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Article

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Efficient Use of Energy Resources of the Generator of Hot Gases in the Thermal Preparation of Motor Vehicles

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ABSTRACT

Generators of hot gases (GHG) are used for thermal preparation of vehicles in cold climatic conditions. Their wide use is caused by the high thermal power and safety of application. The heat released in burning zone is used partly for heating air flow, partly for heating of GHG parts: guide nozzle and the false pallet. The generator of hot gases consumes from 70 to 150 W of the car battery power. In the process of thermal preparation, this leads to a decrease in the battery capacity, and as a result - the impossibility of starting the motor of the vehicle. The issue of reducing the energy consumption of the GHG, without changing its consumer qualities, becomes urgent.

Keywords: Thermal Preparation, Generator of Hot Gases, Guide Nozzle, Thermoelectric Generator, Losses of Thermal Energy, The Temperature Field, Fillers
JEL Classifications: O13, Q40

1. INTRODUCTION

The harsh climatic conditions of the northern countries predetermined the development of a large number of different means and methods of thermal preparation of vehicles for engine start-up and operation during the cold season (Gabitov et al., 2019; Yu et al., 2017). The most promising direction for solving problems is the use of a hot gas generator as a heat module, where heated air flows act as sources of heat energy (Gusev, 2017; Kim et al., 2017; Negovora et al., 2014).

The hot gas generator is designed to prepare vehicles for the operation in the cold season and is used for:

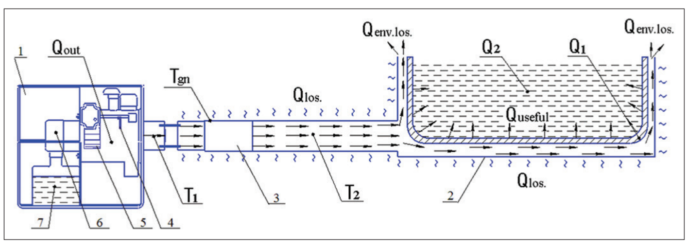
- Warming up the engine oil in the engine crankcase in order to facilitate its start in the cold season;
- Warming up the gearbox housing, transfer case and crankcase of the rear and front axle gearboxes, battery, air brake components and fuel system components;
- Preheating of air-cooled engines;
- Heating of a cabin through a radiator through which heated air is supplied to the passage (Risseh et al., 2017).

The hot gas generator works as follows: The fan 5 forces air into the body of the preheater 1 (Figure 1) and into the combustion chamber (Demir and Dincer, 2017). The nozzle sprays the fuel supplied by the impulse pump from tank 7, the glow plug 4 ignites the injected fuel. At the exit from the heater, a mixture of exhaust gases and air is formed, which has a high (up to 450…550°C) temperature. The essence of the heat treatment of the vehicle units is that the heater nozzle 3 and the false pallet 2 are installed on the heater 1 and the hot gases from the heater are fed onto them. The nozzle 3 and the false pallet 2 provide the supply of the main part of the thermal energy to the units and reduce the loss of heater by scattering into the environment. Such a system is able to provide heating of the operating fluid of various car units to a temperature of 8…10°C for 15... 45 min at an ambient temperature of –40°C (Gusev, 2017).

However, it is necessary to consider that the power source of the heater is mainly the battery of the PBX. And in real conditions of operation during thermal preparation of the equipment, the discharge of the battery occurs, which can lead to the impossibility of starting the internal combustion engine or reducing the life of the battery (Negovora and Razjapov, 2013).

Battery discharge at low temperatures is allowed to be not lower than 25% (Jutt, 2015) and, on the basis of studies of the electric power consumed by the heater during its long-term operation leads to battery discharge below the limiting values, which further leads to a decrease in the service life of the latter, and in actual operation to the impossibility of starting the engine.

Figure 1: Schematic diagram of the hot gas generator: 1-heater; 2-false pallet; 3-guide nozzle; 4-pin filament; 5-centrifugal air blower; 6-supercharger motor; 7-fuel tank; Q_{out} -the amount of heat released; T_1 - outlet temperature from the combustion chamber; T_2 - outlet temperature from the guide nozzle; T_{gn} - heating temperature of the guide nozzle; Q_{los} - loss of thermal energy in the form of radiant radiation and convective heat transfer to the environment; $Q_{env.los}$ - heat loss from the heater coming out of the false pallet; Q_{useful} - useful heat used to heat the unit



Purpose of the study:
- To develop a system to reduce the energy consumed by the heater, which is operated in conditions of negative ambient temperatures
- To develop the design and algorithm of the generators of hot gases (GHG) operation together with a thermoelectric generator (TEG)
- To conduct theoretical and experimental studies of the improved system, and deduce the patterns of the influence of the parameters of the GHG operating cycle on the output parameters of the TEG

2. MATERIALS AND METHODS

In order to determine the amount of electric power consumption of the heating unit for 30 min after switching on, according to the developed algorithm of operation (Figure 2), the parameters of the functioning of its components were taken (Table 1).

Heater power consumers are a centrifugal air blower, a heat pin and a pulse fuel pump.

The rotor speed of the centrifugal air blower is controlled by pulse-width modulation (PWM) of the heater control unit. Power consumption of a centrifugal air blower is determined by the formula:

$$P = U_{res} I \quad (1)$$

Where I is the consumed current of the heater (2.9 A).

The resulting voltage is determined by the formula:

Figure 2: Algorithm of the heater, taking into account the redistribution of electricity consumed

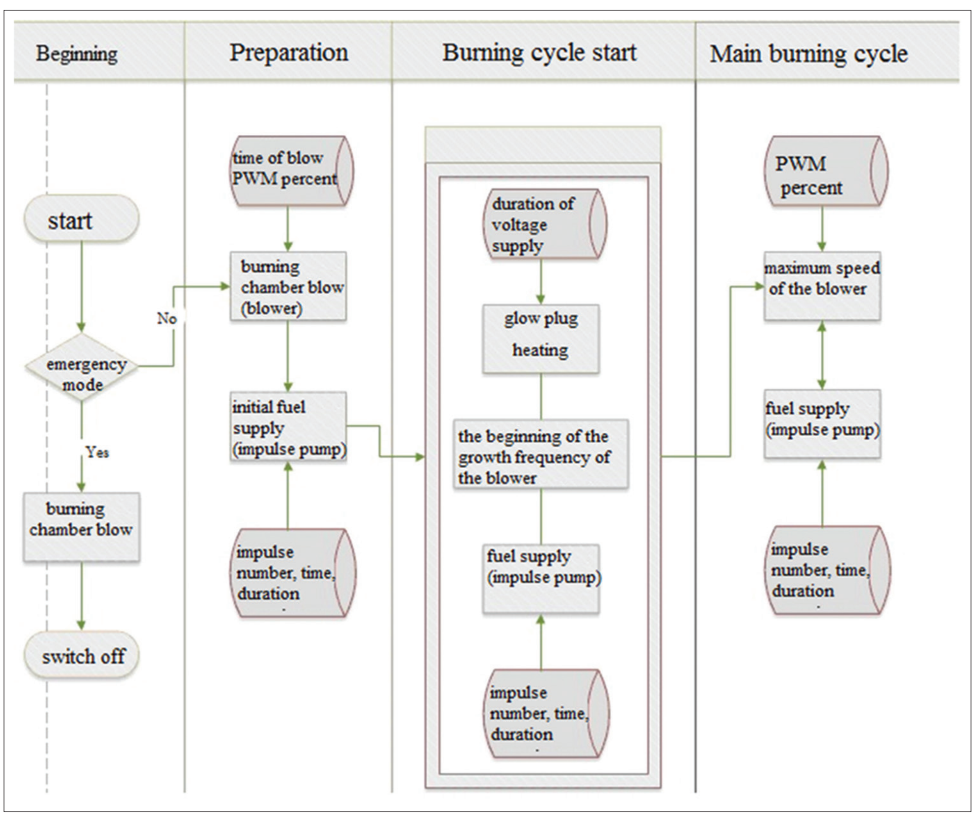


Table 1: Algorithm of operation of the ThermMix-15D heater

GHG components	Burning chamber blow	Preparation	Beginning of burning	Stable work mode
Centrifugal air blower	+	+	+	+
	PWM 80%	PWM 10%	Smooth growth	PWM 90%
Pulse fuel pump	-	+	+	+
	f=0Hz	f=2,5Hz	f=1Hz	f=1,2Hz
Heat pin	-	+	-	-
Time (s)	0-20	20-46	46-114	114-1800
Time scale				

$$U_{res} = \frac{U_u \cdot t_u}{T} \quad (2)$$

Where U_u is the pulse voltage (24 V);

The period of one pulse oscillation (the sum of the pulse time and the pause time) of the PWM signal of the heater control unit is determined by the formula:

$$T = 1/f \quad (3)$$

Where f is the pulse frequency (16 kHz).

The duration of the pulse (Table 2) is determined by the formula:

$$t_u = A \cdot T/100 \quad (4)$$

Where A is the coefficient of the duty cycle of PWM (%).

The heat pin works only at the moment of initial ignition of the fuel-air mixture in the combustion chamber for 26 s. The initial resistance of the heat pin is 5.4 ohms and, as it heats up to the maximum temperature, increases to 7.2 ohms. The impulse fuel pump resistance is 136 ohms, the supplied voltage is U = 24 V. The power consumption of the heat pin and the impulse fuel pump is determined by the formula:

$$P = U^2/R \quad (5)$$

The results of the calculation of the total power consumption from the battery power source of all components of the heater within 30 min are presented in Table 3 and graphically in Figure 3.

The studies have shown that the power consumption of the heater at the time of preparation and ignition of the air-fuel mixture reaches 117.7 W for a short time (Table 3), and after reaching a stable combustion mode it decreases to 66.8 W (without taking into account the internal components of the active and reactive resistances of the electronic components management). At the same time, the main consumer is a centrifugal air blower.

In order to reduce the energy consumption of the GHG from the battery during the heat treatment of the PBX, it was advised to install a source of electrical energy based on a TEG on the heater nozzle.

Let us consider the block diagram of GHG with the proposed system for converting thermal energy into electrical energy. The

Table 2: PWM duty cycle data and the resulting voltage of the centrifugal air blower at the main stages of work

Duration of work (s)	PWM (%)	t_u,c	U_{res},B	P,Вт
20	80	50 10^{-6}	19,2	55,7
46	10	6,25 10^{-6}	2,4	6,9
114	50	31,2 10^{-6}	12,0	34,8
1800	90	56,2 10^{-6}	21,6	62,64

Table 3: The total power consumption of the heater

Duration of work, s	Power consumption from the battery, W			P_{Σ},W
	Air blower	Heat pin	Low pressure fuel pump	
0-20	55.7	0	4.2	59.9
20-46	6.9	106.6		117.7
46-114	34.8	0		39
114-1800	62.6	0		66.8

operation of the GHG (Figure 4) requires three components: Air, fuel and electricity. At the output we get thermal energy, which is spent on thermal preparation of the vehicle, part of the energy from the guide nozzle is dissipated in the form of radiant radiation and convective heat transfer to the environment. Heat energy from the GHG guide nozzle is converted into electrical energy using a TEG, which is connected in parallel to the power supply circuit of the centrifugal air blower of the heater.

According to the heater operation algorithm (Figure 2), after powering up for 20 s after starting the heater, the combustion chamber is purged with a centrifugal air blower (PWM duty cycle 80%). For 21 s, power is supplied to the heat pin for 25 s; fuel is synchronously pulsed into the combustion chamber. Further, the heat flow rate smoothly increases from 5% of the duty cycle of the PWM air blower to the maximum (114 s, 90% of the PWM duty cycle). On the 15th min of the GHG operation, the power to the air blower starts to be supplied from the TEG, cyclically switching until $U_{tgm} \rightarrow U_{kp}$, while decreasing to P_{kp}, the power is switched to the normal battery power supply (Figure 5).

Between the periods of 1-2 ($P_{tgm} \rightarrow \eta_{max}$) on the graph (Figure 5) it can be seen that the generated energy c TEG is not used. For smoothing the work of the developed system, large capacitors are installed in it, which smooth the voltage drop at the moment of reducing the temperature difference and accumulate charge during the growth period. Figure 6 shows a schematic diagram

Figure 3: Power consumption of the heater components during operation t = 30 min

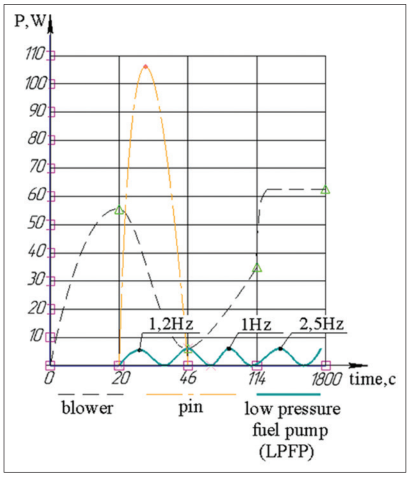
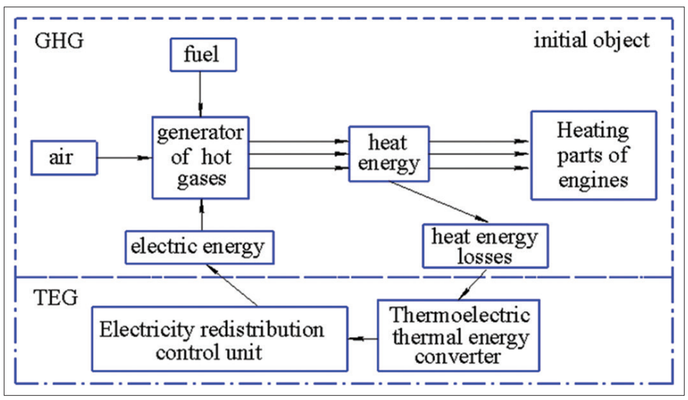


Figure 4: Scheme of operation of a hot gas generator together with a thermoelectric generator



of the connection of TEG modules (TGM) and capacitors with balancing resistors.

Thus, we determined and experimentally proved the possibility of reducing battery power consumption by a hot gas generator using TEG modules adapted to the power supply system.

The following main components and systems can be distinguished in the composition of a TEG: A housing with connecting flanges, TEG modules, a cooling system consisting of radiators, a control and power conversion system. The following options were considered to ensure the necessary parameters of the TEG:

- Design of the TEG case and its heat exchanger, ensuring efficient heat transfer and optimal layout;
- Designs of TEG modules coolers, providing efficient heat transfer;
- Materials of positive and negative branches of TEG modules, having a maximum efficiency for given temperatures, as well as the power of one TGM and their total number in a TEG.

In general, a TEG can be represented as a combination of three components: a heat source, a thermoelectric module and a cooler. For the TEG being developed, a heating unit for the transmission and an internal combustion engine, the heated stream of hot gas acts as a source of thermal energy, and the surrounding air acts as a cooler.

Figure 5: Cyclic process of electricity consumption by a centrifugal air blower GHG from the battery and TEG: 1 - powered by vehicle battery - the period of creating the maximum allowable temperature difference $P_{tgm} \rightarrow \eta_{max}$ tgm (thermoelectric generator modules); 2 - the moment of redistribution of power consumption on a thermoelectric generator; 3 - powered by a thermoelectric generator; 4 - the drop in the output power of a thermoelectric generator below $P_{кр}$

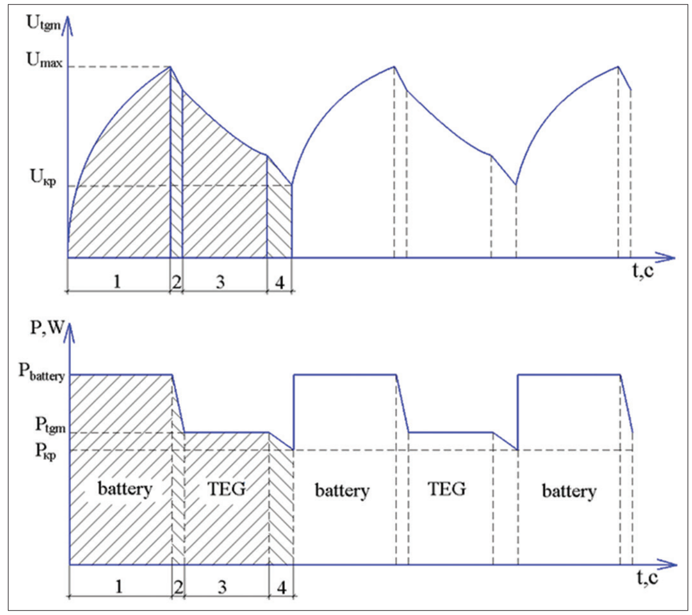
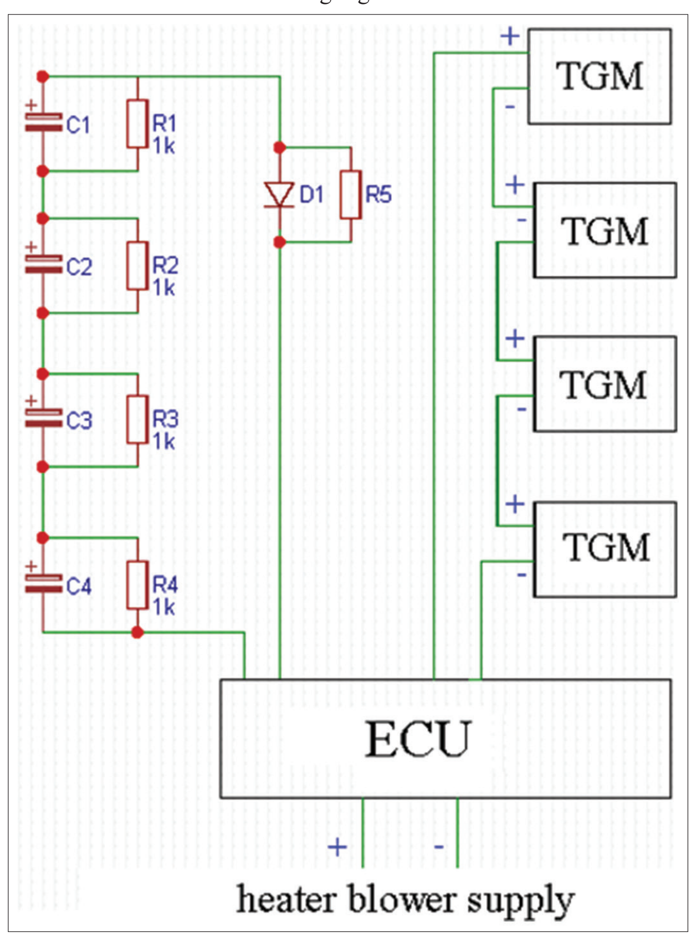


Figure 6: Wiring diagram of capacitors with TGM to the air blower of the hot gas generator



To determine the initial technical parameters of TEG, the power of heat flows from hot gases to TEG modules and, further, to a cooler was calculated.

The heat flow powers will be determined on the basis of the heat transfer and heat conduction equations (Vinogradov et al., 2010), which follow from the Newton-Richman law:

$$Q_1 = \alpha_1 \cdot F_1 \cdot \Delta T_1 \qquad (6)$$

$$Q_{tgm} = k_{tgm} \cdot F_{tgm} \cdot \Delta T_{tgm} \qquad (7)$$

$$Q_2 = \alpha_2 \cdot F_2 \cdot \Delta T_2 \qquad (8)$$

Where - heat transfer coefficient to the wall from the side of the heating coolant, W/m²·K;
F_1 - heat exchange area from the heating coolant, m²;
ΔT_1 - average temperature pressure from the heating coolant, K;
Q_{tgm} - heat flux through TEG modules, W;
K_{tgm} - average coefficient of thermal conductivity of TEG modules, taking into account additional walls, W/m²·K;
T_{tgm} - total area of TEG modules, m²;
ΔT_{tgm} - the average temperature difference between the walls of the heating and heat absorbing coolants, K;
α_2 - coefficient of heat transfer from the wall towards the heat-receiving coolant, J/m²·K;
F_1 - heat exchange area from the heat-receiving coolant side, m²;
ΔT_2 - average temperature pressure from the heat-receiving coolant side, K.

The average thermal conductivity coefficient of TEG modules with regard to additional walls also depends on the design of the TEG module and the materials used and can be determined by the formula:

$$k_{tgm} = \frac{1}{\frac{\delta_1}{\lambda_1} + \frac{\delta_{tgm}}{\lambda_{tgm}} + \frac{\delta_2}{\lambda_2}} \qquad (9)$$

where δ_1 - wall thickness from the side of the heater, m;
λ_1- the coefficient of thermal conductivity of the wall from the side of the heating coolant, W/m·K;
δ_{tgm} - thickness of TEG modules, m;
λ_{tgm} - coefficient of thermal conductivity of TEG modules, W/m·K;
δ_1 - wall thickness on the side of the heat-receiving heater, m;
λ_2 - coefficient of thermal conductivity of the wall on the side of the heat-receiving heater, W/m·K.

In expressions 6-9, many parameters directly or indirectly depend on the geometry of the elements of the TEG being developed, therefore the creation of its simulation mathematical model is impossible without a complete solid-state model. The modules based on bismuth telluride (Xi et al., 2000) TGM-199-1.4-0.8 were used as TEG modules for research.

Based on the analysis of the designs of existing TEG (Konovalov et al., 2012), and also with the aim of minimizing mass and dimensional parameters, a square tube 1 was selected as the TEG housing (Figure 7), on the sides of which four TEG modules 4 are installed. For each module accounted for one cooler 2.

When developing a solid-state model of a TEG, the above solutions were implemented in the CAD system of three-dimensional modeling compass-3D. A general view of the solid model is shown in Figure 7.

To solve this problem, the ANSYS Thermal Steady State package was chosen, which implements the finite element method, the use of which allows calculating the thermal field of heating of the square box surface with a small error. With its help, a thermal

Figure 7: General view of the solid-state model of an improved nozzle of a hot gas generator: 1-square box; 2-cooler; 3-guide nozzle; 4- thermoelectric generator; 5-filler; 6-interfaces between the nozzle and the box

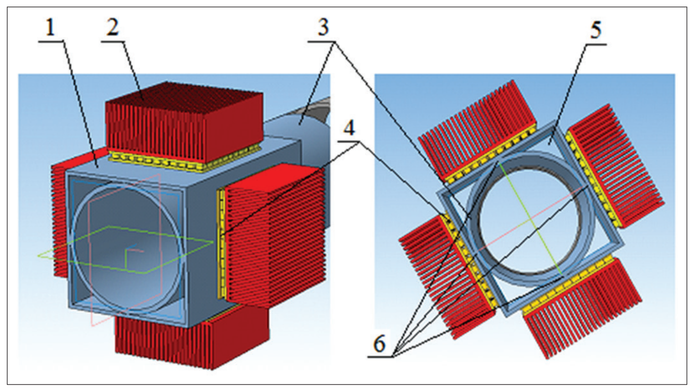


Figure 8: General view of the solid-state model and the finite element network of an advanced hot gas generator in the CAD system

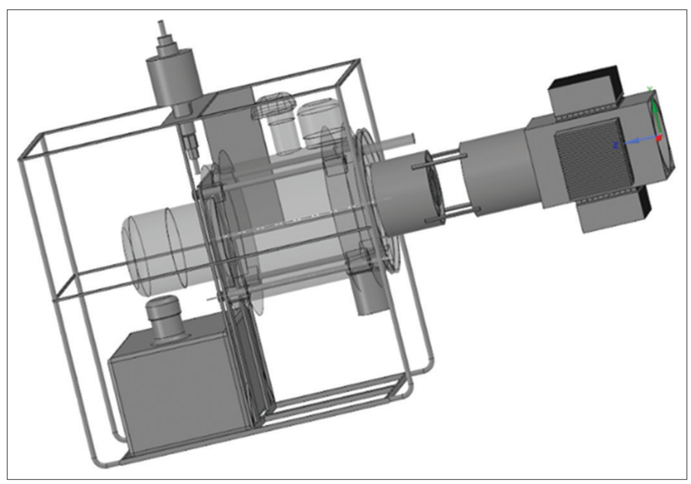
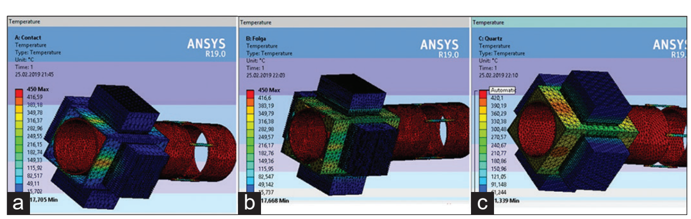


Figure 9: Map of the temperature distribution field through a square box - guide nozzle. (a) Without filter; (b) with foiled filter; (c) quartz sand filter



analysis of the temperature field of heating the square box and intermediate fillers 5 (Figure 7) between the guide nozzle 6 and the square box 1 was carried out.

The first stage of modeling the object under study is carried out in the Compas-3D CAD system, with further import of geometries into the ANSYS environment (Figure 8).

Let us consider the first case of calculating heat transfer without filler, according to the interfaces 6 "square box - guide nozzle" (Figure 7). The temperature during the passage of hot gas through the guide nozzle reaches 450°C. According to the results of the calculation of the temperature distribution field (Figure 9a), it can be seen that the maximum heating point of 250°C is reached in interfaces 6 and decreases evenly to a temperature of 49°C, the average heating temperature of the TGM surface to be contacted is 112°C.

The second option (Figure 9b), unlike the first, has a foil-filled filler. According to the results of the calculation, it can be seen that the temperature distribution over the box surface has an alternating heating temperature of 137-179°C, the average heating temperature is reached up to 158°C.

In the third variant (Figure 9c), quartz fine-grained sand (0.2…0.5 mm) was used as a filler. According to the calculation results, it can be concluded that the distribution is uniform and the average value of the heating temperature of the square box is 250°C. Quartz sand has accumulative properties (Thermoelectric modules and devices based on them, 2004), in the process of heating the sand accumulates heat, and then gives it to the surface of the TGM for a long time.

Thus, the model with quartz filler has the best properties, since according to the results of the calculation, the temperature of heating of the TGM surface is uniform, which further increases the output power of the generated electricity from the modules.

Based on theoretical studies, an experimental model was developed and assembled on a ThermMix-15D heater with a TEG filled with quartz fine sand (Figure 10). A new electronic heater control unit was also assembled with an improved operation algorithm taking into account the operation of the TEG.

To confirm the theoretical studies of the temperature field of TEG heating in the ANSYS software environment, chromel-copel thermocouples were installed on the object under study according to the arrangement scheme shown in Figure 11.

The experimental data was taken in the course of the study using the Zetlab 210 measuring complex.

Figure 12 shows photographs of experimental studies of advanced GHG with reduced battery power consumption.

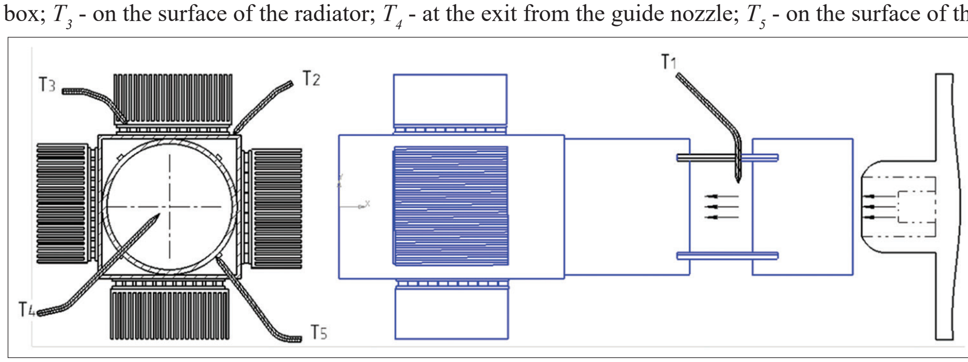
Figure 10: Experimental model GHG

3. RESULTS AND DISCUSSION

Experimental studies of GHG were conducted at the department "automobiles and machine-tractor complexes" of the Bashkir State Agrarian University using quartz fine-grained sand as an intermediate filler, which confirmed theoretical studies. In the course of experimental studies, according to the temperature conditions of operation of the object under study (Table 4), it was found that at an ambient air temperature of −19°C the maximum possible temperature difference T2-T3 stabilizes at 13…14 min of the heater operation, while the square box heating temperature of the cross section is 148°C at the heating temperature of the guide nozzle 458°C.

At this temperature mode, the readings of the generated electricity from the TEG (Figure 13) were taken during the operation of the

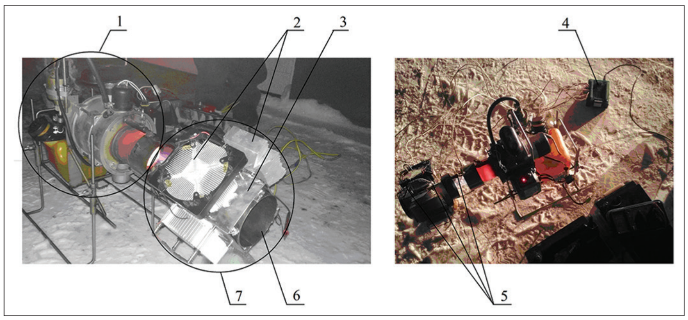
Figure 11: Placement of thermocouples on the surface of the object under study: T_1 - at the exit from the generator of hot gases; T_2 - on the surface of the square box; T_3 - on the surface of the radiator; T_4 - at the exit from the guide nozzle; T_5 - on the surface of the guide nozzle



ThermMix-15D heater. The graph shows that during the creation of the maximum allowable temperature difference, uneven growth of voltage readings is visible, this is due to the influence of wind effects, which increases the coefficient of convective heat transfer from the finned radiators to the environment. The maximum voltage value is 9.07 V, with the temperature difference on the cold and hot side of the TGM 80.8°C, and the critical voltage value is 6 V.

This modernization of the GHG allowed to reduce the heater's electricity consumption, which led to a decrease in battery discharge.

Figure 12: Pictures of experimental studies of GHG: 1 - heater; 2 - coolers; 3 - square tube; 4 - Zetlab; 5 - thermocouples; 6 - guide nozzle; 7 - TEG



4. CONCLUSIONS

In the course of this work, the following results were obtained:

- An algorithm for the operation of a hot gas generator with a system for converting thermal energy of losses from a guide nozzle into an electric one is proposed.
- A method for the redistribution of the generated electrical energy from TEG to the air compressor of the GHG was developed.
- A solid-state three-dimensional model of an improved hot gas generator and a model of the structures of the "nozzle-filler-box-square-section-cooling radiator" guide system was built.
- The hot gas generator with TEG was improved and assembled;
- Experimental studies of the generated electrical energy with TEG in the process of the heater operation were carried out.

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Figure 13: Graph of TEG voltage readings from heater operation time

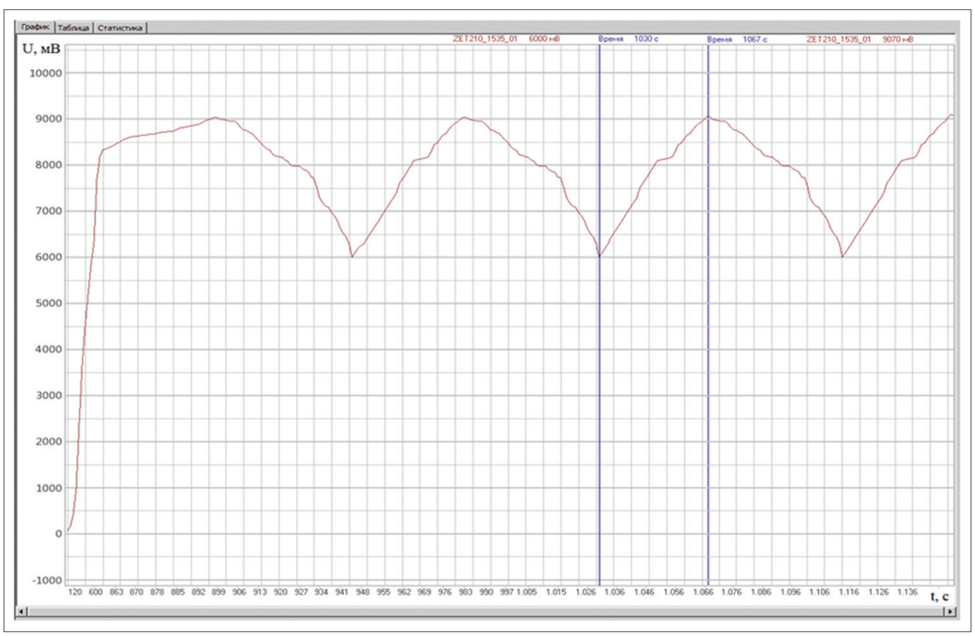

Table 4: The results of experimental studies of GHG

Operation time of GHG, min	U,B	T_1,°C	T_2,°C	T_3,°C	T_4,°C	T_5,°C	T_{env},°C	V_{wind},м/c	T_2-T_3,°C	U_i-U_{i-1}
10	7.33	712.00	110.10	64.20	509.00	451.40	−19.00	2.40	45.90	0.50
11	7.57		122.70	67.80		458.20			54.90	0.24
12	8.69		139.20	68.30		458.10			70.90	1.12
13	8.94		147.30	68.40		458.30			78.90	0.25
14	9.07		148.80	68.00		457.10			80.80	0.13

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