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Creating an Environmentally Friendly Propane-Powered Gas Turbine Device

Marlen SHALAMBERIDZE[1], Tamar TSKIPURISHVILI[2]*, Giorgi LOBZHANIDZE[3], Lali ZIVZIVADZE[4]

[1–4]*Akaki Tsereteli State University, 59 Tamar Mepe Street, 4600, Kutaisi, Georgia*

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***Abstract* – A hypothesis is proposed on the possibility of creating a gas turbine electric power-generating device working on fuel gas, and propane, and the results of preliminary research experiments are given to evaluate the validity of this hypothesis. The criteria for mixing fuel gas-propane with air and assessing the quality of combustion have been identified. In particular, the colour of the fuel gas combustion and the force acting on the gas turbine blade of the flue gas flow injected from the combustion chamber. At atmospheric pressure, without heating, the optimal content of the mixture of propane and air, and the force acting on the gas turbine blade have been experimentally determined. An experimental relationship between the force acting on the gas turbine blade and the diameter of the combustion chamber has been obtained, by which it is possible to determine the diameter and height required for the chamber of a specific capacity according to the force acting on the gas turbine blade. A simplified method is proposed to determine the possible amount of electrical energy depending on the force acting on the gas turbine blade. It has been shown that when burning an optimal mixture of propane with air, two chambers with a capacity of 0.1 m^3 can ensure the nominal operation mode of a 1.5 kW capacity electric generator.**

***Keywords* – Combustion chamber; electric generator; flue gas; thermal electric energy; thermal energy.**

1. INTRODUCTION

Many new inventions and research projects in the field of the thermal power industry are devoted to the development of gas turbine appliances burning gaseous fuels [1]. In order to improve the efficiency of the gas turbine, the flue gas is used for domestic purposes [2]. Also, efficiency is improved by heating up the flue gas to obtain electricity through its reuse [3]. The abundance of similar scientific papers indicates that the already-created gas turbine units cannot meet the requirements imposed on them. Their common disadvantages are low efficiency, complicated design and manufacturing technology, as well as the complexity of the control system used [4] There is some evidence in the scientific literature regarding the fact that to increase efficiency, natural gas is used simultaneously with liquid diesel fuel [5], and electrical energy is obtained using water energy and natural gas [6]. To improve processes and technologies,

* Corresponding author.
E-mail address: Tamar.tskipurishvili@atsu.edu.ge

modelling techniques and simulations of processes are also applied [7]. The studies of thermodynamic processes are aimed at improving the combustion process [8] or offering an additional alternative source of electricity [9].

We have proposed an electric power-generating gas-turbine device with a simple structural design in the form of a diagram (Fig. 1) comprising a low-pressure compressor 1, combustion chambers 2, gas turbine 3, and an electric generator 4. Moreover, the construction and manufacturing technology of the combustion chambers included in the presented scheme is simple, see Fig. 2. Preliminary studies also suggest that the new original device will have improved efficiency due to the simplification of the design [10] and the use of propane as the primary source [11].

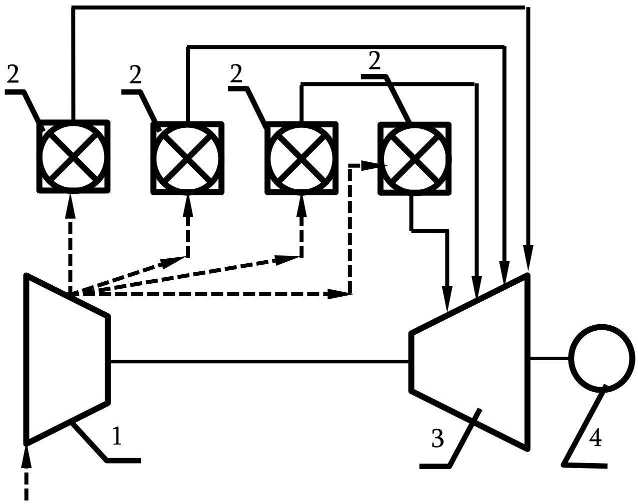

Fig. 1. A scheme of the proposed natural gas-powered gas turbine device. 1 – Compressor; 2 – Combustion chamber; 3 – Gas turbine; 4 – Electric generator.

The creation of the proposed type of gas-turbine electric power-generating devices is based on the hypothesis that we [11] and other authors [12] have derived from preliminary studies that it is possible to model and artificially induce such an unpleasant phenomenon as inflammation and explosion of the natural gas accumulated as a result of leakage in an enclosed space, namely in a residential apartment, which is accompanied by the instant release of large amounts of energy. We also consider it possible to use this energy to produce electricity. Also, the number of gas combustion chambers can be in such a quantity that their total volume is the same as the volume of the gas leakage and accumulation chambers. We also believe that for the presented (Fig. 2) combustion chambers, it is possible, based on research, to determine the required composition of the mixture of fuel gas with air and optimal mixing conditions. According to the hypothesis, we also consider it possible that the flue gas flow generated by the combustion of the mixture in the combustion chambers located around the gas turbine, which will be directed to the gas-turbine blades (Fig. 3), will create a powerful total force (14 daN for two combustion chambers) as the instantaneous explosion flow of the leaked gas mixture would create, and this total force would be able to produce powerful electricity (1320 W). In particular, the proposed calculation methodology shows that 14 daN of force acting on the blade can produce at least 1320 watts of electricity.

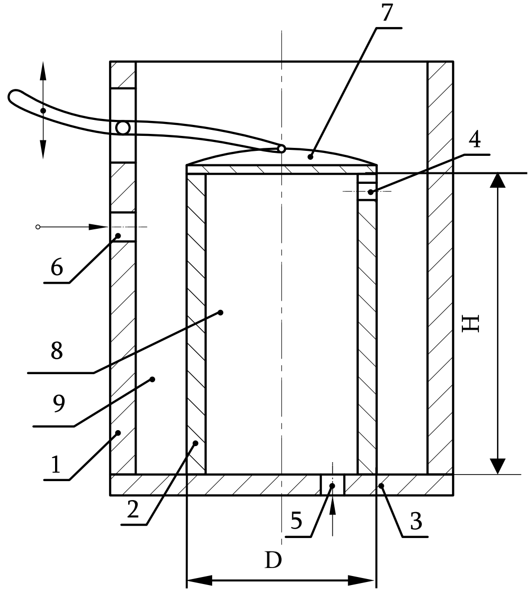

Fig. 2. The combustion chamber design scheme. 1, 2 – The outer and inner walls of the chamber, respectively; 3 – Bottom; 4 – Mixture supply valve; 5 – The valve of the spark supply device for ignition of the mixture; 6 – Water supply valve; 7 – Cover; 8 – Combustion sub-chamber; 9 – Cooling sub-chamber.

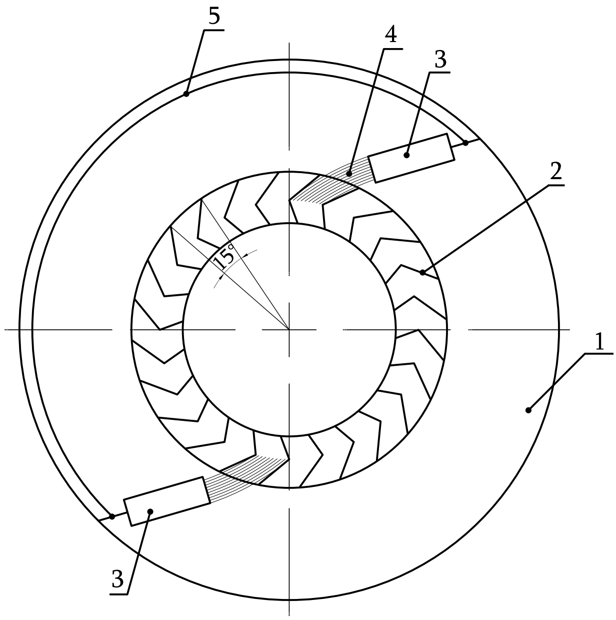

Fig. 3. Schematic diagram of a possible arrangement of combustion chambers on the gas-turbine bladed disc in a working model of a natural gas-fired power generating device. 1 – Disc; 2 – Gas turbine blades; 3 – Combustion chambers; 4 – Flue gas flow; 5 – Connection between the chambers.

2. METHODOLOGY AND EXPERIMENTAL CONDITIONS

According to the hypothesis, the conditions and results of the experiment that we conducted, whose goal was to create a heat-power-generating gas-turbine device running on gaseous fuel, are presented in Table 1. The purpose of the experiment was to determine such an optimal composition of gaseous fuel and air, which would ensure complete combustion of the mixture, the maximum force acting on the air turbine blade, and the immediate release of flue gases from the chamber. At the same time, there would be no CO emission during the combustion process.

During the experiments, it was revealed that the complete combustion of the mixture and the instantaneous release of flue gas from the chamber occurs when the combustion process takes place with a bright blue flame. In this case, there is also no CO emission. Given this factor, the quality of the combustion process in the chamber was determined by the magnitude of the force acting on the air turbine blade and the colour of the mixture's combustion flame - bright blue or yellowish-yellow. With the latter colour, the fuel mixture burned in the chamber for a long time, and the fuel gas remained completely or partially in the chamber.

The experiment was conducted in the combustion chamber of the design shown in Fig. 2, the parameters of which were: (diameter $D = 0.15$ m; height $H = 1.0$ m; and volume $V \approx 0.1$ m^3). In the experiment, due to the long interval between the tests, the combustion chamber did not heat up, which is why no water was supplied to the so-called cooling sub-chamber during the experiment.

In order to reveal the optimal composition of the mixture of propane and air for a combustion chamber of a specific volume and a specific design, the experiment was conducted under atmospheric pressure conditions. During the tests, the air was supplied from the compressor (1, Fig. 1), propane from the gas cylinder, and their mixture was supplied from the combustion chamber 4 (Fig. 2) valve. During the first two tests, the case was considered when fuel gas, propane, was supplied to the combustion chamber from the upper or lower valve, and the case was considered when it was mixed with the air existing in the combustion chamber. However, in both cases, gas ignition from the lower valve could not be ensured. The reason for this was that propane gas, which has a heavier weight than air, covered the resulting spark and isolated it from the air, like argon in aluminium welding [14], [15], and carbon dioxide in automatic and semi-automatic welding [16], and acetylene when welding some high-alloyed steels [17], [18], similarly to argon and carbon dioxides that are used to protect the welding area from the air. The fuel gas was ignited by the sparking device from the upper valve, and the combustion process gradually spread from the top to the bottom. It burned with a bright yellow flame. There was no flue gas escape from the combustion chamber. In all tests, the mixture of fuel gas and air is supplied to the combustion chamber from the upper valve so that its flow hits the wall of the chamber on the opposite side of the valve and is directed towards the bottom, as for better mixing of fuel with air in internal combustion engines: gasoline-powered [19], diesel-powered [20] or with methane in diesel [21]. The chamber was filled with a fuel mixture in approx. 3–5 seconds and ignited using a device installed in the lower valve by spark ignition. We determined the force F_b by means of the so-called wind relay-type transmitter [22] that we made and calibrated piezoceramic transmitters [23]. During the experiments, we controlled the presence of CO in the combustion chamber, and in the flue gas flow released from the chamber, using innovative microprocessor devices created at Georgian Technical University [24].

3. Analysis, Results and Discussion

In the 3rd and 4th tests, the mixture of propane and air contained 5 % or 8 % of propane, respectively. The propane combustion process was instantaneous and complete. The gaseous fuel did not remain in the combustion chamber. The force F_b acting on the gas turbine blade with the flow of blue gaseous fuel discharged from the combustion chamber was $F_b \approx 2.5$ daN and $F_b \approx 7$ daN, respectively. By further increasing the percentage of propane in the gaseous fuel mixture, the force acting on the blade decreases. The colour of gaseous fuel becomes yellow. The combustion process occurs in the combustion chamber for a long time, and after extinguishing, the gaseous fuel partially remains therein. When conducting the last three tests under the same conditions, the mixture of propane and air was additionally preheated up to 70 °C. The optimal percentage of propane in the fuel mixture has increased to 12 %. This also increased the force F_b caused by the flue gas flow on the gas turbine blade up to 10 daN.

TABLE 1. THE CONDITIONS OF THE EXPERIMENT AND THE RESULTS OBTAINED

Test number	**Air%+Propane%**	**The temperature of a gaseous fuel mixture, ˚C**	**The color of the flame of a gaseous fuel mixture**	**The force of combustion flow acting on the blade, daN**	**Note**
1	100 % propane	–	–	–	Did not catch fire
2	100 % propane	–	Yellow	–	Burns in the combustion chamber for a long time
3	98 % + 2 %	–	Blue	≈2	It ignited instantly; the flue gas flow was completely discharged from the chamber
4	95 % + 5 %	–	Blue	≈5	It ignited instantly; the flue gas flow was completely discharged from the chamber
5	92 % + 8 %	–	Blue	≈7	It ignited instantly; the flue gas flow was completely discharged from the chamber
6	85 % + 15 %	–	Yellow, blue around	≈3	The flue gas remained partially in the chamber
7	80 % + 20 %	–	Yellow	≈2	The mixture was burned for a long time in the combustion chamber
8	90 % + 10 %	50 °C	Blue	≈10	The mixture burns instantly; the chamber becomes empty
9	85 % + 15 %	50 °C	Blue	≈10	The mixture burns instantly; the chamber becomes empty
10	80 % + 20 %	50 °C	Yellow	≈3	The mixture was burned for a long time in the combustion chamber

The results of the experiment presented in Table 1 showed that, according to our hypothesis, our own assumption that it is possible to identify the optimal percentage composition of gaseous fuel and air in the combustion chambers shown in Fig. 2 was correct. It is a mixture of 92 % air+8 % propane. At this time, the force acting on the gas turbine blade can be 5 daN.

We propose to check the amount of electrical energy generated by the flue gas flow from the chamber with a capacity of 0.1 m^3 of the presented design. For this, it was necessary to determine the electromagnetic force induced in the electric generator winding according to the well-known law of induction.

$$e = -w\frac{\mathrm{d}\Phi}{\mathrm{d}t} \tag{1}$$

The following scheme is proposed for the approximate determination of the equivalent number of turns w of the generator winding, as well as the rate of change $\frac{\mathrm{d}\Phi}{\mathrm{d}t}$ in the magnetic field flux reduced by the generator excitation winding [25].

We select initially a synchronous generator of estimated capacity, in our case with a capacity of 1 kW, and its specific parameters; depending on the type of winding, the number of nominal revolutions, and the nature of the load, we determine the main values necessary for the calculation. In particular, to simplify the approximate calculation, the magnitude of the electromagnetic force induced in the winding by induction is taken to be only the electromagnetic force e placed along the length l of the winding electrical conductor.

Taking into account this assumption and also considering that, according to Ohm's law, during idle time ($I = 0$), depending on the potential difference between the ends A and C of the length l of the winding, the electromagnetic force induced in this conductor can be determined (Fig. 4).

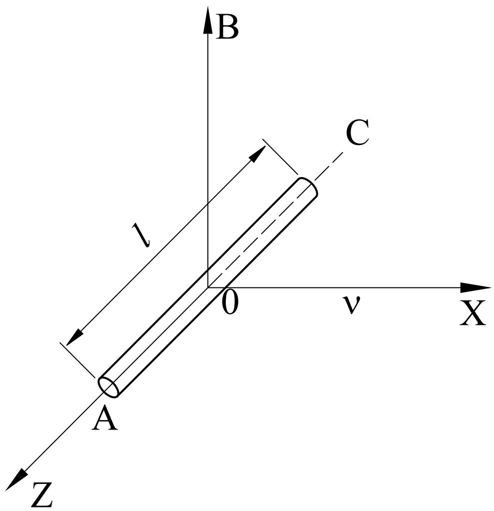

Fig. 4. The directions of through magnetic induction $\vec{B}$ of the electric conductor l and the speed of its movement $\vec{V}$.

$$e = -(\varphi_A - \varphi_C) \quad (2)$$

This permits the calculation of the electromagnetic force e induced in the conductor of the winding with a length l and the known values of the magnetic induction B and its movement at speed υ by the expression [26]:

$$e = -B \cdot \upsilon \cdot \ell \quad (3)$$

And, the magnitude of the electromagnetic force of the rotor of the generator operating in nominal mode, in the case of the known load current I, can be calculated by the formula: [27]

$$F_{em} = B \cdot I \cdot e_w \quad (4)$$

The magnetic conductor of the previously selected generator is made of electrotechnical steel э330, so the maximum value of the magnetic induction B = 1.2 T is allowed for it. The width of its magnetic conductor is b = 30.3, therefore, according to the accepted assumption, the length of the winding active conductor is l = 0.3 m.

The selected generator is a double-pole unit and the frequency of the generated electrical energy is 50 Hz, therefore l = 0.3 m, the speed of movement of the winding conductor in the magnetic field V = 15.7 m/s.

The selected generator has the so-called wave winding and its magnetic conductor has Z = 20 grooves; one rod with a length of l = 0.3 m is placed in each groove.

According to the parameters of the generator, the electromagnetic force induced in a single conductor of the winding is calculated by the expression (5):

$$e = 1.2 \cdot 0.3 \cdot 15.7 = 5.33 \text{ V.} \quad (5)$$

Then the total electromagnetic force induced in the winding is:

$$e_\Sigma = e \cdot \mathcal{Z} = 5.66 \cdot 20 \cdot 110 \text{ V} . \quad (6)$$

Considering that it is desirable that the current passing through the excitation winding does not exceed 12 A, the sum of γ_{int} and γ_{ex} external resistances inside the generator was selected:

$$I = \frac{e}{\gamma_{int} + \gamma_{ex}} = \frac{5.66}{0.5} \approx 12 \text{ A}, \quad (7)$$

then the braking force acting on each winding conductor is according to the image according to the expression (4) is as follows:

$$F_{em} = 1.2 \cdot 12 \cdot 0.3 = 4.32 \text{ N.} \quad (8)$$

And the total electromagnetic force acting on the armature winding is equal to:

$$F_{emw} = F_{em} \cdot Z = 4.32 \cdot 20 \approx 86.4 \text{ N,} \quad (9)$$

since $F_{mech} = 2F_b = 2 \cdot 5 = 10$ daN, then $F_{mech} > F_{emw}$.

According to the experiment, the power capacity developed by the electric generator is:

$$R_{eg} = e_\Sigma \cdot I = 110 \cdot 12 = 1320 \text{ W} . \quad (10)$$

Mechanical power capacity obtained by combustion of natural gas mixture with air in the combustion chamber:

$$P_{\text{mech}} = F_{\text{mech}} \cdot V_{\text{w}} = 100 \cdot 15.7 = 1570 \text{ W}. \tag{11}$$

That is, according to the calculation:

$$P_{\text{mech}} > P_{\text{em}}. \tag{12}$$

The obtained inequalities (9) and (12) indicate that with two combustion chambers with a capacity of 0.1 m^3 (Fig. 4) of the design represented in Fig. 2, it is possible to generate at least 1570 W of electrical energy.

Considering that the gas-turbine device comprises 14 combustion chambers of the same design with a capacity of 0.1 m^3 each, the electrical energy generated by it will be about 10 kW. The gas-turbine device of such a capacity can be used in settlements inaccessible to electrical networks, as well as at tourist sites, as an environmentally friendly source of electrical energy: solar energy [28], [29], wind energy [30], water energy [31], instead of the small-capacity to transfer equipment working on the internal combustion engines. The reason for this is that, as a result of our research, it has been established that in the combustion chamber of the proposed design, there is CO emission during the complete combustion of air and natural gas with optimal content. During each filling process of the combustion chamber, the process of perfect mixing of fuel gas with air and the optimal composition are automatically controlled.

With the following studies, the data of which are presented in Table 2, the experimental expression obtained for the determination of the geometric parameters, diameter, and height of the combustion chamber is proposed.

TABLE 2. THE RELATIONSHIP BETWEEN THE FORCE F_{mech} ACTING ON THE GAS TURBINE BLADE AND THE DIAMETER OF THE COMBUSTION CHAMBER

Test number	**Chamber D; diameter, Y, cm**	**Force F_{mech} acting on the blade, X, daN**	**Chamber capacity, m^3**	**Y^2**	**X^2**	**XY**
1	20.0	7.0	0.1	400	49	140
2	15.0	8.8	0.1	225	77.44	132.0
3	10.0	10	0.1	100	100	1.00
4	7.5	11.5	0.1	56.25	132.25	86.25
5	5.0	12.7	0.1	25	161.29	63.5
∑	57.5	50.0		806.25	519.98	521.75

It represents the relationship between the diameter (Y) and the force (X) acting on the perpendicular plane of the flue gas ejected from the chamber for a 0.1 m^3 capacity combustion chamber.

The relationship is generally found as follows: [32]

$$Y = \alpha + \beta(X). \tag{13}$$

Its coefficients [33]:

$$\beta = \frac{M\Sigma X_i Y_i - \Sigma Y_i X_i}{m\Sigma X_i^2 - (\Sigma X_i)^2} = 2.67 \cdot \tag{14}$$

Correlation relationship coefficient:

$$\gamma = \beta \sqrt{\frac{m\Sigma X_i^2 - (\Sigma X_i)^2_,}{m\Sigma Y_i - (\Sigma Y_i)^2_,}} = 0.97 \cdot \tag{15}$$

Absolute term of the expression (13):

$$\alpha = \frac{\Sigma X_i - \beta \Sigma Y_i}{m} = 38.4 \cdot \tag{16}$$

Finally, Eq. (13) has the form:

$$Y = 38.4 - 2.67\,X \tag{17}$$

In every expression, $m = 5$, while $i = 1.2\ldots5$.

The high correlation relationship coefficient $r = 0.97$ in the expression (13) indicates that, with a high probability, in the case of the same capacities, when the diameter of the combustion chambers is reduced and the height is increased accordingly, the force F_b acting on the gas turbine blade of the flow ejected from the chamber increases.

The chamber of the device comprises the gas combustion and cooling subchambers. Water is supplied to the combustion subchamber, where water vapour is formed due to the heat released during gas combustion. At the end of the combustion process, the chamber is covered with a lid, and the generated flue gas flow, together with the steam mixed therein, collides with the blade of the gas turbine, causing the gas turbine to rotate. When the flue gas is mixed with water vapour, the carbon dioxide released as a result of combustion is conditioned together with water vapour, as a result of which the spread of carbon dioxide in the atmosphere is significantly reduced. Due to this, the electric energy-generating gas turbine device that we created is more environmentally friendly than similar electric energy-generating devices with internal combustion engines, in which the same natural gas is used as the primary source.

In the future, we consider it necessary to investigate to what extent the force acting on the air turbine blade will increase when burning other gases (for example methane and acetylene) in the same combustion chamber, and simultaneously, to study environmental safety.

3.1. The Justification for the Environmental Friendliness of the Proposed Device

As is known, at atmospheric pressure, after hydrogen chloride, carbon dioxide is the most water-soluble. For example, 173 cm^3 of carbon dioxide is dissolved in 100 mL of water. It is also known that the amount of carbon dioxide dissolved in water increases under constant temperature conditions, that is, in proportion to the flue gas flow [34].

In the proposed combustion chamber, the high-pressure flue gas (carbon dioxide) released during combustion mixes with the surrounding water vapour, and the separated flow is directed towards the air turbine blades, turning them and the generator rotor placed on its axis and generating electrical energy. During this process, the carbon dioxide mixed with water vapour dissolves in it and pours out from the blades in the form of an aqueous solution. So, in the process of generating electrical energy with the proposed gas turbine device, carbon dioxide practically does not spread in the atmosphere or spreads in a limited amount.

In the future, it is planned to investigate the combustion process of natural gas as a primary source of electricity in the new design combustion chamber occurring in direct contact with water. In this case, the high-pressure flue gas produced during the combustion of natural gas is directed to the blades of the air turbine. It is expected that at this time, the possibility of the formation of an aqueous solution of carbon dioxide will be further increased.

Given also that when burning natural gas mixture with air in the optimal proportional composition, due to the perfect combustion process, the emission of CO from the combustion gas is practically excluded. Then it is clear that the generation of electrical energy with a gas turbine device without polluting the environment with carbon dioxide is ensured [24].

4. Conclusions

Based on the data previously obtained from studies and calculations, we can conclude that:

1. A powerful explosion caused by a propane leak, accumulation, and ignition in a residential apartment can be simulated and artificially induced. Also, it is possible to use the large amount of energy emitted at this time, in particular, to obtain electrical energy, and it is possible to create an original device for such a purpose.
2. A simple design of the combustion chamber of a gas turbine device was created, for which the optimal content of the mixture of propane and air was experimentally selected.
3. An indicator of the quality of mixing and burning of the mixture of propane and air has been identified, which is represented by the bright blue colour of the flame formed during the combustion process, while the magnitude of the force acting on the gas-turbine blade is a quantitative assessment criterion.
4. An experimental method for determining the geometrical parameters (diameter, height) of the combustion chamber according to the force acting on the blade has been developed for the proposed gas turbine devices.
5. The proposed gas-turbine device will be particularly interesting for the state and private energy companies to provide electricity to remote settlements inaccessible to electrical networks, tourist sites, and ships during their stay in the ports.

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