

Article

Experimental Study of Model Refuse-Derived Fuel Pellets Swelling during Heating and Combustion

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Abstract: Composites of sawdust and crushed polyethylene were obtained by pressing at 5–10 atm. The resulting pellets with a size of about 10–20 mm were then burned in airflow in a muffle furnace at a temperature of 800 °C. The combustion process was recorded, and obtained video data were analyzed. The data obtained made it possible to estimate the change in particle size at different stages of combustion. An increase in linear dimensions during conversion was achieved of up to 2 times. Particle swelling led to a decrease in mechanical strength and destruction of particles before complete burnout.

Keywords: biomass; bloat; ignition; polyethylene; single particle; visualization

1. Introduction

Achieving clean and sustainable environment goals (see, for example, SGS [1]) requires managing municipal waste utilisation problems. Since such waste contains a large amount of organic matter, it is possible to use thermal methods for its disposal. In this regard, the issue of the efficient combustion of municipal waste and refuse-derived fuel is a subject of great practical interest [2].

Waste incineration without prior sorting is almost impossible. First, the waste contains a large quantity of materials that can be reused, so burning them is not economically justified. Secondly, waste may contain hazardous components, which when combusted can result in the formation of harmful substances (both organic and inorganic). Waste without recoverable and hazardous components is called refuse-derived fuel (RDF). It usually contains enough organic material for sustainable combustion. The composition of the waste varies over a wide range. Usually, additional RDF preparation is necessary, for example, grinding, briquetting, drying, etc. Waste gasification technologies (agricultural, forestry, domestic) are discussed in the review [3]. The problems of waste fuel preparation are discussed in [4].

It should be noted that a complete transition to the reuse of waste is not feasible. The return ratio of valuable components is always less than one, so some of the waste, one way or another, has to be disposed [5]. Thermal decomposition and combustion of waste occurs in landfills even without burning it due to air access and self-heating [6]. Low-temperature oxidation products may be even more harmful and dangerous than high-temperature oxidation products [7]. During landfill oxidation, waste partially decomposes, which leads to decrease in its calorific value [8]. In addition, the industry of waste thermal processing can be one of the factors in the development of the economy [9]. Incineration is the most mature thermal utilization technology, which may be organized in close proximity to landfill [10]. The rule of three “T’s” (time, temperature, turbulence) enables reducing the formation of harmful polycyclic substances under controlled combustion conditions [11]. Gasification and pyrolysis technologies may be technically and environmentally more efficient than incineration, but their widespread use requires solving a number of problems,



Citation: Donskoy, I.; Svishchev, D. Experimental Study of Model Refuse-Derived Fuel Pellets Swelling during Heating and Combustion. *Processes* **2023**, *11*, 995. <https://doi.org/10.3390/pr11040995>

Academic Editors: Albert Ratner and Davide Papurello

Received: 28 February 2023

Revised: 13 March 2023

Accepted: 22 March 2023

Published: 24 March 2023



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such as combustible gas conditioning and the development of suitable combustion chambers [12]. Waste gasification is more flexible for energy applications because it enables the accumulation of combustible gas and its use at peak loads [13].

The prospects for the use of waste gasification for the power supply of autonomous consumers are discussed in [14]. A comprehensive feasibility study for the partial replacement of coal by combustion is proposed in [15]. The application of high temperature waste gasification in the energy sector is discussed in [16].

Waste may be used as an additional fuel in the combustion and gasification of fossils. Plant biomass is gradually becoming an important energy source, so the transition to other low-grade fuels, primarily to combustible waste, looks quite straightforward [17]. Waste grinding enables its mixture in different compositions, resulting in multicomponent fuel slurries for efficient combustion [18,19]. Due to reactive and thermal interaction between components, it is possible to achieve stable combustion and low emissions during the combustion of these mixtures [20]. However, the grindability of waste is often very low, and the energy costs for grinding can be quite large.

The authors of [21] attempted to determine the optimal waste fraction in mixtures with woody biomass and agricultural waste using thermodynamic modeling. In another work [22], for the same purpose, a modified thermodynamic model was used, which took into account the kinetics of heterogeneous reactions (fuel carbon conversion).

There are other methods of thermal waste disposal: decomposition in supercritical fluids (including in the presence of catalysts and oxidizers) [23]; hydrothermal pyrolysis [24]; pyrolysis and gasification in molten slag (however, additional fuel is required to maintain temperature) [25]; pyrolysis and gasification of waste using concentrated solar radiation [26]; high temperature air gasification [27]; plasma gasification [28]; waste hydrogenation [29]; and filtration combustion processing [30]. Most of these processes require a significant amount of external energy supply, usually in the form of heat (in the case of plasma gasification, electricity supply), which lowers energy efficiency, but contributes to the deep decomposition of harmful substances in output gases [31].

A high fraction of polymers in the waste can be both a positive and a negative factor [32]. On the one hand, the decomposition of polymers results in products with a stable composition and high heating value. On the other hand, incomplete decomposition products are undesirable due to complex thermal behavior and adhesive/corrosive properties. Various methods are used to capture chlorine compounds and aromatic substances, such as the binding of halogens with minerals [33], catalytic filtration [34], and plasma-assisted purification [35].

To prevent the agglomeration of waste during heating and decomposition, devices with moving parts are often used, for example, furnaces and pyrolyzers with rotating sections [36], augers [37], and special grates [38]. The mineral part influences the design of waste disposal furnaces since it makes a significant contribution to the corrosion of heat exchange surfaces. The corrosion rate for waste incineration is an order of magnitude higher than for fossil fuels [39]. This is due to the high reactivity of mineral deposits, which contain large amounts of halogens [40]. The characteristic temperature points of waste ash and other solid fuels are comparable, but the qualitative behavior during melting can differ significantly due to the high proportion of particulates [41]. The composition of the mineral part affects, among other things, the waste decomposition products [42]. The halogens formed during the dissociation of salts may inhibit some combustion chain reactions [39]. With suitable treatment, bottom ash can be used in the production of building materials [43].

Fixed bed waste gasification is also accompanied by agglomeration, which leads to the formation of clinkers [44]. Increasing the proportion of plastics improves the gas yield and its calorific value but increases the yield of resinous substances [45]. Therefore, the highest possible fraction of plastic for gasification is usually about 20–30% [46]. Waste particles agglomerate, both due to the formation of liquid decomposition products and swelling during heating (which is a subject of the present work). Another possible reason is low-melting ash compositions [47]. The melting of polymers, together with the inhomogeneity

of the composition and non-combustible inclusions, leads to instability of the fixed bed combustion front [48].

Experimental studies are often carried out on mixtures of biomass and waste/plastics [49,50]. Experiments on co-gasification of pellets from biomass and waste in a downdraft gasifier with capacity of 100 kg/h [51] have shown that an increase in the waste fraction led to an increase in underburning and bed agglomeration. The achieved reaction temperature was about 800 °C, and the cold gas efficiency was 50–60%. The authors of [52] reported on the study of an internal combustion engine fed by producer gas obtained from the co-gasification of biomass and waste mixtures (the waste fraction was up to 40%). With cold gas efficiency of the same values, the electrical efficiency of the power plant was 19–22%. With an increase in the waste fraction waste, the efficiency decreased. The authors of [53] investigated the updraft fixed bed gasification process, achieving a cold gas efficiency of 45–60% (reaction temperatures were higher compared to typical downdraft reactors). In this case, however, a higher yield of tarry products was observed. The tar generated during waste gasification contained high concentrations of aromatic components [54,55]. The paper [56] reported on fixed bed waste gasification experiments, where a special device was used to agitate the bed (with a time period of 10–15 min) to prevent agglomeration and the formation of burnouts. In this case, losses with underburning were up to 20%. The authors of [57] carried out low-temperature waste conversion in a laboratory reactor with external heating. Conversion degrees of 90% and higher have been reported (with air-assisted conversion). Oxygen gasification of waste was studied in [58].

The experimental units for studying the processes of decomposition and oxidation of waste can be divided into several groups: quartz tube furnaces; drop tube reactors; and fixed-bed and fluidized bed reactors. These units enable study of the kinetics of pyrolysis and combustion of individual particles, the composition of conversion products (including harmful substances), critical ignition conditions, etc. Fixed bed reactors make it possible to study the dynamics of bed burn-up (velocity of the combustion front, critical air flow) [59], as well as the interaction between different areas of the bed, for example, the deposition of tar on the char [60]. The processes of high-temperature steam waste gasification were studied in [61]. Microwave heating of waste was studied in [62]. The processes of slow low-temperature oxidation were studied in [63]. The authors of [64] described a pilot plant for plasma gasification processes studies (with a capacity of 20 kg/h), which made it possible to obtain gas with a heating value of up to 12 MJ/Nm³.

Among the analytical methods for studying the processes of waste processing, complex thermal analysis has become widespread. Thermogravimetry data, combined with calorimetry and product detection, make it possible to evaluate the reactivity of the waste, the reaction heat of conversion, and the composition of products under different conditions (heating rates, oxidant concentrations, etc. [65]). As a rule, individual waste components (polymers, rubbers, pulp and paper products) or their mixtures [66], including fossils, are studied. Chars obtained during the pyrolysis of different types of waste also have different reactivity [67]. During the mixture decomposition, a qualitative correspondence is usually observed with the decomposition of individual components [68] (in some conditions this correspondence becomes quantitative [69]). However, in the general case, during co-decomposition, the components interact thermochemically. Chemical reactions of destruction and oxidation of polymer molecules, which usually have a radical nature, can influence each other, often in a non-linear manner [70]. More active components can initiate the decomposition of less active ones; moreover, the mineral part may have a catalytic effect. One of the mechanisms of interaction can also be the formation of films, the filling of pores, and the encapsulation of particles during the melting of polymers.

The lack of understanding of the mechanisms of decomposition and combustion of fuel particles hinders the development of mathematical models for describing the processes of waste incineration. Among the problems of municipal solid waste incineration processes modeling, there are issues of providing a detailed description of the interfacial interaction and mechanics of a granular medium [71]. It is also necessary to mention the problems

of appropriate estimation of the component composition [72] and the thermophysical properties [73] of waste.

When heated, the waste particles swell and release a significant quantity of viscous products, as a result of which the particles become covered with a film and stick together [74,75]. The main factors determining the swelling are the melting component fraction and the temperature ranges of its softening and charring, as well as the particle residence time in this temperature range. The effect of particle swelling when heated was studied for coals [76,77]. The swelling of coal particles occurred due to the formation and growth of gas bubbles during the decomposition of the melting organic mass. Similar effects were observed during the degradation of artificial polymers [78].

In the present work, we study features of a wood-polyethylene pellet decomposition to estimate the effect of swelling on single particle combustion. The results may be useful for the analysis of the refuse-derived fuel incineration process. To this end, it is necessary to choose appropriate experimental conditions.

The combustion of single biomass (mainly wood) and waste particles was studied in several works. Statistical models for the ignition and burnout times of wood and sewage sludge particles were proposed in [79]. The authors of [80] used optical diagnostics to detect volatile flame structures and particle size dynamics. Wood particle ignition and burnout in airflow were investigated in [81] using visualisation techniques. An estimate of the drying front position at the ignition moment is given in [82].

Homogeneous and heterogeneous ignition of wood particles at different oxygen concentrations was studied in [83]. The authors of [84] considered the influence of cavity size on cubic-shaped particle ignition. Wet particle ignition for different shapes of wood particles was studied in [85]. The boundaries of different ignition mechanisms for biomass powder ignition were established in [86]. Radiative ignition in a photothermal reactor was used in [87].

Experiments have shown that torrefaction decreases pyrolysis stage reactivity but increases char conversion reactivity [88]. The influence of CO₂ addition and varying O₂ concentration was studied in [89]. Flame dynamics in oxyfuel-combustion conditions were visualised in [90]. The ignition of particle sets was investigated in [91]. Dust explosion experiments were carried out in [92]. Flame diagnostics during the combustion of waste particles with the analysis of released ions was carried out in [93].

Fuel mixtures often demonstrate non-additive behaviour during combustion, which relates to the thermal and chemical interaction between components (and their decomposition products). Mixtures of biofuel and fossils are widely used, both in pellet and slurry form. Methods for studying phase transitions and the combustion of single particles of fuel-water suspensions were proposed in [94,95]. The authors of [96] investigated the combustion of wood particles under intense light radiation conditions. The combustion of coal-biomass pellets was studied in [87,97]. The co-conversion of wood and polyethylene was studied in thermogravimetry methods (for example, see [98]). The pyrolysis of waste and refuse-derived pellets was studied in [75] (cardboard and polyethylene) and [99] (waste and straw).

There are many factors influencing single-particle combustion. When burning, the shape of the particles is smoothed out [100]. Low-temperature melting ash may form a slag film and block access of the oxidizer [101]. During the thermal decomposition of particles, as a rule, shrinking of wood particles occurs; however, upon rapid heating, the particles can expand due to the pressure of water vapour and thermal stresses [102,103]. According to [99], when heated, particles of polymer-containing waste swell, increasing their size up to 1.5 times. Detailed investigation of these phenomena may help in searching for more efficient ways to utilise waste with heat and power production [104].

In our previous works [105,106], we studied the combustion and gasification of sawdust and polyethylene mixtures in a thermogravimetric apparatus and a fixed-bed reactor. The single particle level was an intermediate one, which allowed consideration of chemical interaction and transfer processes linking different scales of the problem. In this work,

we investigated the combustion and fragmentation of model waste particles (sawdust and polyethylene composites) in a muffle furnace. For the first time, we measured wood-polyethylene pellet combustion dynamics under conditions of high-velocity air jet injection. To this end, the technique and equipment proposed in [107,108] were used.

2. Raw Materials and Experimental Setup

The model refuse-derived fuel under study was a mixture of sawdust and polyethylene. Sawdust is a typical representative of lignocellulosic mixtures, and polyethylene is the most common plastic. Lignocellulosic waste and plastic make up the largest fraction of the combustible mass of municipal waste [109]. The raw materials were mixed and pressed under different conditions to obtain pellets. Calibrated pine sawdust of 0.6–1.0 mm and polyethylene granules of 1 mm were used. The polyethylene fraction varied from 0 to 40 wt %. For the pressing, we used samples of 4–5 g. The diameter of the cylindrical pellets was determined by the size of the steel tubes used (20 mm). The height depended on the mixture composition and the pressing conditions. In our experiments, the density varied from 0.8 to 1.28 g/cm³, which corresponded to a pellet height from 8 to 18 mm.

One of the problems of wood and polyethylene mixture pressing is the elasticity of the polymer. After removing the load, the pellets were partially restored in size, so the mechanical strength and density of the mixed pellets were low. To solve this problem, we preheated the mixture to a temperature of about 160 °C. Under these conditions, the polyethylene partially melted, and the pellets were strong even at pressures of about 5 atm (although a small part of the polyethylene was sometimes squeezed out from under the press). For comparison with mixed pellets, experiments were carried out with the combustion of wood pellets without polyethylene additives. Table 1 presents the properties of the pellets.

Table 1. Composition and properties of pellets.

Sample No.	1	2	3	4	5	6	7
PE fraction, % wt.	0	20	20	40	20	20	40
d ₀ , mm	20	20	20	20	20	20	20
L ₀ , mm	13.2	15.0	18.0	20.0	8.0	12.3	13.0
m ₀ , g	4.25	5.01	5.02	4.99	3.22	5.15	4.80
Preheating, °C	-	-	-	-	160	160	160
P, atm	10	10	10	10	5	5	5
ρ, g/cm ³	1.02	1.06	0.89	0.79	1.28	1.33	1.18

The combustion of single particles fixed on a thermocouple was carried out in a muffle furnace (EKPS-10, internal volume 10 L, maximum temperature deviation 20 °C) at a wall temperature of 800 °C in an airflow (Figure 1). The air was supplied from a nozzle with a diameter of 2 mm at a speed of 20 m/s to ensure a sufficiently high combustion rate. Due to its high velocity, the air jet had an indoor temperature (unlike experiments described in [110]). A particle was transported into a heated muffle furnace by a thermocouple-bearing holder. The following thermal decomposition was recorded by a video camera Panasonic HC-V770 (image size 1920 × 1080, 50 fps). For a more detailed description of the experimental rig, see [107,108]. After the experiment, the video images were processed, which made it possible to determine the change in particle size during combustion.

The main goal of the experiments was to observe the swelling of particles upon fast heating. Tests showed that the swelling of particles pressed without heat treatment (even for sawdust without polyethylene) led to rapid fragmentation. The particles pressed after preheating proved to be resistant to fragmentation until the very late stages of

burnout when the air jet pierced the channel at the place where the particle was attached to the thermocouple.

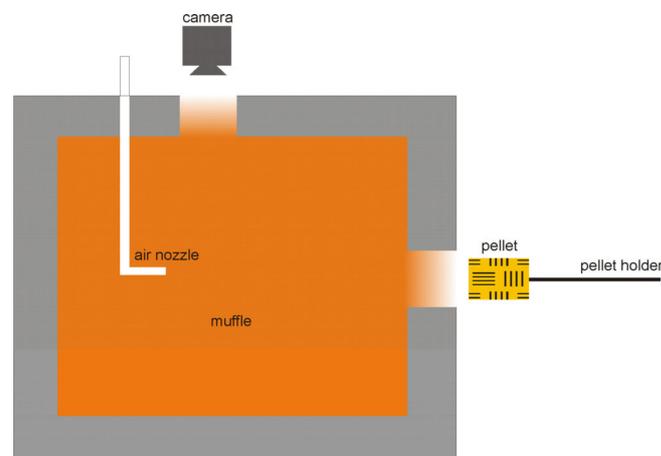


Figure 1. Experimental rig scheme.

3. Experimental Results

Figures 2–4 shows a typical burnout pattern of a single particle (a mixture of sawdust and polyethylene in a mass ratio of 80/20, pressing after preheating, sample No. 5 in Table 1). The whole process can be divided into several characteristic stages: ignition and combustion of volatiles; swelling and burning of the solid residue; particle fragmentation. The combustion of volatiles occurred in a diffusion countercurrent flame with large flow strain rates (about 10^3 s^{-1}). Stabilization of the flame was possible due to the char, which acted as a bluff body. During the heating, the frontal surface of the particle began to smolder. Combustion occurred mainly on the surface, which glowed brightly. The outer layer of the particle became porous and loose, which allowed the air jet to penetrate deeper into the particle.

Figure 5 shows the temperature measurement results (before particle fragmentation). The particles under study had a size of the order of several centimetres; therefore, they had significant thermal inertia. The ignition of volatiles in the near-surface region occurred already by 2–6 s after the particle entered the muffle furnace, but the temperature in the centre of the particle rose slowly. Devolatilization and char oxidation occurred simultaneously [108].

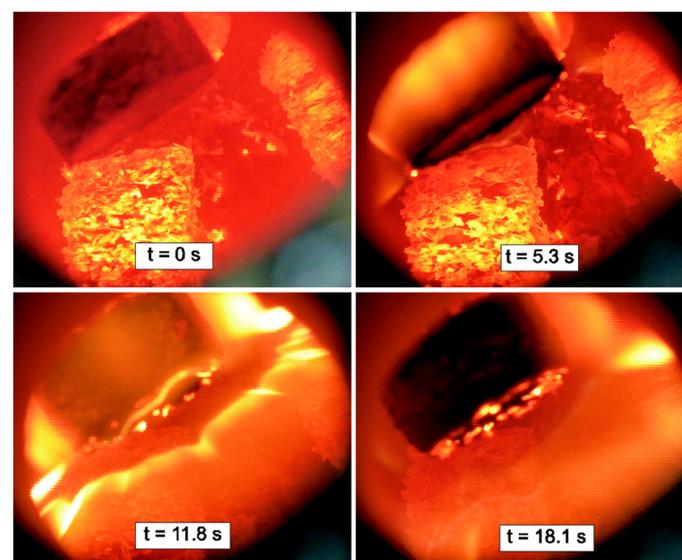


Figure 2. Ignition and combustion of volatiles.

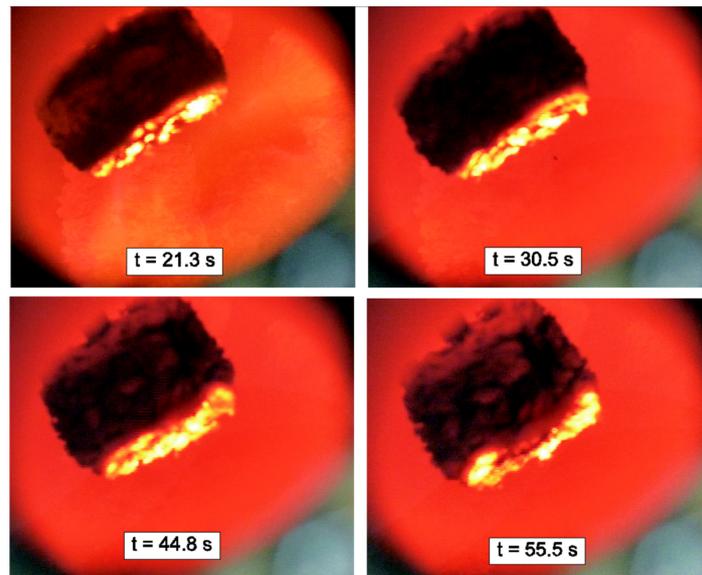


Figure 3. Solid residue combustion and swelling.

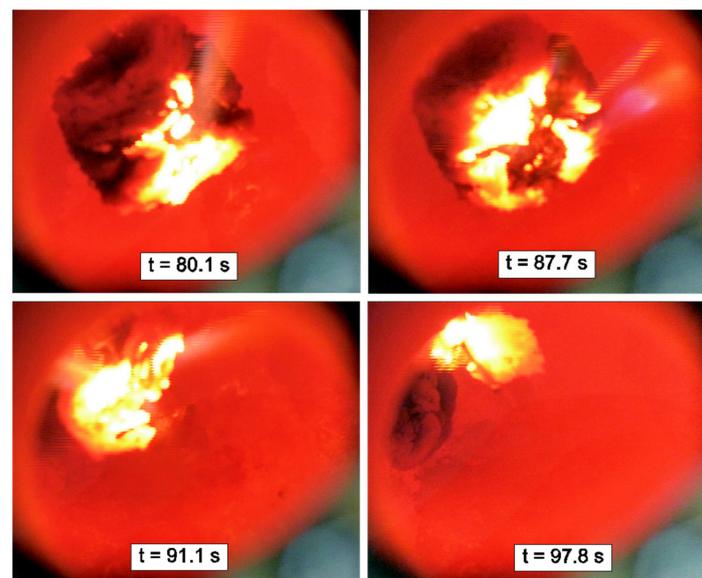


Figure 4. Particle fragmentation.

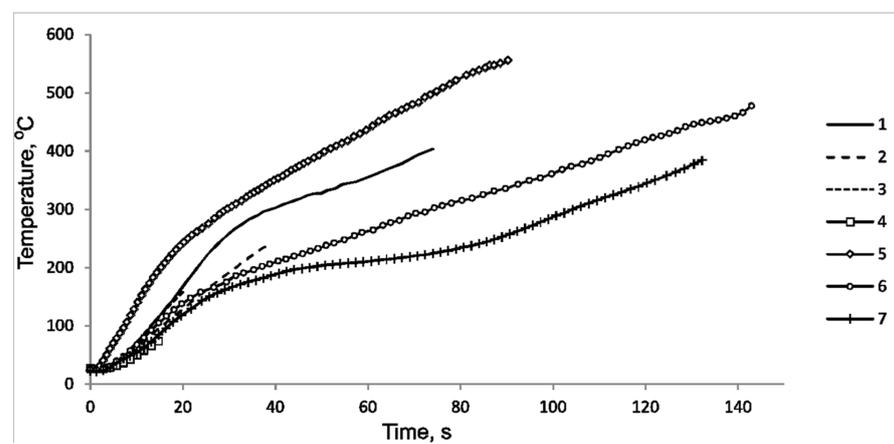


Figure 5. The temperature inside particles.

Particles with a lower mass heated up faster (for example, sample no. 5 compared to sample no. 6). However, large particles began to break down earlier (for example, sample no. 3 compared to sample no. 2). A sharp temperature rise was accompanied by intense combustion of the solid residue and rather quickly led to the fragmentation of the particle.

When processing the images, we measured the particle size at different times by pixels. For comparison, Figure 6 shows the ratio of the current size to the initial size, L/L_0 . In our experiments, the particle size increase was up to 1.6–2 times compared to the initial size. In this case, the observed values were determined not only by the mechanical but also by the reaction properties of the particles. On the one hand, there was a straightening of wood fibres and swelling of the polymer mass; on the other hand, a decrease in size was observed due to combustion.

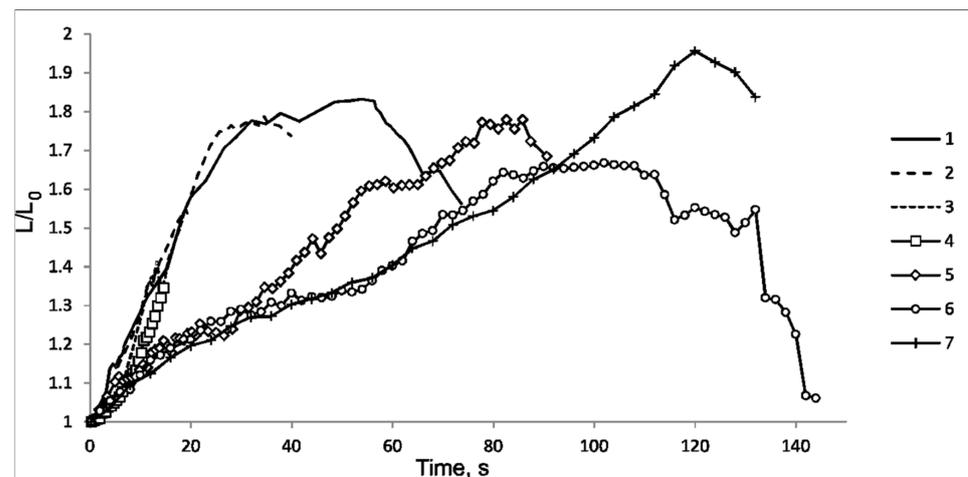


Figure 6. Size of particles, L/L_0 .

Interestingly, swelling was observed even for the sample without polyethylene. The sawdust particles used in this work were longer in the direction of the fibres. When pressed, these fibres were deformed, but meshed or adhered during preliminary heat treatment. During thermal decomposition, when gaseous pyrolysis products were formed inside the particle, and the organic matter became more brittle, the packing density decreased. Therefore, when heated, the pellets increased in size—the structure of the pellets led to deviations from the well-known behaviour of solid wood particles [111].

Swelling was the main cause of particle fragmentation. Particles with less density (with a lower polyethylene content and pressed without preheating) fragmented much faster due to intraporous combustion. In denser particles, the solid residue burning period lasted longer. Polyethylene acted as a binder [112], and particle fragmentation occurred after the decomposition of the polymer component.

4. Discussion

It is interesting to compare the results of the measurements with other works and with fixed-bed combustion.

The authors of [99] studied the swelling of refuse-derived fuel particles during pyrolysis. They observed an increase in particle size of 60%. The authors of [103,113,114] reported slight swelling for sawdust pellets (up to 10–15% of the initial size). It can be assumed that the pelletisation conditions in the present work were closer to [99].

In [106], the results of sawdust and polyethylene fixed-bed co-combustion experiments are presented. It was shown that, after the wood pyrolysis stage, further thermal decomposition of the mixtures significantly slowed down, and with a large polyethylene fraction in the mixture (up to 80%), it practically stopped. This was due both to the chemical interaction of woody biomass with polyethylene [105] and mechanical effects. During fixed-bed conversion, particles were agglomerated, so the air distribution in a bed became very un-

even. During the combustion of single pellets, an intense air jet provided an oxidizer supply straight to the burning surface. Therefore, in contrast, particle fragmentation was observed. It should be noted that an intensive air supply is a feature of the tuyere-equipped downdraft gasifiers; therefore, this organization of air supply may prevent agglomeration during the gasification of polymer-containing wastes. For incineration, similar recommendations are given in [114].

It is necessary to mention the limitations in terms of the applicability of the obtained results. In the present work, we used pellets of the same shape and of a constant diameter. As shown in experimental works [115,116], the particle shape can have a significant effect on the ignition characteristics. In large particles, the devolatilization can be slowed down due to diffusion and hydraulic resistance; therefore, patterns may differ for other particle sizes [117,118]. The sawdust used in the study was dried, which can reduce the mechanical strength of the pellets (for example, the authors of [119] obtained pellet refuse-derived fuel with a moisture content of 20% at a lower temperature, although with a higher pressing pressure). Finally, fixed-bed combustion study requires considering collective effects associated with the interaction of particles [91,120]. In the present work and in the previous work [106], these phenomena were not taken into account.

5. Conclusions

The features of combustion and fragmentation of pellets made of sawdust and polyethylene in a muffle furnace heated to 800 °C were investigated. Visualisation methods were used to measure the decomposing particles' dimensions. When heated and burned, the particles increased in size 1.6–2 times due to the straightening of wood fibres and the thermal decomposition of polyethylene. Swelling led to particle fragmentation which occurred simultaneously with pyrolysis and combustion. The pellets obtained by preheating pressing and containing a higher polyethylene fraction (20–40%) demonstrated higher resistance to fragmentation during heating and combustion. The wood-polyethylene mixtures can be considered as model refuse-derived fuels; therefore, the presented results may be of interest for maintaining the stability of municipal waste combustion processes.

Author Contributions: Conceptualization, I.D. and D.S.; methodology, D.S.; software, I.D.; formal analysis, D.S.; writing—original draft, I.D.; visualisation, I.D. All authors have read and agreed to the published version of the manuscript.

Funding: One of the co-authors (I.D.) was funded by Siberian Branch of the Russian Academy of Sciences (State Assignment Project No. FWEU-2021-0005, the Fundamental Research Program of the Russian Federation 2021-2030).

Data Availability Statement: Data are available by request.

Acknowledgments: The study was carried out using the resources of the High-Temperature Circuit Multi-Access Research Center (Ministry of Science and Higher Education of the Russian Federation, project no 13.CKP.21.0038).

Conflicts of Interest: The authors declare no conflict of interest.

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