

A HIGHLY EFFICIENT METHOD FOR THE GASIFICATION OF CELLULOSE WASTE

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ABSTRACT: The global demand for renewable energy sources is steadily increasing due to the environmental impact associated with the continued use of fossil fuels, including elevated pollution levels and increased emissions of greenhouse gases. Direct combustion of cellulose-based waste typically results in the formation of significant quantities of tar compounds, which deposit on heat-exchange surfaces and consequently reduce thermal efficiency. The technology presented in this study offers an effective method for converting cellulose waste into clean, tar-free combustible gases. The produced gas mixture is suitable for utilisation in various energy conversion systems, including burners, piston engines, and gas turbine modules. Experimental data indicate that the efficiency of converting the energy content of cellulose into gaseous fuel exceeds 80%, demonstrating the high potential of this approach for sustainable energy production.

Key words: gasification, energy efficiency.

ВИСОКО ЕФЕКТИВЕН МЕТОД ЗА ГАЗИФИКАЦИЯ НА ЦЕЛУЛОЗНИ ОТПАДЪЦИ

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РЕЗЮМЕ: Глобалната необходимост от използване на възобновяеми енергийни източници непрекъснато нараства поради негативното въздействие на изкопаемите горива върху околната среда, включително повишените нива на замърсяване и увеличените емисии на парникови газове. Директното изгаряне на целулозни отпадъци обикновено води до образуване на значителни количества катранени съединения, които се отлагат по топлообменните повърхности и по този начин намаляват топлинната ефективност. Представената в настоящото изследване технология предлага ефективен метод за превръщане на целулозни отпадъци в чисти, свободни от катрани горими газове. Получената газова смес може да се използва в различни енергийни системи, включително горелки, бутални машини и газотурбинни модули. Данните показват, че коефициентът на преобразуване на енергийното съдържание на целулозата в газообразно гориво надвишава 80%, което демонстрира високия потенциал на този подход за устойчиво производство на енергия.

Ключови думи: газификация, енергийна ефективност.

Introduction

The use of renewable energy in EU countries has significantly increased in recent years. However, let us take a look at where we stand today. As shown in Table 1, the share of renewable energy in the European Union is still relatively low—comparable to that in Africa. For this reason, the Directive (EU) 2023/2413 was adopted to promote the use of renewable energy.

Table 1. *Energy resources used by continent*

Continent	Fossil Fuels (%)	Nuclear (%)	Renewables (%)
Africa	90	0	10
Asia	85	5	10
Europe	70	20	10
North America	80	15	5
South America	75	5	20
Oceania	65	10	25

The examination of global energy consumption by type shows that renewable energy accounts for only 15% (Fig. 1).

What exactly is biomass? Table 2 presents the elemental composition of several agricultural and forestry residues. Regardless of their origin, they share very similar basic components.

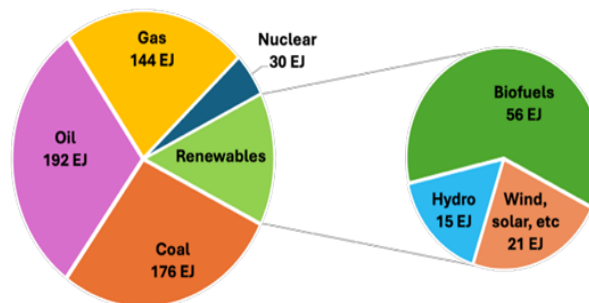


Figure 1. *Global Total Energy Supply in 2023. Source: IEA*

Table 2. *Elemental composition of biomass*

Type of Biomass	C %	H %	O %	N %	S %
Pine with bark	49.5	6.5	42.6	0.12	0.014
Spruce with bark	49.8	6.3	43.2	0.13	0.015
Beech with bark	47.9	6.2	45.2	0.22	0.015
Wheat straw	45.6	5.8	42.4	0.48	0.082
Rye straw	46.6	6	42.1	0.55	0.085
Millet straw	47.5	5.8	41.4	0.46	0.089

Next, the production of various grain crops in Bulgaria over the past few years is reviewed in Table 3. The total quantity exceeds 10 million tons (Global Data), and the amount of straw waste is approximately the same. Currently, this waste is partially used for animal feed and bedding, but most of it is either ploughed into the soil or burned illegally in the fields.

Table 3. Grain production in Bulgaria

Year	Wheat (mln t)	Corn (mln t)	Sunflower (mln t)	Other grains (mln t)
2022	6	2.9	2	0.8
2023	5.5	3.2	1.9	0.7
2023	6.2	3	2.1	0.8

Timber growth in Bulgaria is approximately 14.5 million m³. Only 5–7 million m³ (EFA 2023) is used for production. Waste from the wood processing industry amounts to between 1.5 and 2.5 million m³. Some of this waste is used to produce pellets, but most of it is discarded and pollutes the environment.

Finding a solution for the use of these waste materials is an important issue both for the industry and for improving the environment.

Technological scheme

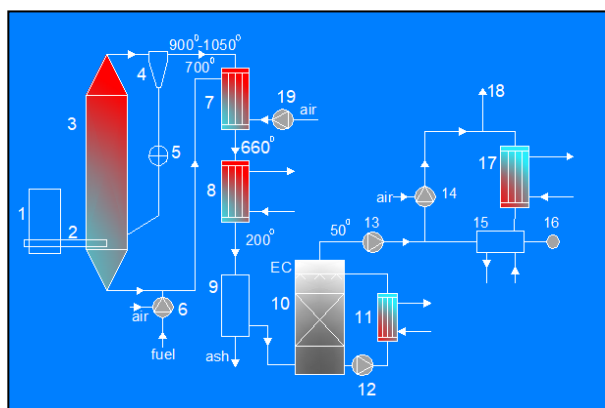


Fig. 2. Technological scheme of the gasification process

The system shown in Fig. 2 consists of the following elements: hopper (1), screw conveyor (2), gasifier (3), cyclone (4), rotary valve (5), burners (6) and (14), recuperative heat exchanger (7), heat exchangers (8), (11), and (17), bag filter (9), economiser (10), pump (12), fans (13) and (19), piston machine (15), electric generator (16), and chimney (18).

How gasification technology works

Agricultural residues are collected from the fields and delivered to a storage facility near the processing plant. It is important to note that these residues have a very low bulk density (around 250–350 kg/m³), which makes long-distance transportation uneconomical. Studies show that transportation within 30 km is cost-effective.

The schematic solution in Fig.2 covers the following steps:

Before entering the hopper (1), the straw is shredded. From the hopper, the material is fed via a screw conveyor (2) into a

gasifier (3). Continuous and uniform feeding is crucial. The temperature inside the gasifier ranges from 700–1050 °C. Material transport is assisted by preheated air at 700 °C. During transport, particles undergo four processes: drying, pyrolysis, oxidation, and reduction, converting them into gas. Particles that do not fully react are separated by a cyclone (4) and returned to the gasifier through a valve (5).

The hot gases at 1050 °C pass through a heat exchanger (7), heating the process air to 700 °C. Then, gases at 660 °C enter a boiler (8), producing steam or hot water. After cooling below 200 °C, gases go to a bag filter (9), where ash is removed. This ash can be used as fertiliser. The cooled, cleaned gases enter a condenser (contact economiser), where water vapour condenses. The outgoing gases at 50 °C and saturated humidity are directed to a fan (13), compressed, and sent to a reciprocating engine connected to an electric generator. Exhaust gases then pass through another heat exchanger (17) for heat recovery before exiting through a chimney (18).

As shown, the system includes two burners: elements (6) and (14). The former is for initial startup, and the latter is for emergency shutdown or before reaching nominal mode.

It is important to note that this solution utilises waste heat at multiple temperature levels:

1. Outside air is heated to a temperature of 700°C in heat exchanger (7). The air is used in the gasification process;
2. Steam or hot water is produced in heat exchanger (8);
3. Hot water is produced at a temperature of 60 °C in heat exchanger (11), as well as in heat exchanger (17).

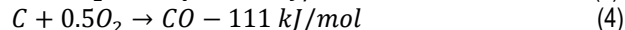
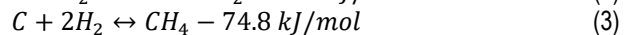
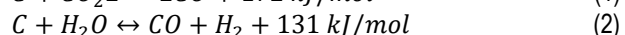
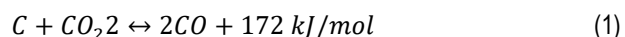
Processes occurring in the gasifier

The processes taking place in the gasifier are:

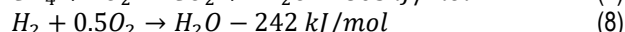
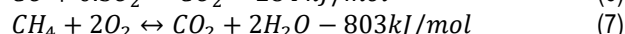
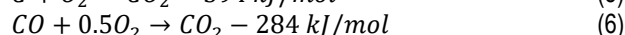
- Drying (100–200 °C)
- Pyrolysis (200–600 °C)
- Oxidation (800–1100 °C)
- Reduction (800–1000 °C)

Reactions taking place in the gasifier:

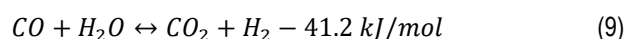
Carbon reactions:



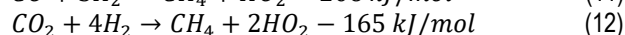
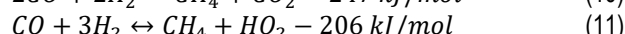
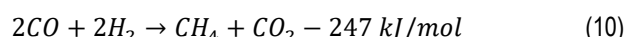
Oxidation reactions:



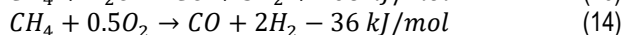
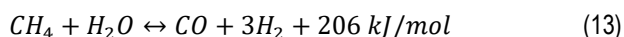
Shift reaction:



Methanation reactions:



Steam-reforming reactions:



The equations provided are well-known in literature. Equations (1), (4), (7), (12), and (13) are by Higman and van der Burgt (2008). Equations (2), (3), (5), and (14) are formulated by Klass (1998). Equations (6), (8), (9), (10), and (11) can be found in (Knoef, 2005). As can be seen from the equations provided, the processes are both exothermic and endothermic. The energy required for the process is obtained from the partial combustion of the biomass.

Using the equations above, an example is provided of the energy obtained when using the proposed new technology.

The processing of 290 kg of straw with 10% moisture content generates 561 nm³ of gas with a calorific value of 9.4 MJ/nm³. This produces 500 kW/h of electricity with an overall efficiency of 34%.

The calorific value of the gas is sufficient for use in conventional combustion systems.

Advantages of the proposed technology

✓ Airflow and temperature control.

By increasing or decreasing the rotational speed of fan (19), the required air quantity for the process can be easily regulated. This enables effective control of the gas temperature at the outlet of the gasifier.

✓ Residence time control of particles.

Adjusting the height of gasifier (3) allows regulation of the particle residence time within the reactor, enabling optimisation of the gasification process.

✓ Prevention of non-gasified biomass losses.

The inclusion of cyclone (4) prevents non-gasified biomass from leaving the process, thereby improving overall process efficiency.

✓ Elimination of the need for preliminary drying.

The simultaneous occurrence of processes within the gasifier eliminates the need for preliminary drying of the biomass, thus simplifying the technology and reducing energy consumption.

✓ High-quality product gas.

The produced gas is of high purity due to its cleaning in filter (9) and subsequent water scrubbing in economiser (10).

✓ Compatibility with existing combustion systems.

The generated gas can be utilised by all conventional combustion installations with minimal adjustments to the fuel-air ratio, facilitating straightforward integration.

✓ Utilisation of additional process heat.

The additional heat generated within the process enables the development of auxiliary technological processes, such as drying, heating, or steam generation.

✓ Potential for gasification network development.

The construction of a network of gasification plants may lead to the establishment of gas pipeline interconnections, enabling large-scale consumers to switch entirely to renewable energy sources.

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