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A New Device for Energy Recovery from Carbon-Containing Waste and Plant Biomass

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Abstract

Today, producing fuel and energy from both renewable sources and various types of waste using gas-generating technologies are prospective directions for development. To this end, a gas generator design with parametric control is recommended. This study presents comparative results from operating an internal combustion engine and a heat generator on generator gas. Technical solutions increased the generator's adaptability to various types of processed raw materials by optimizing the gasification process in the reaction zone. Using generator gas reduced emissions of carbon monoxide by ten times and hydrocarbons by four times. Using generator gas reduced the temperature of the heated air to 30°C. The ratio of the temperature of exhaust gases to the temperature of the heated air at the outlet of the heat generator increased from 3.4% to 7.05%.

Keywords: *Alternative fuel, Generator gas, Gas generator, Energy production, Waste disposal.*

1. Introduction

Human civilization relies on the use and conversion of energy. Its main source of energy is still fossil fuels from organic sources (oil, natural gas, and coal). Their stocks are limited and not renewable. Their primary consumers are transportation and power plants.

The need for developing means for producing generator gas arises from the significant deterioration of the environmental situation in the world, a decrease in reserves of traditional mineral resources, and intensive growth in consumption [1-3].

Utilizing biomass in the energy sector relates to two important objectives: reducing the dependence of energy systems on expensive high-grade fuels and improving the environmental performance of thermal power plants (by processing carbon-containing waste and, in some cases, reducing harmful emissions) [4].

Small distributed heat and electricity generation is developing rapidly. Given the increase in tariffs for electricity and heat energy, the inhabitation of new territories and the technical impossibility of connecting them to the power system, one of the most promising options for providing heat and electricity to isolated consumers is using wood biomass gasification technologies [5-6].

In Russia, 3.4 billion metric tons of municipal solid waste are accumulated annually. More than 40 thousand hectares of fertile land are used for storing solid waste. Some regions annually allocate up to three thousand hectares to landfills. Using solid waste as a raw material to produce electricity and heat energy could theoretically recycle 79% of this waste [7].

Current gas generator models have a number of significant disadvantages: the cyclical operation of the gas generator; moisture and size restrictions of the gasified fuel; "dead weight" in the generator gas – nitrogen, produced by air or air-steam blasting; the heterogeneity of generator gas composition.

Interest in gas generators is irregular but has manifested with enviable frequency in various countries at different stages in history [8-10]. Two main areas are currently developing: transportation gas generators and stationary gas generators that work in conjunction with a power plant’s internal combustion engine.

Transport-type gas generators are currently most common in countries where there are problems with fossil liquid and gaseous hydrocarbons, there is support for alternative energy at the state level, or there are environmental concerns.

Stationary gas generators, working in conjunction with a power plant’s internal combustion engine, are the most common type of gas generator models at present. This is because a stationary gas generator utilizes industrial waste to produce heat energy and to generate electricity. If the goal of the gas generator is to generate electricity, its coefficient of performance (COP) is not very high – only 20% of fuel is used to generate electricity, while 80% becomes thermal energy.

The gasification of solid fuels is the process of converting solid fuels into combustible gases via oxidation with air, oxygen, water vapor or carbon dioxide at high temperatures. The gasification of solid fuels takes place in gas generators and the resulting gases are called generator gases (artificial gases). A study of the variable composition of generator gas and its calorific value depending on the feedstock and the organization of the gasification process was performed in [11], and the data are systematized in Table 1

Table 1 Comparative study of the composition of the synthesis gas

Feedstock	Gasifier	Operating conditions	Technical features	Gas composition at output	Thermal effect of gas synthesis (kJ / mol)
Pine sawdust	Fluidized bed gasifier	Airflow	700°C	CO-44%, H_2-21%,	247.52
			800°C	CH_4-9%, CO-37.5%, H_2-32%, CH_4-8% (vol. %)	247.73
Pine oil cake and brown coal	Fluidized bed gasifier	Airflow	Coal: biomass		
			100:0	CO ~ 19%, H_2 ~ 45%, CH_4 ~ 8%	226.83
			60:40	CO ~ 26%, H_2 ~ 38%, CH_4 ~ 9%	237.72
			40:60	CO ~ 21%, H_2 ~ 37%, CH_4 ~ 10%	229.17
			850°C	(vol. %)	
Low grade coal	Fluidized bed gasifier	Airflow	1040°C	CO-19.2%, H_2-6.9%, CH_4 -0%, CO_2-17% (vol. %)	71.03
Bituminous coal	Entrained flow gasifier	Oxygen vapor	1500°C	CO-58.52%, H_2-27.68%, CH_4 -2.95% (mole %)	256.26
Pine and bituminous coal (2:1)	Fluidized bed gasifier	Vapor	1045°C	CO-36%, H_2-17.66%, CH_4-1.76% (vol. %)	158.73
Bamboo	Downdraft gasifier	Vapor	Humidity (%)-20%	CO-19.5%, H_2-18.8%, CH_4-1.25%, CO_2-11.2%	110.71
			Humidity (%)-5%	CO-20.5%, H_2-17.8%, CH_4-1.15%, CO_2-10.5%	110.31
			850 °C	(vol. %)	
Neem	Downdraft gasifier	Vapor	Humidity (%)-20%	CO-18.5%, H_2-18.2%, CH_4-1.35%, CO_2-11%	107.226
			Humidity (%)-5%	CO-19.2%, H_2-17.5%, CH_4-1.2%, CO_2-10.3%	106.31
			850 °C	(vol. %)	
Eucalyptus	Fluidized bed gasifier	Vapor	750°C	CO-42%, H_2-22%, CH_4-15%	292.4
			880°C	CO-42%, H_2-32%, CH_4-9% (mole %)	268.48
Pine	Fluidized bed gasifier	Vapor	750°C	CO-42%, H_2-28%, CH_4-14%	298.9
			880°C	CO-40%, H_2-36%, CH_4-12% (mole %)	296.56

As Table 1 indicates, the composition of generator gas depends solely on the properties of the fuel, the amount of water vapor entering the gasification chamber and the type of gas generator (its parameters and the prevailing reactions in the reaction zone).

Analyzing current trends in the development of gas generators allows us to identify a number of development directions, such as design changes, including, for example, modernizing the air supply system [12] and optimizing the gas generator's stages for generating heat and energy [13], as well as mathematical modeling of parameters and processes [14-16].

An analysis of freely available materials highlights their common shortcomings: most gas generators, both transport and stationary units, are adapted for modern production conditions but are copies of gas generators from the 1930s and 1940s; the quality of gas produced depends on the feedstock (size, humidity, density, etc.), as well as on the parameters and modes of its production; the gas generator controls the generator gas consumer, and the consumer controls the gas generator; the gas generator works well in steady operation and poorly in transient conditions; the inertia of the gas generator has a negative effect on the duration of the generator gas consumer's transient operating mode.

The purpose of this study is to develop a gas generator design that improves the adaptability of gas generators when operating on various types of processed raw materials. An experimental gas generator prototype was studied in operation with an internal combustion engine (ICE) and a heat generator; the internal combustion engine and heat generator were evaluated for their energy efficiency and the environmental safety of their exhaust gases.

Improving the adaptability of gas generators when operating on various types of processed raw materials by optimizing the gasification process in the reaction zone of the gas generator is of practical significance for developing an innovative way to process energy from carbon-containing waste and plant biomass.

2. Materials and methods

Exploratory studies on an experimental gas generator showed that, for practical operation, they use static and dynamic asynchronous control modes for their blowing tuyeres.

The air flow passing through the blowing tuyere is controlled by a solenoid air valve. The static air flow rate $G_{a.st.}$ (kg/h) through the solenoid air valve can be determined by the formula:

$$G_{a.st.} = \frac{529 \cdot \mathrm{K_v}}{\sqrt{\frac{T_1}{\Delta P \cdot P_2 \cdot \gamma_\text{в}}}}, \qquad (1)$$

where: K_v is the conditional band width coefficient of the solenoid air valve; T_1 is temperature of the medium before the valve, ^{0}K; ΔP is the pressure differential at the valve, kgf/cm^2; P_2 is the absolute pressure of the medium after the valve, kgf/cm^2; $\gamma_\text{в}$ is the density of incoming air, kg/m^3, at t_0 = 0^{0}C and B_a = 101.32472 kPa.

For a group of blowing tuyeres operating in a dynamic, synchronous mode, the total air flow rate, $\Sigma G_\text{в}$ (kg/h), we define as the sum of the air flow through each blowing tuyere for *m* cycles of its operation:

$$\Sigma G_\text{в} = k_{1\,\mathrm{vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}}^{\tau_{4i+4}} f(x)dx + k_{2\,\mathrm{vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}}^{\tau_{4i+4}} f(x)dx + \dots + k_{p\,\mathrm{vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}}^{\tau_{4i+4}} f(x)dx \ , \qquad (2)$$

where $k_{p.\mathrm{vl}}$. is the correction factor characterizing the individual features of the solenoid air valve that controls the blowing tuyere; *p* is the number of the solenoid air valve controlling the blowing tuyere.

If we adjust formula (2) we get

$$\Sigma G_\text{в} = \sum_{i=0}^{m-1} \int_{\tau_{4i+1}}^{\tau_{4i+4}} f(x)dx \left(k_{1\,\mathrm{vl.}} + k_{2\,\mathrm{vl.}} + \dots + k_{p\,\mathrm{vl.}}\right). \qquad (3)$$

Given the time for a single cycle, the number of operating cycles, *m*, of a group of blowing tuyeres operating in dynamic synchronous mode in one hour of operation is calculated using the equation:

$$m = \left(\frac{1}{\tau_4 - \tau_1}\right). \qquad (4)$$

For a group of blowing tuyeres operating in a dynamic asynchronous mode, we find the total air flow rate ΣG_B (kg/h) as the sum of the air flow through each blowing tuyere for *m* cycles of its operation:

$$\Sigma G_{\text{B}} = k_{1\text{ vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}}^{\tau_{4i+4}} f(x)dx + k_{2\text{ vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}+\Delta\tau}^{\tau_{4i+4}+\Delta\tau} f(x)dx + k_{3\text{ vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}+2\Delta\tau}^{\tau_{4i+4}+2\Delta\tau} f(x)dx + \cdots + k_{p\text{ vl.}} \sum_{i=0}^{m-1} \int_{\tau_{4i+1}+(p-1)\Delta\tau}^{\tau_{4i+4}+(p-1)\Delta\tau} f(x)dx \ , \quad (5)[sic]$$

where Δτ is the time step of the asynchronous activation and deactivation of the valve controlling the blowing tuyere.

The concept of parametric regulation of the gasification process, when the engine determines control actions to optimize blowing tuyere modes during the operation of the gas generator, allows high-grade generator gas to be produced on various types of solid fuel. In existing models, an engine's operating mode depends on the gas generator. Parametric regulation of the gasification process expands the variability and versatility of the gas generator based on the types of solid fuel being processed, and minimizes decreases in the generator gas consumer's operational effectiveness when switching from one type of fuel to another. A gas generator with elements of parametric control of the gasification process was used in experiments for the thermal processing of carbon-containing wastes and plant biomass [17]. A 2Ch 7.2/6.0 gasoline internal combustion engine (ICE) (Russia) and an OV - 95 heat generator (Russia) served as the generator gas consumers.

Before the experiments, the 2Ch 7.2/6.0 engine was serviced, and the ignition timing was adjusted. In the experiments, an AB-4 electric generator (Russia) provided the load for the internal combustion engine.

In experiments with the OV-95 heat generator, both a typical combustion chamber was used, as well as one designed for the experiments with enlarged flow areas for supplying generator gas and air. To prevent flame failure, an X - shaped gas stabilizer was installed at the burner outlet.

Three main blowing tuyere modes were implemented in the experiment on the gas generator with parametric regulation of operations in the reaction zone:

1. A static operating mode. Depending on the flow rate of the generator gas, a different number of blowing tuyeres, *k*, is used. At the same time, the outflow rate of air from the gas generator's blowing tuyere varies from the optimal speed by ± Δ υ.
2. A dynamic, synchronous operating mode. Regardless of the flow rate of generator gas, the same number of blowing tuyeres are engaged. In this case, the blowing tuyeres are simultaneously turned on and off in operation (i.e., they work synchronously). By changing the ratio between the tuyere operating and shutdown times (i.e., by adjusting the duty cycle), it is possible to control the volume and rate of air flow from the gas generator blowing tuyere.
3. A dynamic, asynchronous operating mode. Regardless of the flow rate of generator gas, the same number of blowing tuyeres are engaged. However, the blowing tuyeres are turned on and off in operation with a time offset relative to each other (i.e., they work asynchronously). By changing the ratio between the tuyere operating and shutdown times (i.e., by adjusting the duty cycle), it is possible to control the volume and rate of air flow from the gas generator blowing tuyere.

The experiment had three stages. In the first stage, the internal combustion engine and the heat generator operated on traditional liquid fuels. The ICE operated on AI-92 gasoline, and the heat generator used diesel fuel. Measurements were taken of power, temperature and exhaust gas composition.

In the second stage, the ICE and the heat generator operated on a traditional gaseous type of fuel – a propane-butane mixture. Measurements were taken of power, temperature and exhaust gas composition.

In the third stage of the study, the ICE and the heat generator worked on an alternative type of fuel - generator gas obtained from various forms of feedstock. Measurements were taken of power, temperature and exhaust gas composition.

3. Results

To eliminate the shortcomings of known gas generators, a design was developed with elements of parametric control of the oxidizer supply. This makes it possible to regulate the gasification process depending on the raw materials used and the operating modes of the generator gas consumer. Changing the spatial arrangement of the tuyeres in the chamber allows you to control the gasification process, reducing the likelihood of arching when processing bulk waste.

The design of the gas generator (Fig. 1) uses the principle of regulating operating parameters in the planes of the tuyere belt.

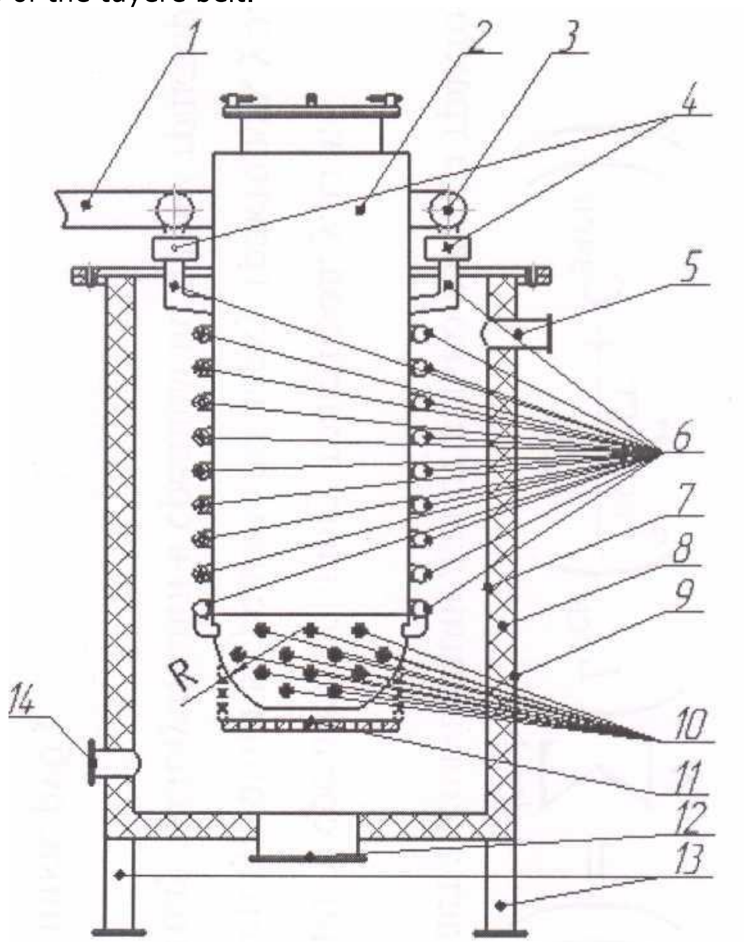


Figure 1. General view of a gas generator: 1 - air pipe, 2 - gasification chamber, 3 - air manifold, 4 - solenoid valve system, 5 - gas outlet pipe, 6 - pipes, 7 - gas tank, 8 - thermal insulation case, 9 - external protective casing, 10 - tuyere belt, 11 - ash grate, 12 - ash pan, 13 - supports, 14 – service hatch, 15 - locking mechanism

Providing an individual air supply to each tuyere is an option in a gas generator. This not only allows the efficiency of the gasification process in the gas generator to be increased by heating the air supplied to the reaction zone through the tuyeres, but also, using the solenoid air valve system, to change the number of tuyeres involved, thereby maintaining a steady air flow rate from the tuyere in different gas generator operating modes. To maintain constant temperatures and reaction zone operating thickness in transient modes, the tuyeres alternate in operation. The solenoid valve system provides a pulse operating mode. The tuyeres are located in different planes along the gasification chamber and are offset relative to each other. The number of tuyeres in each plane can be different. In part of the tuyere, the outlet blow hole is offset from the longitudinal axis by an angle of $\pm \alpha$, which falls in the range of 0 to 45 degrees. This angle depends on the geometric dimensions of the gas generator, the number of rows and the number of tuyeres in a row, the requirements for the generator gas produced, and the type and structure of gasified fuel. The gasification chamber is made as a truncated hemisphere. The radius of its curvature is calculated based on the constant thickness of the reaction zone for a specific row of tuyere belts taking into account the number and section of blowing tuyeres, and the displacement angle of the outlet blow hole from the longitudinal axis by an angle of ± α [18].

Practical testing of parametric control of the oxidizer supply to the gas chamber reaction zone was carried out in the experimental setup shown in Figure 2.

Figure 2. General view of experimental gas generator with ICE 2Ch 7.2/6.0 and electric generator

A significant difference between the proposed generator unit design and previously known solutions is that the gas generator frame is mounted on a fixed base with the ability to tilt in a vertical plane by angle α, which lies between 0° and 90°. Meanwhile, the gas generator housing is mounted for rotation on frame supports around a vertical axis with an angular frequency of $\omega = 10 \div 1000$ hour^{1}. This allows you to organize various methods in the gas generator's gasification chamber to create gasification reactions with solid fuel (surface, layered, in a pseudo-boiling layer, etc.), and to prevent the formation of arches and the uneven supply of solid fuel into the gas generator reaction zone when the fuel freezes or collapses, thereby ensuring the consistency of the physicochemical parameters of the generator gas produced. A general view of the improved gas generator is shown in Figure 3.

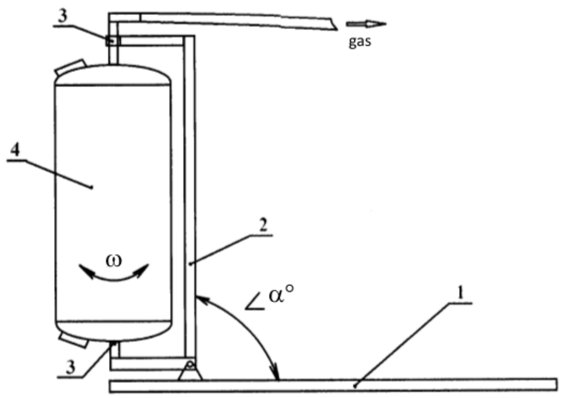
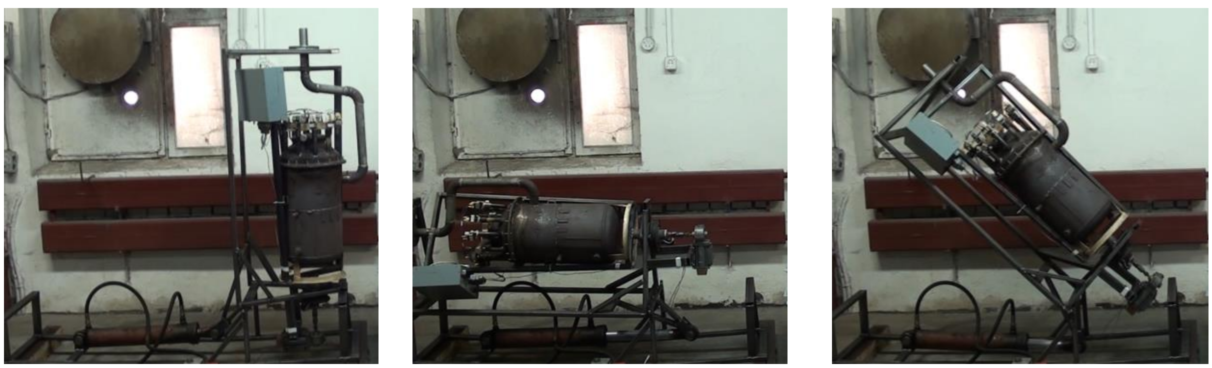


Figure 3. General view of the improved gas generator
1 - fixed base, 2 - movable gas generator frame, 3 - supports, 4 - gas generator body

Practical testing of the developed technological solutions for improving the design of the gas generator was carried out on an experimental prototype, a general view of which is shown in Fig. 4.



a b c

Figure 4. a - initial position, b - horizontal position; in - intermediate inclined position

The results of exploratory research on the operation of the ICE 2Ch 7.2/6.0 on various types of fuels are shown in Table 2.

Table 2. The main operational characteristics of ICE 2Ch 7.2/6.0 and AB-4-O/230-M1 power plants when working on various types of fuel

Type of fuel	Electric power of load, kW	ICE exhaust gas components				
		CO, %	C_mH_n, ppm	CO_2, %	O_2, %	α
Gasoline AI - 92	4±0.4%	0.8	56	13.24	1.3	1.042
Propane - butane (summer) mixture	4±0.4%	0.04	49	11.08	2.9	1.154
Birch coal generator gas	2.9±0.4%	0.12	42	17.44	1.5	1.062
Birch dice generator gas	3.2±0.4%	0.08	14	16.9	2.85	1.12
Birch coal and cattle manure generator gas	3±0.4%	0.96	14	16.72	2.7	1.088
Cattle manure generator gas	2.7±0.4%	0.08	35	14.42	5.05	1.246

Note: α - coefficient of excess air

The results of exploratory research on the operation of the OV-95 on various types of fuels are provided in Table 3 [14].

Table 3. The main operational characteristics of OV - 95 when working on various types of fuel

Type of fuel	Exhaust components						
	CO, %	CmHn, ppm	CO_2, %	O_2, %	α	$t_{(air)}$, ^{0}K	$t_{(exhaust)}$, ^{0}K
Diesel fuel (summer)	0	28÷35	13.18÷13.36	2.95÷3.15	1.16÷1.172	438±0.2	611±0.2
Propane - butane mixture (winter)	0	0	10.7÷10.92	3.45÷3.88	1.192÷1.22	438±0.2	605±0.2
Generator gas (from birch charcoal)	0.2÷0.6	5÷9	17.3÷16.8	2.18÷3.3	1.082÷1.152	408±0.2	603±0.2
Generator gas (from birch firewood)	0.34÷0.58	7÷14	15.42÷15.8	3.6÷3.95	1.116÷1.142	424±0.2	627±0.2
Generator gas (from birch charcoal and cattle manure)	0.18÷0.28	7÷14	14.28÷14.5	3.9÷4.6	1.158÷1.188	427±0.2	610±0.2

4. Discussion

The study results show that parametric control of the oxidizer supply to the gas generator only partially solves the problem of arching. To eliminate it entirely, a technical solution was proposed to improve the gas generator [17].

The decrease in power produced by the generator when working on generator gas did not exceed 20–27.5%. When power plant ICE operate on generator gas, their exhaust gases are less toxic compared to gasoline. For example, CO emissions are reduced by 6.6–10 times, and C_mH_n ppm by 1.33–4 times. However, CO_2 emissions increased 1.27–1.32 times.

When a heat generator operates on generator gas and the environmental criterion dominates, the temperature of the heated air at the outlet of the heat generator is 11–30° K lower, and the ratio of the temperature of exhaust gases to the temperature of the heated air at the outlet of the heat generator increases by 3.4–7.05%, depending on the type of generator gas being used. This leads to a decrease in thermal efficiency due to the generator gas burning out in the exhaust system of the heat generator.

Technological advances have increased the productivity and power of generators. The growing popularity of gas generators and biofuel generators is one of the latest trends observed in the industry, and steady growth is expected on the global market.

A number of foreign and domestic companies are engaged in the production of gas generators. For example, Siemens produces best-in-class, highly efficient, low-emission gas engines and generator units designed for various applications such as power generation, cogeneration and energy saving. LabTech manufactures oxygen and nitrogen generators, as well as ZERO AIR GENERATORS, which are some of the smallest models and have an efficient, carbon-free air purifier system. It uses reliable and efficient heated catalyst technology to reduce methane emissions to less than 0.05 ppm. This research focused on a gas generator that reduces emissions of carbon monoxide, methane, and carbon dioxide, but also allows for parametric control using the rotation and tilt of the working chamber, unlike known analogues.

5. Conclusion

Energy sources based on biomass waste are the missing link in the energy supply system. This is relevant in countries where plant waste in agriculture and forestry forms a powerful raw material base that can serve as a real basis for planning and developing independent alternative energy. The annual renewable power of this raw material base determines the stability of the energy system and is an indisputable advantage.

Generator gas, as a fuel, is quite capable of replacing traditional fossil hydrocarbon fuels. The gasification process must be controlled to ensure the stable operation of generator gas consumers and improve their environmental performance.

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