mass transfer, in turn, is strongly dependent on the hydrodynamic conditions of the fluidized bed, which can vary markedly in different test rigs. In addition, there is currently no generalization and systematic recommendations for the thermal calculation of fluidized and fixed-bed boilers and producers for biomass. The need to take into account the
processes of fragmentation of biomass particles was shown in the development of the three-zone method of engineering calculation of fluidized bed furnaces for biomass combustion [9].

2. Experimental setup and methods
Experiments were carried out using a laboratory tube furnace "SNOL," with a chamber diameter of 35 mm, equipped with a system of supply and measurement of inert gas flow (Figure 1) and scanning electron microscope "Vega3LMH". The investigated particles using a special capture quickly placed in a preheated oven to the process temperature, in the center of the oven chamber tray. The particles were introduced into the furnace from the side of the inert gas outlet through the hole closed by the plug. The trays used were made of heat-resistant three-layer metal mesh with a cell size of each layer of 100 microns. This design allows the tray to provide a good gas washing, and the free flow of volatile particles for the entire surface. At the same time, the small size of the cells and the displacement of the cells relative to each other prevented the failure of small particles that exfoliated in the process of rapid heating and pyrolysis.

After completion of the release of volatile particles from the furnace was cooled to room temperature and the tray with coke particle or fragments thereof was removed from the furnace. During the whole process from the beginning of heating of the furnace to the extraction of the tray, inert gas (high purity nitrogen) was supplied to the furnace at a flow rate of 0.3 l/min to prevent the interaction of particles with oxygen in the process of heating, pyrolysis and cooling. After removing the tray from the furnace, the formed coke particles and their fragments (more than 0.001 g) were photographed and counted, large fragments and fines were weighed on an electronic scale with an accuracy of 0.0001 g, density and equivalent diameter of large fragments were determined, and coke particles and fragments were examined using an electron microscope. To determine the density of the particles (fragments), a prismatic shape was given by manual treatment, after which they were re-weighed and the volume was determined by three characteristic dimensions measured with an accuracy of 0.05 mm.

The wood quasi–circular (cube) and oblong spruce particles of square cross-section with the ratio of longitudinal and transverse dimensions h/a =1 and h/a =8, respectively, and the initial equivalent diameters dv0 = 16.9-24.9 mm for quasi-circular particles and dv0 = 7.3-18.9 mm for oblong particles at process temperatures 800, 850, 900 and 9500C were studied. Average values and range of moisture variation and ash content in the raw mass, and volatiles on the dry ash-free mass by analysis in accordance with the standards of EN 14774-2:2009, EN 14774-3:2009, ASTM E1755-01 (Reapproved 2007), EN 15148:2009 presented in Table 1.
Table 1. The main characteristics of wood particles

| Parameter   | Designation | Value          | The range of variation |
|-------------|-------------|----------------|------------------------|
| Moisture, % | \( W_i^r \) | 5.27           | 6.42-9.32              |
| Ash content, % | \( A_i^r \) | 0.33           | 0.15-0.85              |
| Volatiles, % | \( V_i^{daf} \) | 86.68         | 86.68                  |

The effect of temperature, initial size and shape on the primary fragmentation of large wood particles was evaluated using known criteria of fragmentation: the probability of fragmentation (percentage of fragmentation events) SF, the fragmentation degree (particle multiplication factor) Nf, variation factor of the feed particle Fd and fragmentation index (size reduction index) Sf (SRI [10]), as well as the mass fraction of the fine fraction of coke fragments Xf. When calculating the fragmentation criteria were considered fragments of a mass of not less than 0.001 g (equivalent diameter of more than 3 mm). Fragments weighing less than 0.001 g were taken into account by the mass fraction of fines Xf. The total mass fraction of particles with a mass less than 0.001 g exfoliated as a result of the process was insignificant in all experiments (no more than 0.05), therefore, in the case when large fragments remained fastened together, the coke particle formed was considered not to have lost integrity, and the initial particle was fractured but not fragmented.

3. Results and analysis

Analysis of these experiments, taking into account the five criteria of fragmentation, it seemed that the increase in the temperature of the process in the range 800 – 950 °C intensifies the primary fragmentation of wood particles (Figure 2). This applies both to the proportion of particles fragmented and to the composition of the resulting coke particles. The change of fragmentation characteristics depending on the initial particle diameter is consistent with the existing data and ideas about the nature of the effect of fuel particle size on fragmentation; with the increase in the initial size of the propensity of wood particles to fragmentation increases. The critical fragmentation diameter at a temperature of 9500C may be determined based on consideration of the dependence of SF from the initial diameter \( d_v^0 \) (Figure 3).

![Figure 2. The fragmentation index as a function of temperature.](image-url)
Figure 3. The probability of fragmentation of large wood particles as a function of the initial diameter $d_{v0}$.

In this case, SF oblong particles with $d_{v0}=18.9$ mm is 50% or more in the entire range of the studied temperatures, while for particles with $h/a=1$ even at $d_{v0}=24.8$ mm there is not a single case of fragmentation at temperatures below 850 °C, and SF becomes more than 50% only at a temperature greater than 900 °C. Taking to be the critical fragmentation diameter the value of $d_{v0}$ by which SF= 50%, the critical diameter $d_{v0}^{cr}$ lies in the range of 8-12 mm for particles with $h/a =8$, and $d_{v0}^{cr} =18 – 19$ mm for particles with $h/a =1$.

Smaller values of the critical diameter for elongated particles, as well as a comparison of dependence of the main criteria of fragmentation on the temperature and $d_{v0}$ for particles with $h/a =1$ and $h/a =8$ indicate a greater tendency of elongated particles in the fragmentation in relation to the cubic particles (quasi-circular) forms, ceteris paribus. The explanation of this fact may lie in the nature of fragmentation of wood particles in the studied temperature range. In general, the small values of the fraction of small fragments $X_f$ indicates that the volatile release stresses have a significant value for the fragmentation at a temperature of 800 – 950 °C, and the contribution of thermal stresses is negligible, although slightly increases at temperatures above 900 °C (Figure 4). Oblong particles have a smaller distance between the surface and a random point on the central longitudinal axis of the particle (the center of the particle), compared to a quasi-circular particle of the same equivalent diameter. Therefore, the heating of the particle throughout the volume should be faster, and, consequently, the formation and accumulation of volatiles in the particle core should begin with a lower time delay relative to the zones near its surface. I.e. pyrolysis of the particle will take less time (flow more intensively), and the gas pressure inside the particle will rise and fall faster, reaching higher maximum values. This should result in higher maximum volatile release stresses inside the particle.
The study of fractured unfragmented coke particles using an electron microscope showed that their structure repeats the structure of the original wood particles with the preservation of the inherent soft-wood structural elements: tracheids, medullary rays, simple and bordering pores. In this case, lignocellulose is replaced by carbon in the wall material of hollow elements of the microstructure. Figure 5 shows that kept even the tiniest elements of a structure of wood as a membrane enclosing pores.

Fracturing of rectangular particles is characterized by the presence of a few large cracks dividing the particles into large fragments. The formation of the crack occurs by sequential longitudinal ruptures of the tracheid walls. These cracks originate on the surface and propagate to the center of the particle. On a photo of the Fractured, but not fragmented particle ($d_0=16.9$ mm) it is clearly seen that the particle remains intact (not fragmented) due to the core not affected by cracking (Figure 6).

Destruction of the tracheid walls inside the particle was observed to occur in the planes of both longitudinal and cross-sections. Origin of crack is more probable at the place of irregularities on particle
surface, especially in the places of exit to the outer surface of the particle boundaries of late (autumn) and early (spring) wood gain. Figure 7 shows rupture on the surface of small non-fragmented coke particles ($d_{50} = 9.9 \text{ mm}$) on the boundary of gains.

![Figure 6](image)

**Figure 6.** Cracked non-fragmented coke particle.

![Figure 7](image)

**Figure 7.** The origins of cracks at the place of exit to the outer surface of the boundary of late (autumn) and early (spring) wood gain.

4. **Conclusion**

Based on the analysis of fragmentation characteristics, it can be concluded that:

1. Increasing the temperature and initial size of the particles in the range 800 – 950 °C increases the probability and intensity of fragmentation in the process of rapid pyrolysis of wood particles.
2. The ratio of longitudinal to transverse size and, more broadly, particle shape, has a significant effect on the fragmentation of wood particles and should be considered as one of the main factors affecting the fragmentation of wood particles, as well as temperature and initial size. Oblong particles are more prone to fragmentation than quasi-circular (cubic) particles with the same equivalent diameter.

3. The critical diameter of fragmentation of spruce wood particles at a process temperature of 950 °C is \( dv_0 = 18-19 \) mm for the ratio of longitudinal and transverse size \( h/a = 1 \) and is in the range of 8 - 12 mm for \( h/a = 8 \).

4. For spruce wood particles in the considered temperature ranges and equivalent diameters \( (t = 800 - 950 \) °C and \( dv_0 = 7 - 25 \) mm) is characterized by fragmentation due to the volatile release stresses forming large fragments. The role of thermal stresses is negligible, although it increases slightly with increasing temperature.

5. The decay of spruce wood particles into fragments in the process of rapid pyrolysis under the studied conditions is due to the formation of large cracks arising on the surface and propagating to the center of the particles. The mechanism of fracturing is a consistent, mainly longitudinal rupture of the walls of hollow elements of the wood microstructure (tracheids) due to the volatile release stresses. The irregularities in the places of exit to the outer surface of the particle boundaries of late (autumn) and early (spring) wood gain contribute to the origin of cracks on the surface of the particle.

The obtained values of critical diameters and quantitative characteristics of fragmentation are preliminary, as additional experimental data are accumulated and statistically processed, they can be used to predict and estimate fragmentation during pyrolysis, gasification and combustion in a bed.

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