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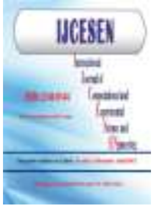

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An Experimental Investigation of Clean Syngas Production from Waste Biomass by Gasification Method

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Abstract:

Gasification technology is crucial for the efficient utilization of biomass and coal at high efficiency. Improved processes and systems are necessary to produce synthesis gas from biomass and coal (especially low calorific coals), making the process more advanced and effective. This study focuses on the direct use of waste biomass and low-calorific coals for heating and cooking to obtain synthesis gas with high calorific value. Biomass is examined for direct gasification and conversion into pellet fuel for gasification, and its use in heating and cooking systems are explored. Gas quality is enhanced in gasification stages like drying, pyrolysis, oxidation, and reduction by maintaining the reactor filled with gas and providing synthesis gas supplementation from the pyrolysis zone. Gas cleaning and conditioning processes, treated as separate operations, are carried out within the designed pilot system in a single device, generating ready-to-use gas at the outlet. A valve system that provides downflow for biomass and updown for coal is developed to enable both to be processed in the same device. Consequently, a system was created that offers more comfortable use and high efficiency (between 10-15%) in gas production compared to direct combustion, especially in rural areas, where heating and cooking are provided through a single device.

1. Introduction

Global warming and climate change concerns have led to efforts to increase the use of renewable energies, improve energy efficiency, and reduce CO_2 greenhouse gas emissions. Solar and wind energy, along with biomass, are considered fundamental renewable energy sources. In a mix of solar, wind, and biomass energy, biomass energy can be utilized as an adjustable and controllable energy source [1].

Since humans discovered how to make fire, biomass has been a primary energy source for thousands of years and still meets over 10% of the world's energy needs today. Furthermore, biomass ranks as the fourth primary energy source globally. In rural agricultural areas, biomass remains a primary energy source for heating and cooking, often serving as the sole energy source in these regions [2]. In developing countries in Asia and Africa, over a third of total energy consumption relies on biomass. One significant advantage of biomass is its universal availability worldwide, unlike coal and natural gas [3-6]. For example, in Turkey, due to the low thermal value of lignite reserves, their use in thermal power plants has been emphasized. Additionally, around 46% of lignite reserves are in the Afşin-Elbistan basin, while the most significant hard coal reserves are found in the Zonguldak region [3]. In contrast, biomass is distributed throughout the country, making it easily accessible. Recent reductions in fossil fuels and the increasing global energy demand have spurred interest in renewable energy, including biomass. The use of biomass as a renewable energy source has significantly increased in industrial applications in the past decade and is now considered a promising energy source for the future [4-8].

Despite its high energy potential, a significant portion of biomass remains unused, causing environmental issues. Understanding the energy content of the abundant available biomass is essential. Biomass can be transformed into energy through various thermochemical processes such as combustion, pyrolysis, and gasification.

Gasification, the subject of this discussion, involves transformation through certain physical and chemical reactions where a fuel (solid or liquid) is converted into a new type of fuel in the gas phase.

The distributor materials that facilitate these reactions include steam, air (or pure oxygen), or a mixture of these [5-10]. The products generated in the gasification process typically consist of a mixture of CO, CO_2, H_2, CH_4, steam, coke, tar, and ash. Gasification is a vital technology for biomass utilization, offering flexibility in producing different chemical products and using various types of feedstocks [4].

The performance of gasifier reactors is influenced by various factors such as feedstock, process design, and operating parameters. Designing gasifier reactors involves a combination of experimental data and mathematical or simulation-based modelling of the gasification process. While experimental data is considered the most reliable, it is best utilized in conjunction with modelling. Models play a crucial role in both applied gasification research and fundamental studies, providing valuable insights into optimizing gasifier operation, exploring operational limits, and understanding the relationship between operational parameters. In applied research, validated models can reliably predict gasifier performance based on feedstock characteristics, offering qualitative and quantitative information for practical operations. Simulations are particularly useful for cost-effective exploration of the benefits, costs, and risks associated with gasification implementation, considering the constraints of time and budget for experimentation. In fundamental research, mathematical models and simulations are extensively used by researchers and equipment manufacturers to understand the physical and chemical phenomena within gasifiers. The combination of experiments and process modelling is essential for gaining a comprehensive understanding of gasification processes [5]. Gasifier models can vary significantly in complexity, with options to include or omit various details. Fine-grained simulations involve modelling heat and mass transfer, multiphase fluid dynamics, chemical transport, and multiple chemical reactions, both heterogeneous and homogeneous. Modelers, whether in applied or scientific contexts, must make numerous decisions regarding the type of modelling approach and what aspects to include, omit, or approximate [6, 7].

In principle, all types of biomass can be converted into synthesis gas through gasification, which primarily comprises hydrogen, carbon monoxide, carbon dioxide, and methane. Apart from different chemicals, this gas can provide various forms of energy or energy carriers (heat, power, biofuels, hydrogen, biomethane). The utilization of existing biomass resources requires high efficiency and sustainability, which gasification offers by providing high potential and process efficiency in biomass utilization [11-16].

Biomass gasification involves the partial oxidation of carbon within biomass at high temperatures using an oxidant like air, steam, or pure oxygen. The composition and properties of the obtained synthesis gas depend on the biomass feedstock, gasifier type, and application conditions. These conditions, such as the oxidant used, temperature, and residence time in the gasifier, can vary.

The existing review articles are not enough to address recent advancements in tar modelling within gasification processes [8]. Current research indicates that gasification models typically handle tar in one of three simplistic ways: as absent, inert, or represented by a single or few model compounds like benzene or naphthalene. These approaches, though oversimplified, raise the crucial question of the error margin introduced by such simplifications. Historically, these simplifications were likely driven more by tar's complexity and variability under different conditions rather than by a precise understanding of the error magnitude. Limited experimental data on tar species due to sampling and analysis challenges further complicates the issue. Recent developments have introduced more sophisticated tar models for scenarios where a refined treatment of tar is crucial, providing a more nuanced understanding of gasification processes. This review aims to offer a comprehensive analysis of these new models, categorize key gasification modelling approaches, present usage frequency statistics, and survey tar modelling and its approximation methods [17-24].

2. Material and Methods

2.1 Biomass analysis

Proximate analysis is an analysis to measure the amount of chemical elements in biomass. These elements are mainly C, H, O, S and N and are determined as percentages in the elemental analysis. Depending on the type of biomass, the elemental analysis can be significantly different, and the ash content can vary considerably. Average values for wood and wood waste are carbon (C) 40-50%, hydrogen (H) 6%, Oxygen (O) less than 40%, Nitrogen (N) less than 1% for most applications and sulphur (S) about 0.5%. Table 1 shows the basic analysis results for some biomasses and lignite. Moisture content is measured by drying the feedstock at 105℃. The ash content, which varies significantly, can be measured by burning the feedstock at 550 °C. The biomass has a composition of 40-80% cellulosic, 25-25% lignin and 15-30% semi-cellulosic by mass [4, 9].

Air gasification typically yields synthesis gas with an approximate heating value of 4-7 MJ/m3, whereas using pure oxygen or steam as the oxidant results in significantly higher calorific value gas production (10-18 MJ/m^3). This introduction provides a comprehensive overview of the significance and potential of biomass gasification as an essential technology for renewable energy, highlighting its various applications and benefits.

Given the depth and importance of biomass gasification in the context of renewable energy, further research and development in this field are essential for sustainable energy solutions [10, 11].

Proximate analysis is typically conducted on biomass, just like on other solid fuels, to determine its content of moisture, ash, volatile matter, and fixed carbon. In ash analysis, the weight percentage of ash in dry biomass (denoted as dry basis, db) or in the as-received biomass is determined. For moisture analysis, the weight percentage in the wet biomass is considered. The total volatile matter accounts for the weight percentage in the dry or as-received (ar) biomass or in the dry and ash-free (daf) biomass. The remaining portion is evaluated as fixed carbon (C) based on mass weight. Table 2 provides the results of proximate analyses for some biomasses and lignite[12].

Table 1. *Proximate Analysis of Biomass and Coal (Dry and Ash-Free Basis)*

Fuel Type	**C (% Weight)**	**H (% Weight)**	**O (% Weight)**	**N (% Weight)**	**S (% Weight)**	**H/C**	**O/C**
Pine	51.6	4.9	42.6	0.9	-	0.095	0.826
Eucalyptus	52.8	6.4	40.4	0.4	-	0.121	0.765
Lignite	56.6	5.6	35.1	1.5	1.2	0.129	0.424
Sub-bituminous Coal	81.2	5.7	8.8	1.0	3.3	0.072	0.239

Table 2. *Basic Analysis Information for Biomass and Coal (Dry and Ash-Free)*

Fuel Type	**Moisture (% Weight)**	**Volatile Matter (% Weight)**	**Fixed Carbon (% Weight)**	**Ash (% Weight)**
Pine (dry)	12	71.50	16	0.50
Eucalyptus (dry)	10.60	74.80	13.90	0.70
Lignite	31.03	34.82	11.86	22.28
Sub-bituminous Coal	29.20	30.80	34.40	5.50

- In dry basis (db),
  Fixed C = 100 – ash (db) – volatiles (db)
- In dry and ash-free basis (daf),
  Fixed C = 100 – volatiles (daf)
- In as-received basis (ar),
  Fixed C=100–moisture content - ash (ar) – volatiles (ar)

The calorific value, which is the heat obtained from the combustion of biomass, can be accurately calculated using the following relationships [1, 13]:

$$\mathrm{HHV} = [34.1\mathrm{C} + 132.2\mathrm{H} + 6.8\mathrm{S} - 1.53\mathrm{A} - 12\,(\mathrm{O} + \mathrm{N})]\ (\mathrm{kJ/kg}) \tag{1}$$

$$\mathrm{HHV} = [146.6\mathrm{C} + 568.8\mathrm{H} + 29.4\mathrm{S} - 6.6\mathrm{A} - 51.5(\mathrm{O} + \mathrm{N})] \times 10^2\ (\mathrm{Btu/lb}) \tag{2}$$

Here, C, H, S, A, O, and N represent the weight percentages of carbon, hydrogen, sulfur, ash, oxygen, and nitrogen in the fuel, respectively. The values obtained from these calculations are suitable with an error margin of approximately 2.1% for many biomass materials [24-27].

2.2 Biomass gasification

Biomass gasification is carried out through five distinct thermal processes. These processes can be named as Drying, Combustion (oxidation), Pyrolysis, Carbonization, and Reduction (as seen in Figure 1). All these operations naturally occur in the flame you see when you strike a match. However, to those unfamiliar with the intricacies of gasification, these stages blend together almost imperceptibly. Gasification, therefore, is a technology used to separate and isolate these "individual processes," making them visible, so that we can interrupt the flaming and channel the resulting gases elsewhere for further use [11, 14].

The thermo-chemical transformation stages in the gasification process can be explained as follows:

a) Drying: In the drying zone, the raw material loaded into the gasification reactor is heated by the high heat from the lower regions and dried to remove moisture. Biomass typically contains 10-30% moisture, a lower percentage than coal. The temperature in this zone generally ranges from 100-200°C.

b) Pyrolysis (Distillation): Heating organic materials in an oxygen-free environment initiates a thermal decomposition process known as pyrolysis. Heating without oxygen up to 500-600°C releases gas components, volatile condensable substances, charcoal, and ash. At higher temperatures, gas components and wood gas are released, consisting of volatile gases such as CO, CO_2, H_2, CH_4, and water vapor. Separating volatile gases results in the formation of charcoal and tar.

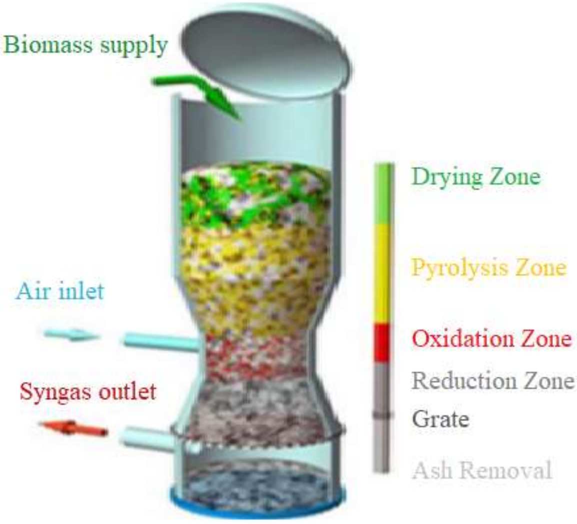

Figure 1. *Biomass gasification*

c) Oxidation: Organic molecules of biomass release heat energy as carbon (C) and hydrogen (H) oxidize through chemical reactions. These exothermic reactions release heat to the surroundings. They subsequently convert to carbon dioxide and water vapor. Combustion also releases ash containing unburned inorganic minerals. The temperature in this zone is typically 750-1000°C.

d) Reduction (Carbonization): Unburned coal moves downward in the reduction zone until gasified. The obtained gas is synthesis gas with a similar content to that obtained in the pyrolysis zone, but with increased combustible gas and reduced tar content. The coal is completely gasified. Gas-water vapor combination reactions are effective above 700°C, with H2 being produced at this temperature. Moreover, tar can be effectively broken down at temperatures exceeding 850°C with suitable residence times.

The process up to approximately 500°C in gasifying organic matter is the pyrolysis stage, where carbon, gases (having a calorific value of up to 20 MJ/m^3), and tar are obtained. When the temperature rises to 1000°C, carbon reacts with water vapor to produce CO and H_2. Depending on the varying oxygen content in the feedstock, additional oxygen input may not be required for the gasification process. The produced gas exits the system from the bottom of the reactor at temperatures of 300-400°C. If the quality of the product gas is sufficient, it can be utilized in internal combustion engine (ICE) applications and gas-fired electric generators. In a typical gasifier, the combustible gas ratio is around 20-35%, with an average calorific value of 5 MJ/m_3. The moisture content of the feedstock fuel should be below 30% [1, 15, 16].

3. Experimental System

3.1 Experimental setup

In this study, it is anticipated that the temperature within the reactor will be higher due to the presence of the reactor in a hot gas environment, leading to higher efficiency and increased gas production, considering the improvements made in some of the reviewed literature studies. It is possible to obtain clean and combustible gas at the system outlet without the need for separate devices for cleaning and filtering processes. Appropriate dimensions have been selected for the gasification stages in sizing the reactor. The top part of the reactor is where the pre-loading takes place. The upper region of the reactor, where drying and pyrolysis processes occur, consists of a cylindrical body with a diameter of 20 cm and a height of 35 cm (Figure 2). Below these regions is the oxidation zone where oxygen-free combustion is carried out.

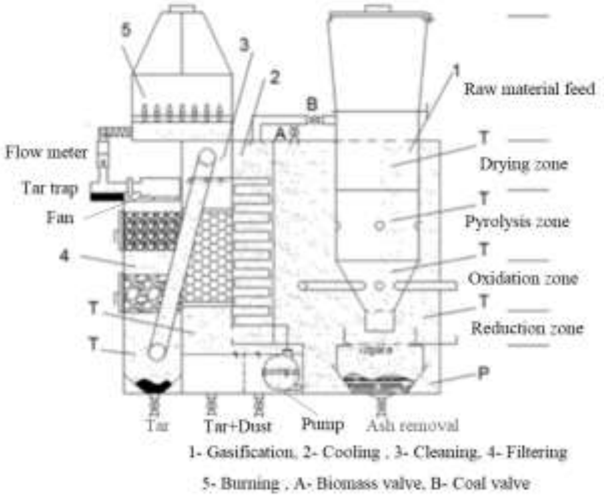

Figure 2. *Experimental setup*

The oxidation zone is made in a conical structure with an outer diameter of 20 cm, inner diameter of 7 cm, and a height of 12 cm. The diameter reduction, following the ideal reduction ratio of 1/3 as indicated in the literature, is suitable for the biomass flow at the selected dimensions. The continuation of the oxidation zone leads to the bottom part of the reactor where reduction reactions take place, and ash and tar removal processes are performed. As solid raw materials move downwards by the force of gravity from these regions, the transformation from the solid phase to the gas phase occurs in each zone. The presence of a movable grate in the reduction zone of the reactor prevents the compaction of solid particles in these regions [17, 18].

3.2 Experimental operation

As an experimental sample, pine, spruce wood, and lignite coal were selected. Additionally, pelletized pine biomass samples were included as samples to analyse gasification performance. The experimental samples included 2x1x1 cm³ blocks for wood, 2 cm³ particles for coal, and 1 cm in diameter and 2 cm in length pieces for pellets. An average of 8 kg of raw material was used for each experiment. The raw material loaded from the top of the reactor moves downwards due to the effect of gravity. Figure 3 shows the raw materials used in the experiment. More experimental details can be found in the previous study [19].

Figure 3. *Feedstocks a) Pine blocks, b) Fir blocks, c) Lignite, and d) Pellets*

The gasification stages of the reactor are completed along the solid material movement, leaving the reactor in the gaseous phase. Besides the gas obtained in the system, some tar, ash, char, and water are generated. Before starting the system operation, the raw material is placed into the reactor and the pre-loading areas. Glass beads, dry wood, and coal particles are placed on grid trays for cleaning and filtering processes. Subsequently, the circulation pump and suction fan are activated. Ignition is provided at the lower part of the reactor, and a steady gas flow is expected until gasification begins by sealing the system tightly. Throughout the experiments, this duration was determined to be approximately 5 minutes. Air supply to the system starts from the upper part, passing through 1/2" steel pipes around the oxidation zone to inflow from the reactor's side parts and inside the unit. This preheats the air before entering the reactor. Moreover, there are six 1/2" diameter holes in the pyrolysis zone to increase temperature and enhance system efficiency. Gas flow moves from the bottom part of the reactor for biomass fuel and from the top part of the reactor for coal fuel to other sections of the unit. Gas flow valves (Figure 2, A and B valves) are connected to the system to regulate the flows. Valves are located at the bottom of each region for ash removal, cleaning, and filtering processes, as well as to remove tar and condensed material from the system. These substances are used to evaluate the overall performance of the system. A flame arrestor is placed at the unit's exit, and gas combustion is conducted in a combustion chamber to prevent flashback. Heat-resistant gaskets and sealing compounds are used throughout all connections of the system to ensure tightness. K-type thermocouples, 50 cm in length, are connected for temperature measurements in the mentioned tube regions of the reactor. Thermocouples are inserted through holes on the reactor's side parts with teeth and ribbed connections to provide sealing and added to the system. Similarly, temperature values are measured with thermocouples of the same characteristics inside the reactor, at the reactor's exit, and in the cleaning and cooling sections. Pressure gauges are connected to measure pressures inside the reactor, at the reactor's exit, and in the cleaning and filtering outlets. A pressure gauge with cooling features is used to measure internal pressure due to high temperatures. Gas samples are taken separately from the reactor's exit, cleaning, and filtering outlets and stored in gas balloons and suitable syringes for further inspection. For this purpose, sampling bags are also used. Gas flow measurement is carried out with a flow meter (rotameter) placed after the fan at the system's exit. The air supply amount is adjusted with the existing fan. By calculating the air flow rate and raw material consumption rate, ideal operating conditions are determined. Ash and tar accumulated at the system's exit are separately weighed and evaluated as system output. Tar and condensate amounts are calculated using suitable methods. Moisture content of the raw materials is determined according to ASTM D3172-73, and ash content is determined according to ASTM D 3174. In this method, three known-weight raw material samples are kept in an electric oven at 100°C for 2-3 hours and then re-weighed to find weight losses, determining the moisture content. Average density is calculated by measuring the dry weight and volume of each particle. Bulk density is determined by measuring the heap volume and weight of the material. Gas composition and calorific value obtained by Gas Chromatography Apparatus (GC) will be determined later. Furthermore, evaluation of the environmental aspect by measuring the content of flue gases resulting from combustion using a flue gas analysis device is planned to be conducted later.

4. Results and Discussions

Throughout the study, five different experiments were conducted for each type of fuel. At the end of each experiment, the remaining amounts of char, ash, tar, and condensate from the system were weighed and preserved. Additionally, temperature and pressure measurements were taken and recorded at specific points of the setup during the experiments. CEM DT-610B Digital Thermometer, along with K-type thermocouples, was utilized for all temperature measurements. The temperatures obtained from the experiments were calculated as average temperatures. The ideal temperature values corresponding to the thermochemical process of gasification, including drying, pyrolysis, oxidation, and reduction zones within the reactor, were reached. The temperature in the oxidation zone, crucial for gasification, exceeded 700°C. After cooling and purification of the synthesis gas, the maximum temperature suitable for combustion chamber use, which is below 50°C, was achieved.

At the conclusion of the experiments, gas samples were taken for different fuel types and filled into gas sample templar bags. The analyses were conducted at the Middle East Technical University Institute of Petroleum Research laboratory. The equipment used for the analyses was the Agilent 6890 Gas Chromatography Device, and evaluations were carried out according to the ASTM D1945 method. The technical specifications of the device are provided in the Appendix. The gas sample taken with the gas-holding syringe from the gas sample collection bags is injected into the device inlet. Argon gas is used as the carrier gas throughout the flow. The flow pressure is maintained at 10 psi. The column is kept at a constant temperature of 50°C for 8 minutes. Subsequently, the temperature is increased to 185°C, with a rate of 12°C per minute, and held for 4 minutes. Finally, the temperature is raised to 200°C at a rate of 20°C per minute and held for 10 additional minutes. The determined results are monitored on the data display screen.

Table 3 presents the ultimate analysis of biomass and coal on a dry and ash-free basis. The ultimate analysis, which represents the elemental composition of the fuels, provides insights into their calorific value and combustion characteristics. The highest carbon content is observed in sub-bituminous coal (81.2%), followed by lignite (56.6%), eucalyptus (52.8%), and pine (51.6%). The lowest carbon content is found in pine, indicating its lower energy density compared to coal. The highest hydrogen content is found in eucalyptus (6.4%), followed by lignite (5.6%) and pine (4.9%). The lowest hydrogen content is observed in sub-bituminous coal (5.7%). The oxygen content demonstrates a decreasing trend from biomass to coal, with pine having the highest oxygen content (42.6%) and sub-bituminous coal having the lowest (8.8%). This trend reflects the decreasing amount of volatile matter in fuels as they progress from biomass to coal. Nitrogen content shows a moderate variation among the fuels, with lignite (1.5%) having the highest and pine (0.9%) having the lowest content. The sulphur content is negligible in biomass fuels, with pine and eucalyptus showing no detectable sulphur. Sub-bituminous coal has the highest sulphur content (3.3%).

Table 3. *Comparison of gas analysis results according to fuel types*

Content	Pine block	Pellet	Hazelnut shell	Pinecone	Biomass blend
Oxygen, %mol	0.274	1.696	1.406	0.07	0.07
Nitrogen, %mol	72.09	67.53	67.645	72.592	74.726
Carbon Dioxide, %mol	1.972	2.891	3.126	<0.01	<0.01
Methane, %mol	2.288	6.367	5.761	0.513	1.444
Ethane, %mol	0.132	0.733	0.489	0.035	0.028
Propane, %mol	0.045	0.225	0.126	0.035	0.026
i-Butane, %mol	0.012	0.014	0.016	0.017	0.012
n-Butane, %mol	0.024	0.054	0.049	0.042	0.034
i-Pentane, %mol	<0.01	<0.01	<0.02	<0.01	<0.01
n-Pentane, %mol	<0.01	0.021	0.02	0.022	0.018
C6+, %mol	<0.01	0.018	0.047	0.046	0.038
Hydrogen, %mol	4.293	3.233	4.434	5.01	3.01
Carbon Monoxide, %mol	18.86	17.20	16.874	21.69	20.668
Hydrogen Sulfide, %mol	<0.08	<0.08	<0.09	<0.08	<0.08
Total, %mol	100.0	100.0	100.0	100.0	100.0

The H/C and O/C ratios provide further insights into fuel characteristics. The H/C ratio represents the hydrogen-to-carbon ratio and influences the fuel's flame length and soot formation. The O/C ratio indicates the oxygen-to-carbon ratio and affects the fuel's reactivity and ignition temperature. The H/C ratio shows an increasing trend from sub-bituminous coal (0.072) to pine (0.095). The O/C ratio also shows a decreasing trend from pine (0.826) to sub-bituminous coal (0.239). These trends suggest that biomass fuels have a higher tendency to form soot and exhibit lower reactivity and ignition temperature compared to coal.

The provided table presents the ultimate analysis of various biomass and coal fuels, including their elemental composition and derived ratios. The analysis shows that pine has the highest oxygen content (42.6%), while sub-bituminous coal has the highest carbon content (81.2%). Biomass fuels, such as pine and eucalyptus, exhibit higher H/C and O/C ratios compared to coal, indicating their tendency to form soot and lower reactivity. In conclusion, the ultimate analysis reveals significant differences in elemental composition and derived ratios between biomass and coal fuels. These differences influence their combustion characteristics, such as reactivity, ignition temperature, and soot formation, and are crucial for understanding their suitability as energy sources.

Table 4 presents the composition and lower heating value (LHV) of various solid fuels used in gasification processes. Each fuel type is characterized by its percentage composition of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), carbon dioxide (CO_2), nitrogen (N_2), and other components. Pine blocks exhibit a relatively balanced composition with significant nitrogen content, while hazelnut shells have higher methane and carbon dioxide percentages. Pinecones contain a high amount of carbon monoxide and negligible methane and carbon dioxide levels. Pellets show a diverse composition with moderate methane content, and biomass mixtures have elevated nitrogen levels and noticeable amounts of other components. The LHV values, representing the energy content of the fuels, vary across the types, influencing their suitability for gasification applications.

Table 4. *Comparison of produced combustible gas content and lower heating values (LHV) according to fuel types*

Fuel type	CO [%]	H_2 [%]	CH_4 [%]	CO_2 [%]	N_2 [%]	Other [%]	LHV [MJ/kg]
Pine blocks	18.86	4.29	2.288	1.972	72.1	0.49	17.60
Hazelnut shell	16.87	4.43	5.761	3.126	67.6	2.16	18.36
Pinecone	21.69	5.01	0.513	<0.01	72.6	0.71	19.10
Pellet	17.20	3.233	6.367	2.891	67.5	2.76	19.40
Biomass mixture	20.66	5.01	1.444	<0.01	74.7	3.15	18.61

Figure 4 illustrates the size evolution of solid fuel blocks during the gasification process. It displays four different types of fuel: a) pine block, b) pellet, c) hazelnut shell, and d) pinecone. Each row represents a different stage of the gasification process, with the initial state on the left and the final state on the right. The images demonstrate the gradual reduction in size and change in shape of the fuel blocks as they undergo gasification. Thus, the solid-to-gas conversion process is clearly laid out for each feed fuel. It is important to note that this is a different process from direct drying, such as shell drying [20].

Figure 4. *Size evolution of solid blocks in the gasification process a) pine block b) pellet d) hazelnut shell d) pinecone*

5. Conclusions

The optimization of biomass gasification processes plays a crucial role in achieving efficient energy conversion and minimizing environmental impacts. The moisture content in the fuel significantly impacts both the gasification operation and the quality of the product gas. The moisture limitation for the fuel depends on the type of gasifier. The acceptable upper limit for a downdraft gasifier is 30%. For many biofuels, the moisture content falls between 11-18%, which is considered ideal for internal combustion engines and heating applications. In this study, some biomass fuels such as pine, spruce, and beech have moisture content ranging from 10-15%. The maximum particle size in our study is specified as one-eighth of the gasifier throat diameter. The dimensions of the raw material fuels used average approximately 1x1x2 cm, which is close to this specified value. The absolute and bulk density of biomass is crucial. High bulk density biomass requires less reactor volume during reloading. However, low bulk density biomass can lead to inadequate flow under gravity, resulting in low heating value and combustion in the reduction zone. The bulk density of wood pieces is determined to be between 250-300 kg/m³. In the experiments, the aim is to prevent combustion in the reduction zone. Furthermore, it was observed that the quality of the product gas remained consistent throughout the study, indicating favourable flow characteristics. Gas analysis results will be provided once the relevant devices are obtained.

Elevated volatile matter in biomass increases the tar content in the product gas, which must be removed significantly before it can be utilized for heating purposes. Comparatively, less tar formation is noted in biomass gasification compared to coal

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper
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- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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