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XIII INTERNATIONAL SYMPOSIUM OF YOUNG RESEARCHERS

Silesian University of Technology
Faculty of Transport and Aviation Engineering

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**Keywords:** synthesis gas, internal combustion engines, biomass, methanol, Fischer-Tropsch process, hydrogen

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# PROSPECTS OF USING SYNTHESIS GAS AS FUEL FOR INTERNAL COMBUSTION ENGINES

**Summary**. The article reveals the prospects of using synthesis gas obtained from biomass as an ecologically clean fuel for use in transport in order to replace fossil fuels and reduce environmental pollution. Features of the use of synthesis gas and liquid transport fuels based on it for internal combustion engines are given. Comparative experimental studies of the gasification process of torrefied energy willow under different technological regimes were carried out. It was established that the addition of a catalyst to torrefied biomass increases the hydrogen content in synthesis gas. On the basis of the conducted research, a new method of biomass gasification was developed, which provides for the production of hydrogen-enriched synthesis gas. The use of enriched synthesis gas will increase the efficiency of internal combustion engines and expand the prospects for its use as a renewable fuel in transport.

# PERSPEKTYWY WYKORZYSTANIA GAZU SYNTEZOWEGO JAKO PALIWA DO SILNIKÓW SPALINOWYCH

**Streszczenie.** Artykuł ukazuje perspektywy wykorzystania gazu syntezowego otrzymywanego z biomasy jako ekologicznie czystego paliwa do stosowania w transporcie w celu zastąpienia paliw kopalnych i zmniejszenia zanieczyszczenia środowiska. Podano cechy wykorzystania gazu syntezowego i opartych na nim płynnych paliw transportowych do silników spalinowych. Przeprowadzono porównawcze badania eksperymentalne procesu zgazowania toryfikowanej wierzby energetycznej w różnych reżimach technologicznych. Ustalono, że dodatek katalizatora do toryfikowanej biomasy zwiększa zawartość wodoru w gazie syntezowym. Na podstawie przeprowadzonych badań opracowano nową metodę zgazowania biomasy, która zapewnia produkcję gazu syntezowego wzbogaconego w wodór. Zastosowanie wzbogaconego gazu syntezowego zwiększy wydajność silników spalinowych i rozszerzy perspektywy jego wykorzystania jako paliwa odnawialnego w transporcie.

## 1. INTRODUCTION

The development and functioning of road transport is currently determined by two contradictory trends. On the one hand, there is an increase in the production and operation of cars, which demonstrates the growing potential for the development of modern society, and on the other hand, the negative impact of cars on the environment is increasing. In other words, vehicles not only improve mobility and multifaceted human activity, but also cause damage - significant environmental pollution [1].

Despite strict restrictions on emissions of toxic substances, introduced almost everywhere, and significant technical progress in environmental technologies for engines, road transport remains one of the largest sources of air pollution in populated areas [2].

The greenhouse effect and its impact on climate change is one of the disadvantages of the widespread use of fossil fuels [3]. Therefore, there is an urgent need for the transport industry to improve the efficiency of engines and use advanced fuel technologies to help achieve carbon neutral status [4]. On the way to the implementation of a fully decarbonized global energy system for powering internal combustion engines, it is necessary to replace the use of traditional fossil fuels with renewable types. Engine technologies must use fuels that minimize greenhouse gas emissions to meet global emissions legislation [1].

The next generation of environmentally friendly fuels must meet the following requirements: availability of raw materials, production efficiency, minimal impact on the environment, rational distribution and storage, safe use, compatibility with engines, vehicles and transport systems, public recognition [5].

The use of biomass as an energy source can not only reduce dependence on imported oil, but also benefit the environment by reducing emissions of greenhouse gases and pollutants that affect air quality [6].

In this scenario, synthesis gas and fuel based on it will play a certain role [4]. Synthetic gas obtained as a result of biomass gasification is an important intermediate product for the synthesis of a large number of industrial products, including biofuels [1]. It can be burned to obtain heat or electricity, used for the synthesis of liquid transport fuel, hydrogen or other chemicals [7].

Currently, synthetic gas is mainly produced from fossil natural sources, such as natural gas, as well as hard coal. Obtaining synthesis gas from biomass will not only allow to obtain renewable fuel, but will also contribute to the effective utilization of agricultural, forestry and household waste. At the same time, the existing methods of gasification need improvement in technical and economic aspects to obtain hydrogen-enriched synthesis gas. Equally relevant is the issue of developing criteria for a new concept of biomass processing, which can be implemented by integrating the agricultural and forestry industry, as well as the energy sector.

## 2. REVIEW OF LITERATURE

### 2.1. Use of synthesis gas for internal combustion engines

Currently, there are no real alternatives that can compete with internal combustion engines (IC) engines in the full range of applications they cover. Therefore, IC engines are constantly being improved [8].

Synthetic gas can be used at 100% for spark ignition internal combustion (SI) engines and mixed with diesel fuel (dual fuel mode) in the case of compression ignition engines.

In most cases, SI engines that run on 100% syngas use carbureted or port fuel injection technologies. Since the net heat of combustion of synthetic gas is lower than that of typical fuels such as gasoline and natural gas, the output power and torque of the engine is reduced by 20-40% [9]. This disadvantage makes the use of 100% syngas in SI engines inefficient for vehicle applications. However, this technical solution is acceptable for stationary applications.

One of the promising options is the use of synthesis gas in dual-fuel engines. The operation of dual-fuel engines with premixed fuel and pilot injection of diesel fuel has shown advantages in terms of efficiency and emissions compared to conventional diesel fuel combustion [10].

Most modern dual-fuel engines can alternate between either gaseous fuel with liquid pilot ignition or full liquid fuel injection, similar to diesel engines. Accordingly, the dual-fuel engine, as a rule, retains most of the positive features of the diesel engine [11]. Diesel engines cannot run on synthetic gas alone without injecting a small amount of liquid fuel because the properties of synthetic gas will not allow ignition to occur in a diesel engine. Therefore, the diesel engine must be dual-fuel. At the same time, the efficiency of the engine increases with the increase in the content of hydrogen in the gaseous fuel [12, 13].

In work [14] it is reported that for an internal combustion engine with a hydrogen concentration of 45% in the composition of the synthesis gas and the corresponding parameters of the engine, the efficiency equivalent to operation on diesel fuel alone was achieved. This effect makes it possible to partially replace diesel fuel with synthesis gas (up to 65%), which will reduce harmful emissions and have a significant economic effect.

From the above analysis, it can be concluded that the quality and chemical composition of synthetic gas significantly affects the performance of the engine. The technical characteristics of the internal combustion engine improve with an increase in the hydrogen content in the synthesis gas. Based on this, the production of synthesis gas with a high hydrogen content is an urgent issue.

It should be noted that the gasification process does not yet directly lead to the production of modern liquid biofuels. They are produced through an intermediate product - synthesis gas.

Biofuels obtained on the basis of synthetic gas have the advantage that they are compatible with existing types of fuel. This is very important for the development of fuel infrastructure and obtaining fuel mixtures (traditional fuel + alternatives).

One of the effective methods of processing synthesis gas into liquid fuels is the Fischer-Tropsch process [4]. Using this process, you can get synthetic gasoline and synthetic diesel.

Fischer-Tropsch fusion fuel is fully compatible with existing infrastructure and engines, which is problematic for other alternative fuels. Due to their high characteristics, namely the cetane number, which is about 70 (while for petroleum fuel 45-55), they are often mixed with petroleum diesel to improve the quality of the latter. The advantages of such fuel are recognized, in particular, by the US Air Force, which has tested and certified 50/50 jet fuel mixtures for its aircraft [15]. It is worth noting that for the effective implementation of the Fischer-Tropsch process, a high $H_2$ content in the synthesis gas and a $H_2/CO$ ratio equal to two are necessary [16].

Dimethyl ether (DME) is a promising derivative of synthesis gas [1]. Despite the fact that DME, compared to traditional diesel fuel, has lower energy consumption and lubricity, this motor fuel has a number of significant advantages. The chemical composition of DME determines the high efficiency of its combustion in a diesel engine and reduces emissions of soot, nitrogen oxides and sulfur in exhaust gases. Compared to diesel fuel, it has a lower ignition temperature - $235^0C$ and boiling point - $25^0C$ [4]. The use of such fuel allows you to reduce the overall noise and increase the engine resource. In addition, DME has excellent starting characteristics at low temperatures.

Methanol has already been widely tested as an alternative fuel in various attempts to reduce dependence on gasoline and diesel [7].

Compared to conventional gasoline, methanol has only half the energy density of gasoline, but the octane number is about 20% higher than that of 92 gasoline. In addition, it is low in carbon and contains no nitrogen, and the oxygen content is almost twice that of gasoline, which makes it recognized as an environmentally friendly fuel. Therefore, it is easier for it to achieve complete combustion than for conventional fuels. Thus, the disadvantages of the lower energy density of methanol are partially compensated by the reduction of emissions of pollutants in exhaust gases and improved fuel efficiency [17].

Methanol, which can be used as a convenient liquid fuel for fuel cells that increase the range, can also play a role in improving the performance of electric vehicles [18]. Electric cars have a significantly lower range due to the deterioration of battery performance in winter [19]. According to the China Automobile Consumer Research and Test Center, the range of electric vehicles decreases by about 39% in winter, while the range of methanol vehicles does not change. Thus, methanol vehicles can be an effective addition to the electrification of passenger vehicles [20]

Based on the urgent need to achieve a carbon-neutral status for the transport industry in the coming decades, it can be concluded that the use of synthesis gas for internal combustion engines has great prospects, both in the form of direct fuel and fuels based on it. At the same time, the efficiency of using synthesis gas for both stationary engines and for engines installed on vehicles is limited by its chemical composition, namely the hydrogen content. Therefore, the production of synthesis gas with a high hydrogen content is an urgent task.

### 2.2. Features of obtaining synthesis gas from biomass

Gasification is the process of thermal decomposition of solid or liquid substances into synthesis gas. Synthetic gas mainly consists of CO, $H_2$, $CO_2$, $CH_4$., among which hydrogen attracts a lot of attention due to its unique properties in terms of the status of a carbon-free energy carrier, high specific energy density, excellent physicochemical properties, etc. Gasification is one of the effective methods of converting biomass into various types of energy [6]. The conversion efficiency during gasification ranges from 70% to 90%, depending on the technological parameters of the process and the equipment used.

Biomass is a universal source of energy, which can be used both for the production of electrical and thermal energy, and for obtaining biofuel for transport needs [21].

Also, unlike fossil fuels, biomass has a fairly large territorial distribution and a relatively low annual yield. These factors lead to problems of effective organization of production from biomass processing into finished products due to relatively long distances of raw material delivery [2]. Therefore, in this case, it is advisable to carry out primary processing of biomass with subsequent transportation to the main place of accumulation.

One of the most effective methods of primary processing of biomass is the torrefaction process. Torrification is an energy-efficient process of converting biomass into a carbon-enriched substance by heating it to a temperature of 200 to 300°C. The obtained torrefied biomass does not require high requirements for storage and transportation and is not subject to biological degradation, which makes it a competitive intermediate product for further processing into various biofuels [21]. Comparative characteristics of the technical parameters of conventional biomass, conventional pellets, and torrefied biomass are presented in Table 1.

According to the data in Table 1, the moisture content in the torrefied biomass is minimal, which in turn reduces the amount of energy needed to ensure the gasification process. Similarly, torrefied biomass is distinguished by the stability of thermal characteristics, chemical composition, and the possibility of its rhythmic supply for further processing, which is positive for the technology and organization of production as a whole. Therefore, gasification of torrefied biomass can be a promising process.

Table 1

Technical parameters of different types of biomass [21]

| Technical parameters | Units | Wood | Wood pellets | Torrefied pellets |
|---|---|---|---|---|
| Moisture content | [%] | 30 - 45 | 8 -10 | 2 - 5 |
| Lower heating value | [MJ/kg] | 9 -12 | 15 - 16 | 19 - 24 |
| Fixed Carbon | [%] | 20 - 25 | 20 - 25 | 28 - 35 |
| Bulk density | [kg /l] | 0,2 – 0,25 | 0,55 -0,75 | 0,75 – 0,85 |
| Grinding requirements | | Increased | Increased | Ordinary |

Air, steam, oxygen or carbon dioxide can be used as a gasification agent for the gasification process. It is promising to use water vapor as an agent. In this case, a relatively high yield of $H_2$ and CO is achieved, so the final synthesis gas mixture has a higher calorific value. The use of steam enhances the formation of $H_2$ and produces valuable heating gas without nitrogen, which allows avoiding expensive methods of gas separation [22]. It is reported that the presence of catalysts, in particular calcium oxide, allows reducing the biomass gasification temperature to 650-700°C [23].

Currently, methods of biomass gasification are under development. However, they are expected to play an important role in future energy systems. In the medium term, there is a significant need for advanced biomass power generation technologies, while in the long term, the replacement of fossil fuels for transportation purposes will have great promise.

Therefore, the goal of our biomass gasification research is to improve the process of producing synthesis gas with maximum hydrogen content due to its higher calorific value for use in internal combustion engines.

## 3. METHOD

A batch reactor with a fixed bed was used for the research (Fig. 1). The reactor 8 is made of stainless steel, with a main reaction chamber, which has a height of 200 mm and an internal diameter of 40 mm. The reactor was heated from the outside with the help of an electric heater 10. The temperature inside the reactor was determined with the help of thermocouples 4. The torrefied wood mass of energy willow 7, chopped to the size of 2-4 mm, was subjected to gasification. Steam was used as a gasification agent. Water from tank 1 was fed into steam generator 3 using pump 2, after which the resulting steam was sent to the lower part of reactor 3. Steam supply to the reactor was regulated using tap 6. The produced synthesis gas was cooled in refrigerator 9 before being fed to collector 12. To determine the composition of the obtained gases, a NeoCHROM 11 gas chromatograph equipped with a flame ionization detector was used. The obtained data were sent to the process control panel 5. To establish the efficiency of the gasification process, various series of experiments were conducted: without a sorbent catalyst at different temperatures and with its participation. Calcium oxide CaO was used as a sorbent catalyst. The ratio of steam to torrefied biomass for all studies was (S/B) = 1.0 [24].

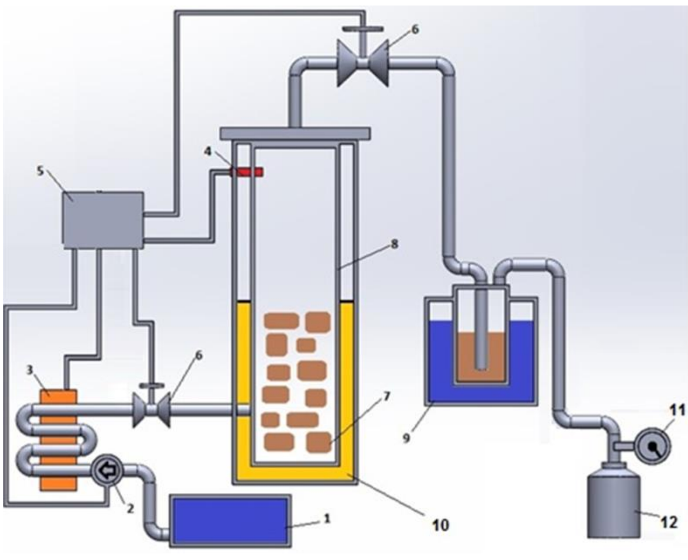


Fig. 1. Scheme of the experimental installation: 1 - water, 2 - pump, 3 - steam generator, 4 - thermocouple, 5 – control panel, 6 – tap, 7 – biomass, 8 – reactor, 9 – cooler, 10 electric heater, 11 - NeoCHROM gas chromatograph; 12 - vessel for synthesis gas
Rys. 1. Schemat instalacji doświadczalnej: 1 - woda, 2 - pompa, 3 - generator pary, 4 - termopara, 5 - panel sterowania, 6 - kran, 7 - biomasa, 8 - reaktor, 9 - chłodnica, 10 grzałka elektryczna, 11 - chromatograf gazowy NeoCHROM; 12 - zbiornik na gaz syntezowy

## 4. RESULT AND DISCUSION

### 4.1. Gasification of biomass without the use of a catalyst

In reactor 1, water vapor was passed through the crushed (2-4 mm) wood mass of torrefied energy willow in the ratio (S/B) = 1.0. The gasification temperature was - 850°C. All the organic content of biomass was subjected to gasification, as a result of which synthesis gas was formed. The research data are shown in Table 2.

According to Table 2, the yield of hydrogen was 39%, carbon monoxide - 25%, carbon dioxide - 26%, methane 7%. Three percent were other gases.

Table 2

Synthesis gas composition during gasification of willow at 850 $^0$C

| Synthesis gas Components | Chemical formula | Units | Value |
|---|---|---|---|
| Hydrogen | $H_2$ | [wt%] | 39 |
| Carbon monoxide | CO | [wt%] | 25 |
| Methane | $CH_4$ | [wt%] | 7 |
| Carbon dioxide | $CO_2$ | [wt%] | 26 |
| Other gases | | [wt%] | 3 |

In a simplified form, the gasification process using superheated steam can be represented using the following chemical reactions: water gas reaction - 1; water gas shift reaction - 2; Boudouard reaction 3; Methanation of carbon monoxide 4 and 5:

$$C + H_2O = CO + H_2 \quad , \tag{1}$$

$$CO + H_2O = CO_2 + H_2 \quad , \tag{2}$$

$$C + CO_2 = 2CO \quad , \tag{3}$$

$$CO + 3\,H_2 = CH_4 + H_2O \quad , \tag{4}$$

$$CO_2 + 4\,H_2 = CH_4 + 2H_2O \quad . \tag{5}$$

Analysis of the steam gasification process shows that the production of enriched synthesis gas is mainly facilitated by the flow of reactions of water gas 1 and water shift 2.

The size and shape of the biomass and its porosity play a significant role in the activation of reactions and their efficiency. Grinding biomass into small particles significantly increases the reaction contact area per unit mass of input biomass, since the diameter of the particles is inversely proportional to the free surface area. These factors increase the rate of gasification, due to efficient heat exchange [25]. In [26], it is stated that the use of small particles promotes "water-gas" reactions, carbon gasification, and secondary cracking, which increases the content of CO and hydrogen in the source gas. The increased reactivity of gasification ultimately increases the production of hydrogen and carbon monoxide.

In this case, it is important that torrefied biomass is much easier to grind than raw and has a uniform porous structure. In particular, the value of the Bond work index, which reflects the material's resistance to grinding, for torrefied biomass is 16 Kwh/t, while for ordinary - 413 Kwh/t. This effect has a positive effect on the efficiency of the gasification process as a whole.

Despite the significant advantages of steam gasification of wood biomass, its significant drawback is the high temperature of the process, which leads to a decrease in its energy efficiency and low cost-effectiveness. One of the factors for improving the steam gasification process can be the use of catalysts and sorbents for chemical reactions.

### 4.2. Gasification of biomass using a catalyst

The research was conducted at a steam flow rate of steam/biomass ratio (S/B) of 1 and a CaO/biomass ratio of 1.0 and a temperature of 700$^0$C. The process of obtaining synthesis gas without adding calcium oxide and with its addition was studied. In the work [27] it was established that the optimal action of the catalyst and sorbent CaO is achieved exactly at a temperature of 700$^0$C. When the temperature increases to 750 or 800 °C, the catalytic effect of the CaO sorbent is unfavorable and in this case the amount of $CO_2$ absorption will decrease.

At the beginning of the research, a given amount of raw materials and the CaO catalyst were mixed in given mass ratios and placed in the reactor. When the temperature reached 700$^0$C, steam was supplied. From this moment, gasification with water vapor began, and the gas that accumulated in bag 12 was removed. Similarly, to establish the effect of the sorbent at the specified temperature, studies of steam gasification without the addition of a sorbent were carried out.

The mixture of gases leaving the gasifier moved to the cooler 9, where they were sufficiently cooled and excess moisture was condensed. The composition of synthesis gas was analyzed offline using a NeoCHROM gas chromatograph equipped with a flame ionization detector. Data from studies using CaO as a catalyst and sorbent are shown in Table 3.

Tab. 3

Synthesis gas composition during gasification of willow at 850 $^0$C

| Synthesis gas Components | Units | Without catalyst | With a catalyst |
|---|---|---|---|
| Hydrogen | [wt%] | 33 | 54 |
| Carbon monoxide | [wt%] | 20 | 17 |
| Methane | [wt%] | 6 | 7 |
| Carbon dioxide | [wt%] | 38 | 19 |
| Other gases | [wt%] | 3 | 3 |

In the first case, without the use of a catalyst, at a temperature of 700$^0$C, the yield of hydrogen was 33%, carbon monoxide - 20%, carbon dioxide - 38%, and methane - 6%. Three percent were other gases. In the second case, at a temperature of 700$^0$C with the addition of a catalyst, the yield of hydrogen was 54%, carbon monoxide was 17%, carbon dioxide was 19%, and methane was 7%. Three percent were other gases. In this way, steam catalytic gasification of torrefied biomass allows to increase the hydrogen content in synthesis gas from 33% to 54% and, in this connection, to increase its thermal value.

According to the carbonation reaction - 6, CaO acts as a sorbent to absorb $CO_2$ to form $CaCO_3$. As a result of a decrease in the partial pressure of $CO_2$, the reaction of the water gas shift - 2 towards the formation of hydrogen intensifies, according to the principle of Le Chatelier.

$$CaO + CO_2 = CaCO_3 \quad . \qquad (6)$$

Since the carbonation reaction of CaO is exothermic, the heat released facilitates the endothermic gasification process. The resulting gas after dust removal can be directly used in an internal combustion engine.

Analyzing the data in Tables 2 and 3, we can conclude that the hydrogen content in synthesis gas increases with increasing temperature. Thus, for the conditions of steam gasification, it increased from 33% at a gasification temperature of 700$^0$C to 39% at a temperature of 850$^0$C. At the same time, when adding a catalyst at a temperature of 700$^0$C, the hydrogen content increases to 54%. Thus, it can be concluded that in the case of adding the CaO catalyst, the gasification process is more efficient and in this case it is possible to obtain synthesis gas with a higher hydrogen content at a lower temperature.

It is worth noting that the CaO sorbent loses its chemical activity in the process of operation, so after a certain time it is necessary to regenerate it. One of the methods of regeneration is calcination of spent CaO by burning unreacted torrefied biomass. After the regeneration process, the reduced calcium oxide is returned to the gasifier.

In this case, in addition to effective disposal of the remains of unreacted torrefied biomass and obtaining additional heat, which enters the gasifier together with the burnt sorbent, carbon dioxide is released in its pure form. Pure carbon dioxide is separated in the process of calcium oxide regeneration and is stored in an additional tank. Then it can be used for various technical and commercial purposes.

Thus, on the basis of the conducted research, it is possible to propose a new and more effective method of gasification. This method involves gasification in three stages.

First, primary processing of biomass is carried out with the help of torrefaction. With the help of the torrefaction process, the maximum amount of moisture is removed, raw materials for gasification are obtained with a uniform chemical composition and geometric dimensions, which allows to standardize the gasification process.

Before the start of the gasification process, the torrefied biomass is mixed with a catalyst - a CaO sorbent in a certain ratio. It is worth noting that torrefaction of biomass can be carried out both separately and in conjunction with the gasification process.

The third stage of gasification involves the regeneration of CaO by burning unreacted coal. Due to this, a clean stream of carbon dioxide is separated. The regenerated CaO is then returned to support the gasification process, where it captures carbon dioxide, facilitates the water-gas shift reaction, and improves the thermal balance of the process.

## 5. CONCLUSIONS

1. The article reveals significant prospects for the use of synthesis gas for internal combustion engines.
2. It was established that the use of CaO additive improves the efficiency of the biomass gasification process - it lowers the temperature of the process and increases the hydrogen content of the obtained synthesis gas.
3. A new method of biomass gasification has been developed, which provides for the production of hydrogen-enriched synthesis gas.
4. The use of hydrogen-enriched synthesis gas for stationary internal combustion engines will increase the efficiency of their work, allow to partially replace diesel fuel with synthesis gas, which will reduce harmful emissions and have a significant economic effect
5. The production of synthesis gas with a high hydrogen content will allow more efficient Fischer-Tropsch processes and methanol synthesis, which will lead to a wider use of the obtained renewable fuel in road transport.

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