Prospects for the development of green technologies for producing alternative energy resources

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Abstract. The transition to “green technology” is caused by the negative action of human life on the environment. “Green technologies” are environmentally friendly for human health. To reduce the negative burden on the environment, it is necessary to decrease the consumption of resources while reducing the growth of production and consumption waste. The negative impact of municipal solid waste (MSW) on the environment leads to climatic change, increases the greenhouse effect and the number of natural hazards. These facts necessitate the search for solutions to reduce harmful emissions into the atmosphere, to increase fuel efficiency, as well as energy efficiency, for example, transport systems, by improving the technology for producing the generator gas as an alternative fuel. The article discusses technologies to reduce the concentration of nitrogen oxides in any device for burning solid, liquid and gaseous fuels in internal combustion engines.

1. Introduction

Green technologies are innovations that are based on the principles of sustainable development and the reuse or saving of natural resources. The main purpose of Green Technologies is to reduce the negative action on the environment. Green technologies cover the fields of power production from renewable sources such as solar energy, wind energy, biofuels, etc.

The main hopes in solving the most acute environmental problems (including resource ones) are assigned today to technological breakthroughs. In recent years, the developed countries have reoriented their development towards the implementation of an environmentally oriented growth strategy, one of the main components of which are green technologies [1-3]. The general approach involves achieving their main purpose — to reduce the negative impact on the environment, for example, by reducing the amount of waste, increasing energy efficiency, improving the design to reduce the amount of resources consumed.

At the present stage, the researchers are increasingly recalling the negative impact of human activities on the environment. “Green technologies” are becoming popular as they are sparing for the environment and human health. There are a lot of areas of “gardening”: the use of energy-saving technologies, aerators, separate collection and recycling of waste, the use of eco-identified products, the reduction of plastic consumption, the use of non-toxic materials, etc. Today, as never before, all
scientists of the world are faced with the urgent problem of conservation environment. This served as the impetus for finding and developing new alternative energy sources, for the emergence of “green technologies”.

Air pollution by gases leads to climate change, to an increase in the greenhouse effect (as evidenced by many scientific facts) and an increase in the number of natural hazards. The leading role in greenhouse gas emissions belongs to CO$_2$, the main source of which is the energy sector (mainly the burning of fossil fuels: coal, oil and gas). The accelerated growth in the number of transport vehicles with internal combustion engines, especially diesel ones, has led to a significant deterioration in air quality in urban agglomerations. The most negative action on the state of the air is exerted by emissions of nitrogen mono- and dioxides in the exhaust gases of internal combustion engines, including those using natural gas as fuel [4-11].

The most important measure aimed at reducing the concentration of nitrogen oxides in any device for burning solid, liquid and gaseous fuels is to reduce the temperature of the mixture in the combustion zone. This can be achieved by using wood fuel resources and solid industrial and household waste, that is, by recycling all waste and producing new energy from them. The main criterion of “green technology” is the subsequent saving of resources during operation. A positive example is China where the concept of “Ecological environment, resource saving, progressive ecology and circular economy” is being actively introduced.

Following this concept, it is necessary to pay attention not only to public cars, but also to motor transport vehicles that release a large amount of toxic gases into the atmosphere. It is necessary to develop organizational and technical measures aimed at introducing energy-saving technologies on automotive vehicles with environmentally friendly engines using local wood fuel resources and solid industrial and household waste.

The purpose of the work is development of a technology for converting gas-diesel engines of automotive vehicles to environmentally friendly and energy-saving gas generating and diesel processes.

2. Methods of achieving the purpose
The most important directions of reducing the nitrogen oxide content in the exhaust gases of heavy diesel vehicles include the use of part of the deeply cooled gases during two-stage cooling to a temperature of +50° C for recirculation in the engine power supply system. This allowed SCANIA motor vehicles to reach Euro 5 standards in 2007 without the use of urea additives [10].

The use of synthetic combustible gas based on generator gas produced from solid industrial and household wood waste, including the polyethylene containing additions both on mobile and stationary installations can be taken as a promising direction [11]. Figure 1 shows a general view of a gas generator, which can be either stationary or mobile. A striking example of such technologies is the use of economical gas-generating trucks, tractors and traction tractors [12,13] for the needs of the rear and population movement during the Second World War (“war of engines”) in Russia and Volkswagen Type 82 cars with a boxer engine and gas generator, working on wood (1944) in Germany [14,15].

Further research on improving the efficiency of air-cooled engines, such as an engine of the Volkswagen Type 82 type, was devoted in [16]. At present, the role of autonomous diesel power plants, which have been converted to local fuels, to ensure the livelihoods of people in remote areas, in emergency situations, in agriculture and forestry, is being increased.

Previous research work to reduce the exhaust gas toxicity of a converted diesel engine for use in a stationary power plant did not show a significant reduction in the content of carbon monoxide CO and nitrogen NO$_x$ with the combined consumption of gaseous fuels — methane CH$_4$ and liquid fuels (10-20% when using conventional diesel cycle).

To solve this objective it is necessary to determine the content of harmful substances in the exhaust gas, taking into account the effect of a gas-enriched air mixture ignited by a minimum dose of diesel fuel [6].
The most important measure aimed at reducing the concentration of nitrogen oxides (and therefore, at reducing respiratory tract diseases) in any device for burning solid, liquid and gaseous fuels, is to reduce the temperature of the mixture in the combustion zone. The practice of operating thermal power plants has shown that at combustion temperatures of any fuel-air mixtures up to 850-950°C (when carbon monoxide burns in air, the temperature reaches 2300°C) air nitrogen practically does not oxidize to the state of NO\textsubscript{x} oxides [8].

3. Results and discussion

The main task of this work is the theoretical justification of an improved technology for using wood crushed fuels to produce generator gas and its use in gas-diesel engines ignited by a minimum dose of diesel fuel [6].

The producing generator gas can be used both in vehicle engines with a diminished content of nitrogen and carbon oxides in exhaust gases, and in industrial power plants.

The initial products of the gasification process: fuel consisting of carbon C, hydrogen H, oxygen O, nitrogen N, hygroscopic moisture W and ash; air consisting of oxygen O\textsubscript{2} and nitrogen N\textsubscript{2}; water H\textsubscript{2}O. The final products are generator gas components produced from gasification: combustible components CO, H\textsubscript{2}, CH\textsubscript{4}, C\textsubscript{n}H\textsubscript{m}, fuel ballast CO\textsubscript{2}, O\textsubscript{2}, N\textsubscript{2}, H\textsubscript{2}O and dust consisting of furnace bottom ash and furnace soot. These components are present in MSW, in particular in wood cellulose C\textsubscript{6}H\textsubscript{10}O\textsubscript{5} and polyethylene (C\textsubscript{2}H\textsubscript{4})\textsubscript{n}, when they are used as fuel.

Calorific value is an indicator of the practical value of the fuel. If the water contained in the fuel and generated during the combustion of hydrogen fuel is present in the form of steam, then the calorific value is called the lower \(Q_{n}\) (MJ/kg). All municipal solid waste has its original moisture content.

The lower calorific value or the calorific value of solid and liquid fuels in oxygen and air at a stoichiometric ratio of the components can be approximately determined using the empirical D.I. Mendeleev formula

\[
Q_{n} = 0.34 \text{C} + 1.03 \text{H} - 0.11 \text{(O-S)} - 0.0525 \text{W},
\]

where in parentheses is the percentage (wt.% content of the corresponding elements in the fuel composition, and dry combustible gases — according to the formula

\[
Q_{n} = 0.108 [\text{H}_2] + 0.126 [\text{CO}] + 0.358 [\text{CH}_4] + 0.5 [\text{C}_2\text{H}_2] + 0.234 [\text{H}_2\text{S}],
\]

where in parentheses is the percentage (volume %) of the corresponding gases in the mixture [12,17].

We estimate the calorific value of generate gas produced from a mixture of wood- and polyethylene-containing household waste according to the proposed method taking into account that

![Figure 1](image-url)
polyethylene and plastic containing materials are found in MSW up to 20%. The net calorific value \( Q_l \) is determined taking into account the fuel-air mixture total volume entering the ICE cylinders [18].

All important engine parameters depend on the excess air coefficient \( \alpha \). Due to very complex chemical and physical combustion processes, engine design parameters in terms of power, torque, fuel consumption and harmful substances emissions are always the sum of a trade-offs’ large number.

When carrying out theoretical calculations to justify the technology of gas-generation and combustion of a gas-air mixture in ICE cylinders, the following restrictive conditions were accepted:

- For conventional average diesel fuel — between C\(_{16}\)H\(_{34}\) cetane with a density of 0.7733 g/cm\(^3\) with a cetane number of 100, a boiling point of 286.5°C and a calorific value of 44.2 MJ/kg; and alpha-methyl-naphthalene C\(_{11}\)H\(_{10}\) — an aromatic hydrocarbon of 1.0179 g/cm\(^3\) with a cetane number of 0 and a boiling point of 241°C and a calorific value of 42 MJ/kg. The estimated formula C\(_{14}\)H\(_{30}\) with a density of 0.83 g/cm\(^3\) and an ignition temperature of 210°C was taken conventionally for the cetane numbers of diesel fuel 45-55 units.

- To assess the magnitude of the increase in gas temperature of the air mixture in the engine cylinders, a conditional formula is adopted that relates the average heat capacity, heat supplied during combustion, and the mass of gases involved in the processes of oxidation and reducing reactions

\[
Q = cm(t_i - t_0).
\]

Then the value of the gas temperature rise is found by the formula

\[t_i - t_0 = \frac{Q_i}{cm},\]

where \( t_i - t_0 \) are temperatures at the end and beginning of processes (°C); \( Q_i \) — released heat (MJ); \( c \) — the average mass heat capacity of gases, accept \( c = 1 \text{ J/(g·deg)} \); \( m_i \) — mass of gases (g).

- The developed effective engine power \( N_e \) and the effective torque \( M_e \) on its shaft can be estimated by the heat density of the working mixture in the ICE cylinders after gas combustion in the air mixture according by the formula:

\[
Q_{pci} = \frac{Q_i}{V_i},
\]

where \( V_i \) — the volume of the working mixture (m\(^3\)); \( Q_i \) — the calorific value of the gas-air mixture (MJ).

- It is conventionally accepted that the value of heat \( Q_i \) released during combustion of the gas-air mixture in the ICE cylinders can be estimated by the value of “burning” 1 m\(^3\) of air (O\(_2\) + 4N\(_2\)) and approximately equal to 3.8 MJ. With the consumption of 5 kmol of air (O\(_2\) + 4N\(_2\)) in a volume of 112 m\(^3\), heat \( Q_{pc} = 426 \text{ MJ} \) is released for fuel combustion.

Theoretical calculations to justify the technology of gas-generation and combustion of a gas-air mixture in ICE cylinders will be carried out according to three options for various engine power supply systems: when operating in conventional diesel mode (1), (2) and generator gas-diesel (3). In the first version, the values of temperature rise and heat density of the gas mixture in the ICE cylinders operating according to the conventional diesel process were calculated with an excess air coefficient \( \alpha = 2.0 \).

The balance equations (3) and (4)-(6) are grounded on the conservation laws: the mass of matter and energy. They show the initial and final states of the components involved in the reactions and take into account the thermal effect (exothermic and endothermic) of chemical reactions and physical transformations (evaporation, condensation, etc.)

Approximate equations for the combustion of diesel fuel in a mixture with air with a coefficient \( \alpha = 2.0 \):

\[
C_{14}H_{30} + 2.0 \cdot 21.5 (O_2 + 4N_2) = 14CO_2 + 15H_2O + 21.5O_2 + 172N_2 + Q_1,
\]

where the amount of released heat can be determined by the formula:
Q₁ = 21.5(22.4 + 4·22.4)·3.8 = 9150 MJ

The estimated mass of gases in the engine cylinders is determined by the formula:

\[ m_1 = m_1\text{CO}_2 + m_1\text{H}_2\text{O} + m_1\text{N}_2 + m_1\text{O}_2 = 616 + 270 + 4816 + 688 = 6390 \text{ kg}. \]

The estimated increase in gas temperature of the fuel mixture after combustion is equal to

\[ t₁ - t₀ = \frac{Q₁}{m₁} = \frac{9150·10^6}{6390·10^3} = 1434°C \]

If we take the ignition temperature of diesel fuel at the level of +210°C, then we should expect the highest temperature in the process of the fuel-air mixture combustion of +1644°C.

To determine the heat density we should take into account the volume of gas in the air mixture after combustion, which is equal

\[ V₁ = 43·(22.4 + 4·22.4) = 4816 \text{ m}^3. \]

Then the estimated heat density of the gas of the air mixture in the engine cylinders will be

\[ Q₁₁ = \frac{Q₁}{V₁} = \frac{9150}{4816} = 1.90 \text{ MJ/m}^3. \]

According to the second option, the values of temperature rise and heat density of an engine operating according to the gas-diesel process in the mode of injection into the cylinders of 10% liquid fuel and 90% methane CH₄ with an excess air coefficient \( \alpha = 1.9 \) were calculated according to the results of previous studies.

The combustion processes of the fuel-air mixture in the ICE cylinders can be presented by the approximate formula:

\[
0.00724\text{C}_{14}\text{H}_{30} + 0.1·1.9·2\cdot(\text{O}_2+4\text{N}_2) + 0.9\text{CH}_4+0.9·1.9·2\cdot(\text{O}_2+4\text{N}_2) =
= 1.004\text{CO}_2 + 3.823\text{H}_2\text{O}+15\text{N}_2+1.8\text{O}_2+\text{Q}_₂. \] (4)

An estimated calculation of the released heat during the combustion of 90% methane and 10% diesel fuel can be performed using a stoichiometric formula with an air excess coefficient \( \alpha = 1.0 \)

\[ Q₂ = 3.8·2·112 = 851.2 \text{ MJ}. \]

The estimated volume of the burnt fuel-air mixture is approximately determined by the formula

\[ V₂ = 22.4(1.004 + 3.823 + 15.2 + 1.8) = 488 \text{ m}^3. \]

The estimated mass of the gas mixture in the ICE cylinders after combustion is determined by the formula

\[ m₂ = m₂\text{CO}_2 + m₂\text{H}_2\text{O} + m₂\text{N}_2 + m₂\text{O}_2 = 68,6 + 44,17 + 426 + 57.5 = 596.27 \text{ kg}. \]

The estimated temperature rise in the ICE cylinders after the combustion of the fuel-air mixture is determined by the formula

\[ t₂ - t₀ = \frac{Q₂}{m₂} = \frac{851.2·10^6}{596.27·10^3} = 1430°C, \]

and the full temperature during combustion will reach 1640°C that corresponds to the results of previous studies.

The estimated heat density of the gases in the ICE cylinders is determined by the formula:

\[ Q₂₁ = \frac{Q₂}{V₂} = \frac{851.2}{488} = 1.74 \text{ MJ/m}^3. \]

Of particular interest may be the estimated coefficient of diesel engine power reduction \( K_{ne} \) after converting to gas-diesel mode

\[ K_{ne} = \frac{Q₂₁}{Q₁₁} = 1.74/1.90 = 0.915, \]

that is, we should expect a decrease in power by 8.5% under equal conditions of engine operation.
As a design, the third version of the gas-diesel process is considered when using wood generator gas at 90% of engine power and 10% of power on diesel fuel with an air excess coefficient $\alpha = 1.4$.

The balance equation (3) represents approximate composition of the generator gas produced from wood with 20% initial humidity and containing in 1 m$^3$ 97 g of moisture, 3.5 g of dust, 0.5 g of resin.

$$0.054(C_6H_{10}O_5 + 2.2H_2O) + 0.097(O_2 + 4N_2) = 0.161H_2 + 0.209CO + 0.092CO_2 + 0.023CH_4 + 0.388N_2 + 0.009O_2 + 0.117H_2O + Q_3,$$

where $Q_3$ — the heat generated by the reaction of producing the generator gas from wood.

After cooling and cleaning, the generator gas in a mixture with air enters the ICE cylinders and is ignited by diesel fuel injection.

The approximate equation of combustion of the fuel-air mixture with an excess air coefficient $\alpha = 1.4$ in the engine cylinders can be

$$0.161H_2 + 0.209CO + 0.092CO_2 + 0.023CH_4 + 0.388N_2 + 0.009O_2 + 0.117H_2O + 1.4\cdot 0.222(O_2 + 4N_2) + 0.0444(O_2 + 4N_2) + 0.00165C_{14}H_{30} = 0.349H_2O + 0.357CO_2 + 0.116O_2 + 1.888N_2 + Q_3,$$

where $Q_3$ the released heat can be determined by the formula

$$Q_3 = 3.8\cdot 1.2\cdot 0.222\cdot 112 = 113 \text{ MJ}.$$

The estimated volume of the burnt fuel-air mixture is determined by the formula:

$$V_3 = 22.4\cdot (0.349 + 0.357 + 0.116 + 1.888) = 60.5 \text{ m}^3$$

The estimated mass of the gas mixture is determined by the formula:

$$m_3 = m_3CO_2 + m_3H_2O + m_3N_2 + m_3O_2 = 6.29 + 15.7 + 53 + 3.7 = 78.69 \text{ kg}.$$

The estimated increase in gas temperature in the ICE cylinders after combustion of the fuel-air mixture is determined by the formula

$$t_3 - t_0 = Q_3/m_3 = 113\cdot 10^6/78.69\cdot 10^3 = 1440^\circ\text{C},$$

and the full temperature will reach 1652$^\circ$C.

The estimated heat density in the engine cylinders is determined by the formula

$$Q_{pci} = Q_3/V_3 = 113/60.5 = 1.87 \text{ MJ/m}^3.$$

The estimated coefficient of diesel engine power reduction after conversion to diesel plus generator gas will be

$$K_{ne31} = Q_{31}/Q_1 = 1.87/1.90 = 0.982.$$

Figure 2 presents comparative diagrams: of the coefficients of excess air $\alpha$ (figure 2a), temperature rise of the fuel-air mixture ($t_3 - t_0$)$^\circ$C (figure 2b), and the heat density of the gas working mixture $Q_{pci}$ (MJ/m$^3$) (figure 2c). The diagrams respect various options of engine power supply systems when operating in the mode of a conventional diesel engine (1), gas-diesel engine (2) and generator gas-diesel engine (3).

The estimated coefficient $\alpha_1 = 2$ for a conventional diesel engine and $\alpha_2 = 1.9$ for a gas-diesel engine running on methane CH$_4$ was taken proceed from combustion of the hydrocarbon components. For option 3, the estimated coefficient $\alpha_3 = 1.4$ was taken based on the combustion of hydrocarbons, C$_n$H$_m$, carbon monoxide CO and hydrogen H$_2$. 

\[ (5) \]
Figure 2. Comparative diagrams for various options of engine power supply systems when operating in the mode of a conventional diesel engine (1), gas-diesel engine (2) and generator gas-diesel engine (3): а — air excess coefficients \( \alpha_i \); б — temperature rise of the fuel-air mixture; с — heat density of the gas working mixture.

The estimated values of the temperature rise of the fuel-air mixture in ICE cylinders during combustion reach values of 1640-1730°C. Heat density varies between 1.90-1.74 MJ/m³.

The analysis shows that when converting the diesel engine of option 1 to the gas-diesel mode of option 2 with the consumption of methane \( \text{CH}_4 \), a power drop of 8-9% occurs due to losses of combustion and evaporation of the \( \text{H}_2\text{O} \) being formed. For option 3 of a gas-generator with a diesel engine, a lower power drop will occur due to the presence in the generator gas of a large amount of carbon monoxide \( \text{CO} \), the combustion temperature of which in air is 2300°C.

Of great importance from an economic point of view is the introduction of a new type of motor transport gas-generators for remote areas [11]. For the transportation of 1 ton of gasoline over a distance of 6,000 km, motor transport work of 6,000 t-km is expended, while the useful work performed by automobiles per 1 t of transported gasoline is only 5,400 t-km with average performance. The use of transport vehicles to work on local types of solid fuels will also contribute to the natural resources development, and, therefore, to develop industry in areas remote from railway and waterways.

Comparison of fuel costs for various options is conveniently carried out at the price of diesel motor fuel in the area of public highways \( T_{st} = 50 \) rubles/liter and the price of wood fuels \( T_{sd} = 2 \) rubles/kg, 9.7 kg of wood fuel and 0.33 kg of diesel fuel with a volume of 0.4 liter are required to obtain the heat of 113 MJ in option 3. Power carrier costs will be

\[
3_c = 3_w + 3_d = 9,702 + 0,4 \cdot 50 = 39,4 \text{ rubles.}
\]

Specific costs per 1 MJ are

\[
3_w = \frac{3_c}{Q_3} = \frac{39.4}{113} = 0.349 \text{ rubles/MJ.}
\]

For the basic version of a diesel engine, to obtain heat of \( Q_1 = 9150 \) MJ, 198 kg of diesel fuel with a volume of 239 liters is spent at a cost of 11950 rubles, then the unit cost of obtaining 1 MJ for option 1 will be 1.31 rubles/MJ.

In some areas, the price of diesel fuel can reach 100 rubles/liter. The cost of 1 MJ of heat in the cylinders of a gas-generating vehicle will be 0.491 rubles, while for a diesel car 2.62 rubles/MJ. In this case, transport and production logistics benefit to a greater extent. So, for the usual conditions for the delivery of motor fuel by URAL trucks on local roads without artificial turf, the fuel consumption in the loaded direction is 75 liters/100 km and in the empty direction 40 liter/100 km. For the delivery of 5 tons of fuel to a distance of 1000 km and the return trip of the car, 1150 liters of fuel will be used with the cost up to 115000 rubles.

Figure 3 shows the estimated prices of power carriers (ruble/liter, ruble/m³, ruble/kg) for an engine with various power supply options 1, 2, 3 taking into account their percentage in the total fuel (100% of diesel fuel DT; 10% of diesel fuel DT and 90% of methane gas; 10% of diesel fuel DT and 90% of
generator gas (WOOD). Figure 4 shows the specific energy costs for an engine with various power supply options 1, 2, 3.

![Figure 3. Estimated prices of power carriers for the engine of various options of power supply systems, taking into account their percentage in the total fuel.](image)

![Figure 4. Specific power carriers costs of various options for engine power supply systems: a conventional diesel engine (1), gas-diesel engine (2) and generator gas-diesel engine (3).](image)

In the case of the equipment of motor vehicles with gas-generating units, the need for liquid motor fuel, which means transport operation of cars in the pendulum mode, can be reduced by 4-5 times, ceteris paribus, performed local work in industry, agriculture and forestry.

4. Conclusions

The use of gas-generators on automotive vehicles is equivalent, in terms of reducing the level of nitrogen oxides and carbon monoxide in the exhaust gas, of the installation of a recirculation system on SCANIA vehicles, which allows reaching the Euro 5 standard without the application of additional chemicals.

The use of gas generators on gas-diesel engines will reduce the coefficient of excess air from 2.0 to 1.4 while maintaining in the temperature rise of combustion of the fuel-air mixture in the cylinders at the level of 1640°C.

The use of gas-generators running on wood and converted gas-diesel engines can be accompanied by a reduction in power by 2-8%.

In the case of the equipment of motor vehicles with gas-generating units, the need for motor liquid fuel, which means the transport work of cars in the pendulum mode, can be reduced by 4-5 times, ceteris paribus, the work performed in industry, agriculture and forestry.

The fuel efficiency of automotive vehicles can be increased if solid waste containing polyethylene and polystyrene materials is used in gas-generators in addition to wood fuel.

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