IMPROVING PERFORMANCE OF WHEELED TRACTOR WITH GAS ENGINE AS PART OF TRANSPORT MACHINE UNIT

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Abstract. Increasing requirements for the environmental performance of agricultural transport vehicles require improvement of their design that will reduce emissions of harmful substances from exhaust gases. A method of estimating fuel efficiency and environmental performance of a wheeled tractor with a gas engine when performing transport works has been developed. A mathematical model of the wheeled tractor movement along the driving cycle has been developed. The mathematical model used the results of experimental studies of a gas engine. Bench tests of a diesel engine that was converted into a spark ignition gas engine for operation on natural gas were performed and they confirmed its operability and showed good operational performance. A wheeled tractor was converted to run on gas fuels using the same technology and elements. Its test results showed that there are certain peculiarities of driving such tractor due to the fact that the diesel tractor engine is equipped with an all-mode crankshaft speed regulator which is not used in a gas engine. A driving cycle was chosen to study the performance of a wheeled tractor when performing transport works. Environmental indicators and fuel consumption of a specific engine, that are used in the mathematical model, are described by polynomial models based on its experimental characteristics. Using the mathematical model of tractor movement during the driving cycle, the appropriate ways of controlling the transmission and gas engine during tractor movement were determined, in particular, the proper order of gear shifting when the tractor is accelerating. The total emissions of harmful substances during the driving cycle of a tractor both with a gas engine and a diesel engine were calculated, which prove the environmental feasibility of using gas fuel. The total toxicity of exhaust gases, reduced to carbon monoxide CO, of a tractor with a gas engine is 1.9 times lower than of a diesel engine.

Keywords: gas engine, wheeled tractor, natural gas, mathematical modelling, environmental indicators.

Introduction

It is well known that agricultural machinery is equipped with diesel engines which have good fuel efficiency and are easy to operate and maintain. However, the growth of requirements for environmental indicators of transport vehicles, including agricultural ones, requires improvement of their design, which will provide a significant reduction of emissions of harmful substances with waste gases. This is due to the fact that a significant number of wheeled tractors in agricultural production are constantly used as technological transport for servicing livestock complexes, greenhouses, storage facilities, etc. At the same time, their arrival and long work in the premises take place, thanks to which damage is caused to the health of people and other biological objects. It was established that maximum permissible concentrations of emissions of harmful substances with exhaust gases exceed the permissible norms after several minutes of engine operation in a closed room. Therefore, the improvement of environmental indicators of technological vehicles is very relevant.

Natural gas is considered one of the best substitutes for oil fuels today. On the one hand, it is compatible with conventional spark ignition engines or compression ignition engines, and on the other hand, it is more environmentally friendly due to lower emissions of harmful substances with exhaust gases [1-2]. There are many scientific works that recognize natural gas as environmentally friendly fuel [3-12]. A favourable ratio of hydrogen to carbon in methane is responsible for lower CO_2 emissions compared to gasoline up to 30% [8]. In fact, as stated in [4], natural gas combustion results in the lowest CO_2 emissions among fossil fuels. Moreover, if you use methane from biogas obtained from recycling, it is even more effective.

In addition, as stated in [9], the natural gas engine emits smaller amounts of CO carbon monoxide and unburned CH hydrocarbons. An additional feature of natural gas engines is methane, which has little reactivity in the photochemical cycle of smog and the main unburned hydrocarbon in the exhaust gases.

The work provides the results of studies of a gas engine with spark ignition on the basis of a tractor diesel engine D-21A. The compression ratio was reduced to 9.5 by boring the combustion chambers in the pistons. The rated power of 18.4 kW was achieved during natural gas operation. Fuel efficiency deteriorated by 11% compared to the base diesel engine at rated power mode. Soot is absent, nitrogen oxide and carbon oxide emissions have decreased at the rated power mode in exhaust gases.

The results of research on a spark-ignition gas engine based on the YaMZ-236 diesel engine are known. Microprocessor control of power and ignition systems is designed for this engine. The operation of such engine can be ensured on very poor gas-air mixtures at partial load modes. Thanks to this, we have received good environmental and economic indicators. However, the cost of such engine is quite high. You can create such engines only in the conditions of a motor plant. It was concluded that a diesel engine with a high compression ratio of 17.5 may be suitable for conversion in terms of performance and emissions for a certain ignition advance angle at high load and speed. The potential of natural gas to significantly reduce carbon black and particulate emissions is extremely important in the application of EURO7 in the future. It will take into account nanoparticles smaller than 23 nm [9; 10].

The impact of ignition moment on performance, combustion characteristics and emissions was investigated in the work [11]. The results showed that the maximum pressure in the cylinder increased. Two peak formations can be seen in heat generation depending on the ignition time. Maximum torque and thermal efficiency are reduced.

Previous scientific studies have shown that one of the effective ways to improve the environmental performance of vehicles with diesel engines can be their transfer to work on compressed natural gas (CNG) [12].

Analysis of the results of the research of vehicles with engines converted from diesel engines for operation on gas fuels showed that studies of the influence of the parameters of transmission and gas engine control on the operational performance of wheel tractors in the transport process were not carried out. This determined the purpose of the work. Hence, we determine that the purpose of the work is improving the operational performance of the wheeled tractor during its transport work.

Tasks of work: to carry out experimental studies of a gas engine with spark ignition and a wheeled tractor with a gas engine; to determine by mathematical modeling rational methods of controlling the tractor transmission and gas engine.

Materials and methods

The study of the features of driving the transmission and the gas engine of the wheeled tractor was carried out on the mathematical model of tractor movement according to the accepted driving cycle [12]. Controlling the transmission and gas engine of the wheeled tractor is characterized by the following parameters: the operator's choice of the gear number of the gearbox U_i during acceleration, the speed of the engine crankshaft n_e, when the switch to higher gear during acceleration occurs, the opening angle of the throttle flaps of the gas-air mixer φ_1 and the opening speed of the throttle flaps of the gas-air mixer V_1. These parameters determine the operating modes of the gas engine, the hourly gas consumption G_{gas} and air G_{air}, as well as the concentration of harmful substances in the exhaust gases. The ratio of the engine torque and movement resistance forces determines the speed of the wheeled tractor V_{tr} and acceleration dV_{tr}/dt. The movement of a wheeled tractor equipped with a gas engine is described by a system of differential and algebraic equations in the driving cycle (DC) in each mode of operation.

The movement of a wheeled tractor with a trailer on the road is simulated in the mathematical model. Engine operating modes (crankshaft rotation frequency n_e and rarefaction Δp_k behind the throttle valves of the gas-air mixer) are determined at each moment of cycle execution. Fuel consumption, harmful emissions, traction and speed properties of the wheeled tractor on the elementary section of the road are calculated taking into account the features of the engine operation in undisturbed modes and the type of fuel according to the loading characteristics experimentally determined in operation (in mode and for the entire cycle of the tractor movement).

The equation of motion of a wheeled tractor, obtained from the traction balance, has the form:

$$\frac{dV_{tr}}{dt} = \frac{1}{\delta \cdot M_0 \cdot \left(1 + \frac{\lambda \cdot U_i^2 \cdot U_0^2 \cdot U_k^2 \cdot \eta_T}{\delta \cdot M_0 \cdot r_1 \cdot r_2}\right)} \times \left(\frac{M_e \cdot U_i \cdot U_0 \cdot U_k \cdot \eta_T}{r_2} - P_f \pm P_i - P_w - P_1\right), \tag{1}$$

where M_0 – own weight of the wheeled tractor, kg;

r_1 – rolling radius of the tractor driving wheel, m;
r_2 – dynamic radius of the driving wheel, m;
λ – experimental coefficient of transient mode;
U_i – gear ratio of the *i*-th gear;
U_0 – gear ratio of the main gear;
U_k – gear ratio of the wheel drive;
M_e – effective engine torque, N·m;
P_f, P_i, P_w – resistance forces respectively rolling, lifting and air, N;
δ – coefficient that takes into account the rotating masses of the tractor;
η_T – transmission efficiency;
P_1 – resistance force on the hook, N.

Coefficient, which takes into account the rotating masses of the tractor and the forces of rolling resistance, lifting, air and resistance forces on the hook:

$$\delta = 1 + \frac{2 \cdot (J_1 + J_2)}{M_0 \cdot r_2^2} + \frac{J_e \cdot U_i^2 \cdot U_0^2 \cdot U_k^2 \cdot \eta_T}{M_0 \cdot r_2^2} + \frac{\sum_{i=1}^{n} J_i}{(M_1 + M_2) \cdot r_2^2}, \quad (2)$$

where J_1 – moment of inertia of the tractor front wheel, kg·m^2;
J_2 – moment of inertia of the rear wheel of the tractor, kg·m^2;
J_e – moment of inertia of the engine, kg·m^2;
J_i – moment of inertia of the tractor trailer wheels, kg·m^2;
M_1 – own weight of the trailer, kg;
M_2 – cargo weight, kg.

Resistance force on the hook [12]:

$$P_1 = (M_1 + M_2) \cdot f_0, \quad (3)$$

where f_0 – coefficient of rolling resistance of the tractor and trailer wheels.

The sequence of tractor modes is set by a set of parameters in the form of a universal matrix, according to which the corresponding mode of movement is set at each section of the driving cycle for implementation on a personal computer (PC).

Effective and environmental indicators during operation of the gas engine in various speed and load modes are described by quadratic polynomial models depending on the crankshaft speed n_e and liquefaction in the inlet pipeline Δp_k, obtained from the results of experimental studies of the gas engine.

For example, for hourly gas flow, the polynomial dependence is as follows:

$$G_{gas} = 2.4509 + 0.62955 \cdot n_e - 0.79128 \cdot \Delta p_k - 0.64732 \cdot n_e^2 + 0.21317 \cdot \Delta p_k^2 - 0.28547 \cdot n_e \cdot \Delta p_k. \quad (4)$$

The adequacy of the resulting polynomial models describing the gas engine is confirmed by Fisher's criterion.

Experimental studies of the indicators of a gas engine, converted from the D-243 diesel engine were carried out. For this purpose, the D-243 diesel engine, installed on the test stand, was converted to a spark ignition gas engine (Fig. 1). Diesel conversion was carried out with minimal expenditure of funds due to the use of serial gas equipment, the serial ignition system of the MeMZ-245 gasoline engine and small changes in the engine design. In particular, the compression ratio was reduced from 16 to 12 by installing additional cylinder head gaskets. Therefore, it is possible to resume work on a diesel cycle. The scheme of the combustion chamber of a gas engine converted from a D-243 diesel engine is shown in Fig. 2. Technical characteristics of diesel D-243 and its gas modification are given in Table 1. MTZ-80 wheeled tractor was converted to work on natural gas. Ignition systems and power supply elements used in stand tests of the gas engine were installed. In addition, the diesel fuel pump control drive was replaced by the throttle control drive of the gas-air mixer. The tractor was tested during transport work with a fully loaded trailer both on a road with an asphalt concrete surface and a dirt road in hilly conditions. The convenience of driving the tractor has not deteriorated. The normal temperature mode of the gas engine was provided by a serial cooling system at an ambient temperature of 25... 30 ºC and long-term operation.

Fig. 1. **Gas engine converted from diesel D-243 on a test stand**

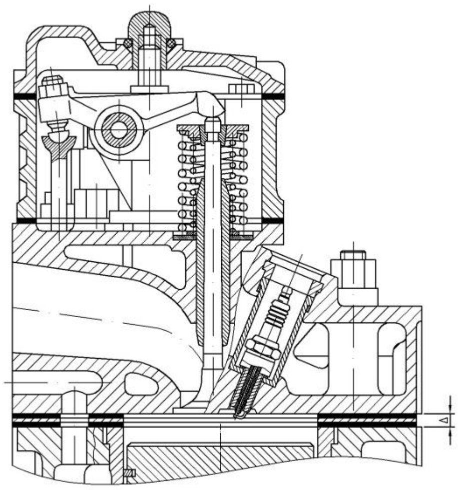

Fig. 2. **Scheme of the combustion chamber of a gas engine converted from a D-243 diesel engine**

Table 1

Brief technical characteristics of diesel D-243 and its gas modification

No. p/p	Parameter names	Parameter values	
1.	Engine type	diesel	gas
2.	Number and arrangement of cylinders	4, straight-line, vertical	
3.	Working volume, l	4.75	
4.	Compression ratio	16	12
5.	Rated power, kW	55.1	57.3
6.	Maximum torque, Nm	274	280
7.	Method of mixing	internal	external
8.	Method of ignition of fuel-air mixture	self-ignition	forced ignition from spark

The adequacy of the mathematical model of the tractor movement in the driving cycle was checked by comparing the design speeds and fuel consumption with the data of experimental studies obtained during the driving cycle in road conditions. Special sensors were installed on the tractor. They were connected to the laptop through an analog-to-digital converter in the tractor cab.

Results and discussion

Experimental studies of the gas engine confirmed its performance in the entire range of speed and load modes with a maximum power of 1.98...4.3% and a higher equivalent specific effective fuel consumption of up to 20% than that of a diesel engine. The composition of the gas-air mixture is close to stoichiometric (Fig.3). The optimal ignition advance angle for the highest torque of the engine installed on the test stand was determined and set before carrying out the experiments. It was found that the total toxicity of the gas engine is 1.83 times less than that of the diesel engine, due to the absence of soot in the processed gases and lower specific emissions of CmNn and NOx.

Road tests of the wheeled tractor with a gas engine showed that tractor control has its own characteristics. Acceleration of the tractor with a loaded trailer should be carried out with a gear shift. Acceleration of the tractor in one gear, like a diesel engine with an all-mode regulator, is practically impossible. This is due to the difference in the nature of the flow of the speed characteristics of a gas engine and a diesel engine with all-round regulation and, accordingly, a lower torque margin when operating on partial speed characteristics.

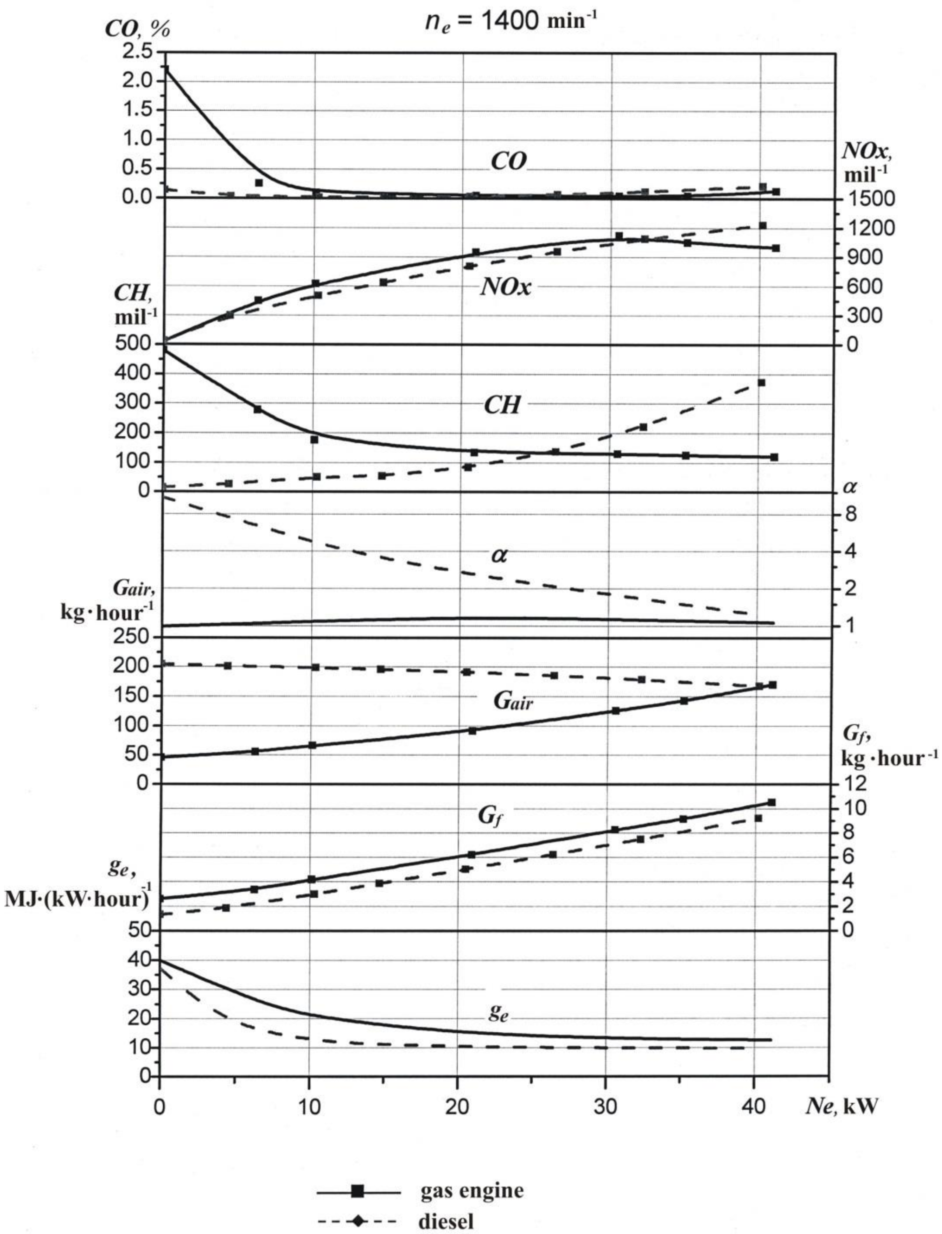

Fig. 3. **Loading characteristics of the D-243 gas engine and basic diesel engine with measurement of the toxicity of the worked gases**

Tractor engines operate in almost the same conditions as automobile engines. They have a wide range of changes in loading and speed modes in case of carrying out transport work. These modes are determined by the driving conditions of the wheeled tractor in the traffic flow: idling, acceleration, steady motion, engine braking (forced idling). Ecological and fuel-economic indicators of the vehicle can be evaluated by imitating its movement along the same driving cycle on different types of fuels. The driving cycle, which includes the most characteristic modes of its movement, is accepted (Fig. 4), as there are no standard driving cycles for wheeled tractors.

As a result of the calculations carried out on the mathematical model of the movement of the wheeled tractor, the running fuel consumption and emissions of harmful substances were determined when the engine was running on different fuels according to the accepted driving cycle. The minimum specific gas consumption of the MTZ-80 tractor engine is observed when switching gears in order of 6-8-9. Reducing the fuel consumption by 3.9...9.8% can be achieved in this case (Table 2). The final speed of the crankshaft in each gear must be not higher than 1600 min^{-1} to provide traction speed indicators. They should be close to the indicators of a tractor with a diesel engine and the least harmful emissions.

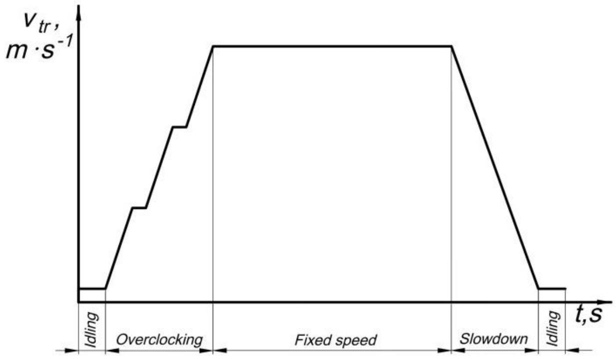

Fig. 4. **Accepted driving cycle of a wheeled tractor**

Table 2

Specific gas consumption g_{gas} by a wheeled tractor with the coefficient of rolling resistance of the wheels f_0 = 0.016 with different order of gear shifting

Indicator	Gear shift order of 9-stage tractor box						
	4-5-9	4-6-9	5-6-9	5-7-9	5-8-9	6-7-9	6-8-9
g_{gas}, g·km^{-1}	520.5	527.4	518.1	530.6	535.5	528.2	515.1
t_a, s	224.6	218.1	214.7	217.5	207.4	201.9	196.1

Increasing the speed of opening throttle flaps from 50 to 250%·s^{-1} leads to an increase in the total specific emissions of HS (harmful substances) by 6.6% (Fig. 5), reduced to carbon monoxide $g\Sigma CO$ ($g\Sigma CO$ – total toxicity of exhaust gases reduced to CO carbon monoxide). Gas consumption also increases by 5.2%. Thus, the obtained data show that the speed of opening throttle flaps affects the environmental indicators and fuel consumption of the wheeled tractor during acceleration. It is advisable to open throttle flaps smoothly at a speed of not more than 75%·s^{-1}. An increase in emissions of harmful substances and the fuel consumption by the engine is observed with a sharp opening.

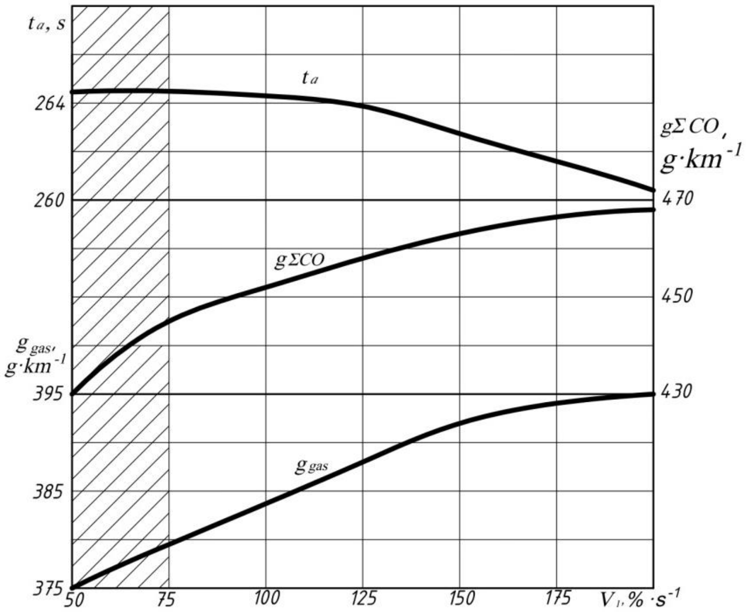

Fig. 5. **Indicators of a wheeled tractor in the process of acceleration at different speeds of opening throttle flaps of the gas-air mixer**

The results of increasing the power of the gas engine and increasing the fuel consumption can be explained by the operation of the gas engine on richer mixtures compared to diesel. Reduction of total toxicity of exhaust gases of the gas engine can be explained by absence of soot in exhaust gases.

The main value of this work lies in the proposed and tested method of forecasting the environmental and fuel-economic indicators of technological vehicles using various ways to improve these indicators.

Conclusions

1. The operability of the gas engine was confirmed by experimental studies. It was found that the maximum power of the gas engine is up to 4% higher, the specific effective fuel consumption is up to 20% higher than that of a diesel engine. The total toxicity, reduced to carbon monoxide CO, of the gas engine is 1.83 times less than that of diesel. This is mainly due to the absence of soot in the exhaust gas of the gas engine.
2. Mathematical modeling determined the expedient order of gear shifting and expedient parameters of engine control during acceleration of a wheeled tractor with a gas engine.

Author contributions

Conceptualization, V.Z.; methodology, V.Z. and O.Z.; software, V.Z.; validation, M.T. and N.T.; investigation, V.Z., O.Z., M.T. and N.T.; data curation, V.Z. and O.Z.; writing – original draft preparation, V.Z.; writing – review and editing, O.Z. and N.T.; visualization, O.Z., M.T. and N.T. All authors have read and agreed to the published version of the manuscript.

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