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Original Study Article

The individual tubular low-toxic combustion chamber

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ABSTRACT

BACKGROUND: intensive works in improvement and development of microturbine power plants for energy and transport continues worldwide. These works are still relevant due to near-to-zero emissions of microturbines, as well as due to the fact that microturbines efficiency can be increased up to 50% and above, which opens the potential to compete with well-known power plants in the foreseeable future, including in terms of efficiency. Therefore, the work on the study of a low-toxic combustion chamber for a microturbine seems relevant as well.

AIM: Computational and experimental study of an individual tubular low-toxic combustion chamber of a 50 kW microturbine with an increase in pressure at the inlet to the chamber.

METHODS: The description of the experimental facility for combustion chamber testing and the results of its experimental study are given. A sufficient convergence of the experimentally obtained parameters of the combustion chamber with the parameters obtained from the simulation modeling of flow and combustion in the combustion chamber was obtained.

RESULTS: In the course of the calculated and full-scale studies, hydraulic losses, nitrogen oxide emissions, and temperature unevenness at the outlet of the combustion chamber with increasing air pressure at its inlet were determined.

CONCLUSIONS: The calculated study showed a significant effect of an increase in air pressure from 3 to 3.5 bar at the entrance to the combustion chamber on its main parameters. Thus, hydraulic losses have more than doubled and nitrogen oxide emissions have increased almost 1.3 times. The conducted experimental study of the combustion chamber generally confirmed the results of mathematical modeling and thereby tested the computational model used. Thus, the discrepancy in the experimentally and computationally obtained values of relative pressure losses in the combustion chamber does not exceed 15%, and in emissions of nitrogen oxides 7%.

Keywords: microturbine; microturbine combustion chamber; low-toxic combustion chamber; tubular individual direct-flow low-toxic combustion chamber.

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Оригинальное исследование

Трубчатая индивидуальная малотоксичная камера сгорания

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АННОТАЦИЯ

Обоснование. В мире продолжаются интенсивные работы по совершенствованию и созданию микротурбинных энергоустановок для энергетики и транспорта. Эти работы продолжают оставаться актуальными в силу экологической чистоты микротурбин, а также в связи с тем, что микротурбины обладают потенциалом роста КПД до 50% и выше, что обеспечивает им возможность конкуренции с известными энергоустановками в обозримом будущем, в том числе, по эффективности. В силу вышесказанного работа по исследованию малотоксичной камеры сгорания для микротурбины также представляется актуальной.

Цель работы — расчетно-экспериментальное исследование индивидуальной трубчатой малотоксичной камеры сгорания микротурбины мощностью 50 кВт при повышении давления на входе в камеру.

Материалы и методы. Приводится описание объекта исследования — малотоксичной индивидуальной трубчатой камеры сгорания, экспериментальной установки для ее испытаний и результаты расчено-экспериментального исследования.

Результаты. В ходе проведённого расчетного и натурного исследований были определены гидравлические потери, величины выбросов оксидов азота, и температурная неравномерность на выходе камеры сгорания при повышении давления воздуха на ее входе.

Заключение. Расчетное исследование показало существенное влияние повышения давления воздуха с 3 до 3,5 бар на входе в камеру сгорания на ее основные параметры. Так более чем в два раза увеличились гидравлические потери и почти в 1,3 раза выбросы окислов азота. Проведенное экспериментальное исследование камеры сгорания в целом подтвердило результаты математического моделирования и тем самым аппробировало используемую расчетную модель. Так расхождение по экспериментально и расчетно полученным значениям относительных потерь давления в камере сгорания не превышает 15%, а по выбросам окислов азота 7%.

Ключевые слова: микротурбина; камера сгорания микротурбины; малотоксичная камера сгорания; трубчатая индивидуальная прямоточная малотоксичная камера сгорания.

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BACKGROUND

Intensive work to create and improve microturbine power plants for energy and transport continues worldwide [1, 2, 3, 4, 5]. These works are important due to the environmental friendliness of microturbines, as well as because microturbine efficiency can be increased up to 50% or more, which gives them the potential to compete with well-known power plants in the foreseeable future, including in terms of efficiency. Therefore, work on the study of a low-toxicity combustion chamber for a microturbine seems relevant as well.

AIMS AND OBJECTIVES

From 2019 to 2022 at the Central Scientific Research Automobile and Automotive Engines Institute (NAMI) in Moscow, Russia, a tubular individual direct-flow low-toxicity combustion chamber (CC) was used in the design of a 50-kW regenerative microturbine [6]. It implements the concept of rich–lean combustion with rapid mixing (RQL; Rich burn, Quick mix, Lean burn) (Fig. 1) [7, 8].

The CC was designed to high-level standards. The temperature fields obtained through mathematical modeling of flow and combustion in the CC are presented in Fig. 2, and the main parameters are presented in Table 1 [16]. The CC was designed for an inlet air pressure of 3 bar, but during modifications to the NAMI microturbine the inlet air pressure was increased to 3.5 bar. The impact of this discrepancy on the CC performance requires further investigation.

Table 1. Main properties of the low-toxic combustion chamber of the microturbine with the power of 50 kW

Таблица 1. Основные показатели малотоксичной камеры сгорания микротурбины 50 кВт

Nitrogen oxide emissions, ppm	Relative pressure loss, %
7,8	1,2

This work is a computational and experimental study of the developed CC with the inlet air pressure increased from 3–3.5 bar.

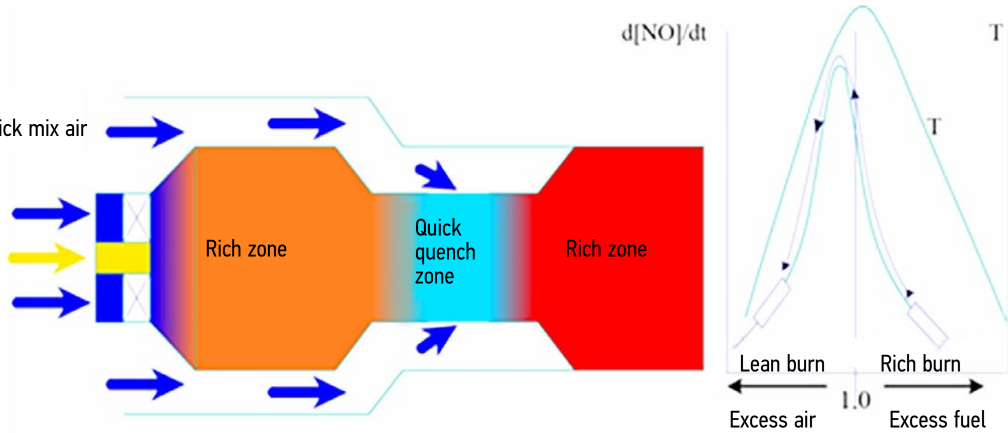

Fig. 1. The individual tubular direct-flow low-toxic combustion chamber with rich-lean burn [5].
Рис. 1. Трубчатая, индивидуальная, прямоточная малотоксичная камеры сгорания с обогащено-обедненным сгоранием [5].

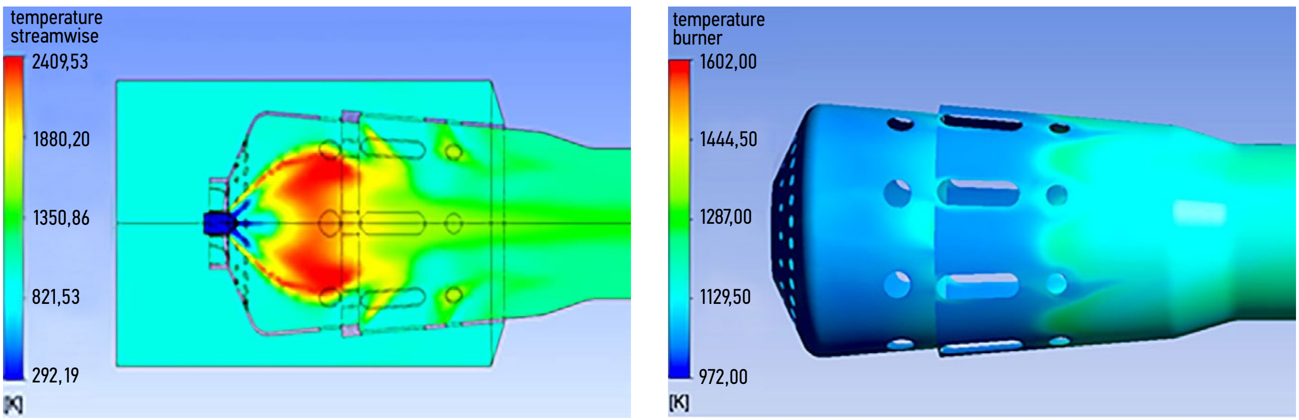

Fig. 2. Temperature fields of flame (on the left) and the flame tube of the combustion chamber.
Рис. 2. Поля температур пламени (слева) и стенок жаровой трубы (справа) камеры сгорания.

STUDY OBJECT

To solve the problem, mathematical modeling of the flow and combustion processes in the CC and an experimental study of the CC with an inlet air pressure of 3.5 bar were performed. Mathematical modeling was performed similarly to the previously reported modeling of the CC at an inlet pressure of 3 bar [6]. In particular, the Mentor SST model [9, 10] was used to simulate the turbulent flow regime in the chamber, and the combustion simulation was performed based on an ensemble of one-dimensional laminar flamelets [11–13].

Figure 3 presents CC liner with fuel nozzle and swirler. Figure 4 presents a schematic diagram of the test rig used to conduct an experimental study of the CC.

Fig. 3. The flame tube with an injector and a swirler of the individual tubular combustion chamber.
Рис. 3. Жаровая труба с форсункой и завихрителем трубчатой, индивидуальной камеры сгорания.

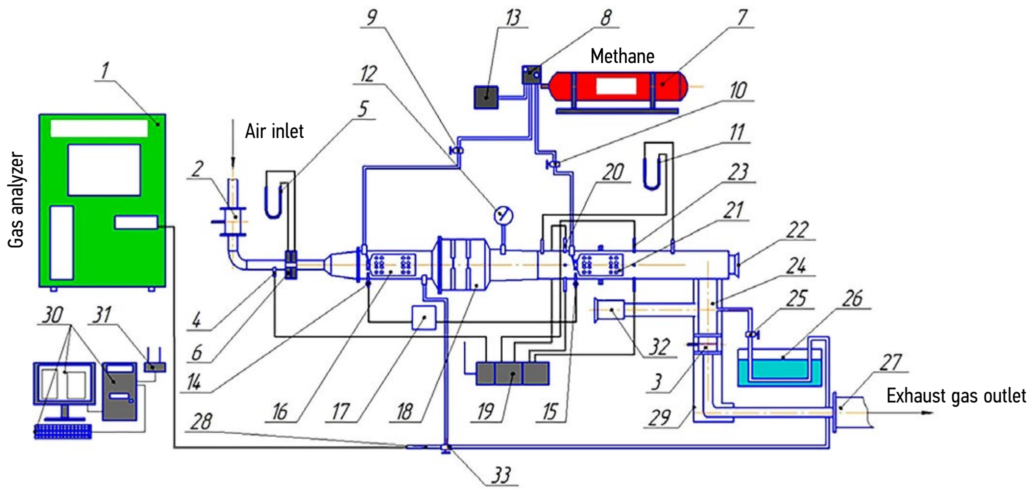

Fig. 4. Principal diagram of a test rig for combustion chamber testing: *1* — a gas-analyzer; *2, 3* — water-gate valve; *4* — the № 1 thermal couple; *5, 11* — differential pressure gauges; *6* — a measuring orifice; *7* — a gas cylinder; *8* — a gas-pressure reducer; *9* — a valve of gas supply to the №1 combustion chamber; *10* — a valve of gas supply to the № 2 combustion chamber; *12* — a pressure gauge; *13* — an electrical heater of the gas-pressure reducer; *14* — an ignition spark of the № 1 combustion chamber; *15* — an ignition spark of the № 2 combustion chamber; *16* — the № 1 combustion chamber; *17* — the combustion chamber ignition control unit; *18* — a receiver for flow temperature equalization in front of the № 1 combustion chamber; *19* — a control unit for transferring data of thermal couples; *20* — a thermal couple at the № 1 combustion chamber inlet; *21* — the studied № 2 combustion chamber; *22* — a viewpoint; *23* — a thermal couple at the № 1 combustion chamber outlet; *24* — an exhaust pipe; *25* — a valve of the № 2 combustion chamber exhaust gas offtake; *26* — a water reservoir; *27* — an exhaust pipe; *28* — a sampling probe of the gas-analyzer; *29* — an exhaust pipe cooling screen; *30* — a personal computer; *31* — a Wi-Fi- router for transferring data of thermal couples; *32* — a compressor for air supply for exhaust pipe cooling; *33* — the № 1 combustion chamber exhaust pipe for NO_x measurement.
Рис. 4. Принципиальная схема стенда для испытаний камеры сгорания: *1* — газоанализатор; *2, 3* — задвижки Лудло; *4* — термопара № 1; *5, 11* — дифманометры; *6* — мерная шайба; *7* — газовый баллон; *8* — редуктор газовый; *9* — кран подачи газа к КС № 1; *10* — кран подачи газа к КС № 2; *12* — манометр давления газа; *13* — электроподогреватель газового редуктора; *14* — свеча зажигания КС № 1; *15* — свеча зажигания КС № 2; *16* — КС № 1; *17* — блок управления зажиганием КС; *18* — ресивер для выравнивания температур потока перед КС № 1; *19* — электронный блок приема передачи показаний термопар; *20* — термопара на входе в КС № 2; *21* — исследуемая КС № 2; *22* — смотровое окно; *23* — термопара на выходе из КС № 2; *24* — труба отвода выходного газа; *25* — кран трубки отбора выходного газа КС № 2; *26* — резервуар с водой; *27* — труба отвода выходных газов в атмосферу; *28* — пробоотборный зонд газоанализатора; *29* — экран охлаждения трубы отвода газов; *30* — персональный компьютер; *31* — Wi-Fi устройство для приема/передачи показаний термопар; *32* — компрессор подачи воздуха для охлаждения контура выхлопной трубы; *33* — трубка отвода газа от КС № 1 для замера NO_x.

The compressed air is supplied to the rig from a screw compressor. The air in front of the CC (No. 2) is heated by an auxiliary CC (No. 1). A mixing device is installed between the CCs to level the temperature field downstream of the auxiliary CC (in front of the CC under study). The fuel (methane) is supplied to the CCs from a gas cylinder (7) through a reducer (8) with external heating of the supply tube by an electric heater (13). The pipelines downstream of the CC are cooled by atmospheric air. The gas outlet tubes for measuring nitrogen oxides concentrations are water cooled. Visual observation of the fuel combustion process in CCs No. 1 and No. 2 is performed through a viewport (22).

The pressure at the CC inlet and outlet, as well as the air flow required for testing, were set using water-gate valves.

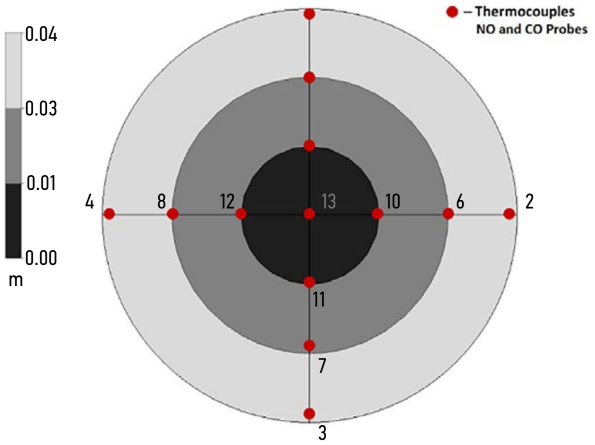

Fig. 5. Diagram of thermal couples location at the outlet of the studied combustion chamber.
Рис. 5. Схемы расположения термопар на выходе исследуемой камеры сгорания.

The required temperature in front of the test CC was set by adjusting the fuel supply to the auxiliary CC (No. 1).

During testing, the following parameters are measured on the test rig:

- pressure, temperature field, and nitrogen oxide content at the inlet to CC No. 1;
- pressure, temperature field, and nitrogen oxide content at the outlet of CC No. 2;
- pressure drop across CC No. 2; and
- air flow, pressure, and temperature at the inlet to CC No. 1.

The layout of thermocouples at the outlet of the tested CC No. 2 is presented in Fig. 5.

Sensors and instruments used in the experiments included the following:

- Chromel/Alumel thermocouples (Type K), Thermo Sensor GmbH T-010;
- pressure gauge A-Flow series G30 pressure gauge, A-Flow series G64 differential pressure gauge; and
- Testo 350 gas analyzer.

The following equipment was used to record and process signals received from the thermocouples:

- NIcDAQ-9188 data acquisition board with 9,213 modules designed to work with the thermocouples;
- MOXA Airworks AWK-3121 wi-fi router, connected to the data collection board for a wireless connection with a computer;
- D-Link DIR-300 wi-fi router, connected to a computer to create a wireless connection with the data acquisition board;
- a personal computer with the LabView program installed and drivers connecting National Instruments equipment with the LabView program.

Figure 6 is a photograph of the experimental setup.

Experimental CC studies were conducted in

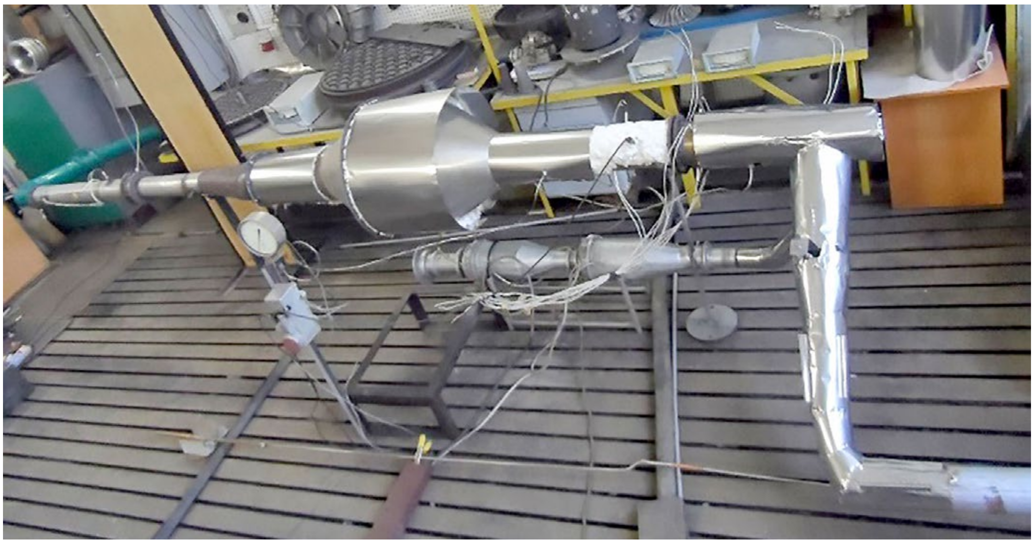

Fig. 6. The experimental facility for combustion chamber testing.
Рис. 6. Экспериментальная установка для испытаний камеры сгорания.

a mode corresponding to the nominal operating mode of the microturbine. In this mode, the pressure of the flow at the CC inlet is 3.45 bar, its temperature is 704°C, and its velocity is 0.415 kg/s.

PROCESSING THE TEST RESULTS

The following parameters were calculated.

Mass flow:

$$G = F \cdot \alpha_{\text{flow}} \cdot \sqrt{2 \cdot \rho \cdot \Delta P},$$

where F is the cross-sectional area of the orifice meter; α_{flow} is the flow coefficient; ρ is the working fluid density; and ΔP is the pressure drop across the meter.

Pressure loss in the chamber, %:

$$\sigma = \frac{\left(\Delta P^*\right)}{\left(P_{\text{in}}^{\ *}\right)},$$

where ΔP^* is the total pressure loss in the combustion chamber (CC) and $\Delta P_{\text{in}}^{\ *}$ is the total air pressure at the inlet to the combustion chamber.

Emissions of nitrogen oxides in the CC under study (No. 2) were determined as the difference in gas analyzer readings at its outlet and inlet.

Temperature unevenness is determined by the radial diagram of the relative average excess temperatures:

$$\theta_{iav} = \frac{\left(T_{giav} - T_c\right)}{\left(T_g - T_c\right)},$$

where θ_{iav} is the relative average excess gas temperature at the i^{th} radius of the CC outlet section; T_{giav} is average temperature at i^{th} radius; T_g is average gas temperature at the CC outlet; and T_c is the air temperature at the CC inlet.

In addition, an important indicator to ensure the operation of the turbine nozzle blades is the radial diagram of the maximum relative excess gas temperatures at the CC outlet, which is defined as:

$$\theta_{i\max} = \frac{\left(T_{gi\,max} - T_c\right)}{\left(T_g - T_c\right)},$$

where $\theta_{i\max}$ is the maximum relative excess gas temperature at the i^{th} radius of the CC outlet section and $T_{gi\,max}$ is the maximum value of the gas temperature at the i^{th} radius вof the CC outlet section.

Table 2 presents the measurement results, including the measured temperatures at the points indicated in Fig. 5. The modeled temperature unevenness was calculated using Eq, X for the relative excess temperature for four relative radii in accordance with the layout of the thermocouples for the test chamber. The experimental temperature unevenness was calculated using 30 relative radii at the CC outlet.

Figure 7 presents a comparison of temperature unevenness obtained by modeling and through experimental measurements. The modeled temperature unevenness is in good qualitative and quantitative agreement with the measurement data. The discrepancies between experimental and modeled values do not exceed 10%.

Hydraulic losses, nitrogen oxide emissions, and temperature unevenness at the CC outlet were determined during the tests.

Table 3 lists the main parameters of the CC layout, obtained through testing in the nominal mode (Ne0)

Table 2. Measurement results
Таблица 2. Результаты измерений

Measured parameter	Result
Temperature TK1, C	975
Temperature TK2, C	950
Temperature TK3, C	943
Temperature TK4, C	937
Temperature TK5, C	915
Temperature TK6, C	911
Temperature TK7, C	906
Temperature TK8, C	911
Temperature TK9, C	938
Temperature TK10, C	936
Temperature TK11, C	970
Temperature TK12, C	941
Temperature TK13, C	1019
Nitrogen oxides at the gas sampling point at the CC inlet, ppm	41,5
Nitrogen oxides at the gas sampling point at the CC outlet, ppm	52
Pressure drop between the combustion chamber inlet and outlet, Pa	5865
Gas consumption, kg/s	0,412
Ambient air temperature in the room, K	299
Relative air humidity, %	62
Atmospheric pressure, mm Hg	632
Total air pressure at inlet, Pa	351 065
Air temperature at the inlet to combustion chamber No. 2, K	1215

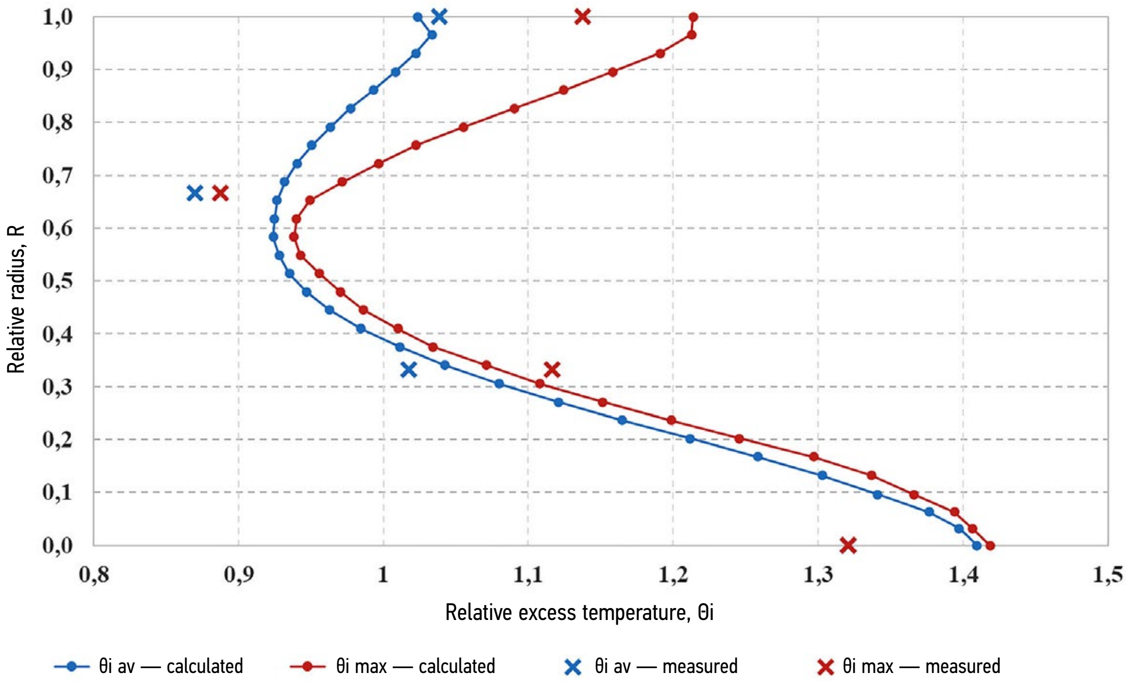

Fig. 7. Calculated and experimental curves of temperature inequality.
Рис. 7. Расчётные и экспериментальные профили температурной неравномерности.

of microturbine operation, as well as by mathematical modeling of flow and combustion in the CC.

According to Table 3, the experimental and modeled parameter values of the CC are quite close.

A comparison of flow and combustion parameter calculation results in a CC with an inlet pressure of 3 bar (Table 1) and in a CC with an inlet pressure of 3.5 bar (Table 3) indicates the major influence of increasing inlet air pressure on the parameters. According to the tables, hydraulic losses more than doubled, and emissions of nitrogen oxides increased by almost 1.3 times.

In addition to the obtained CC parameters, the CC was determined to be fully operational. The combustion of the air–fuel mixture without the flame touching the flame tube walls was visually recorded. A visual inspection of the CC flame tube after the tests did not reveal any defects, traces of oxidation, or other damage and, as a result, confirmed the absence of local overheating of the flame tube and overall operability of the developed CC.

CONCLUSIONS

A computational study revealed the significant effect of increasing air pressure from 3–3.5 bar at the combustion chamber inlet on the main CC parameters. Thus, hydraulic losses more than doubled, and emissions of nitrogen oxides increased by almost 1.3 times.

The experimental study confirmed the results of mathematical modeling and thereby validated the calculation model. Thus, the discrepancies between the experimental and modeled values of relative pressure losses in the CC do not exceed 15%, and for nitrogen oxide emissions, not more than 7%. The experimentally

Table 3. The results of the computational and experimental study of the combustion chamber layout
Таблица 3. Результаты расчетно-экспериментального исследования макета камеры сгорания

Name	Modeled value	Measured value
Output temperature, °C	944	942
NO emissions, ppm	9,8	10,5
Pressure loss, %	2,7	3,1
Temperature at the inlet of the combustion chamber under study, °C	704	723

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obtained temperature field at the CC outlet is remarkably close to the modeled one.

During the experimental studies, the overall performance of the tested CC was demonstrated.

ADDITIONAL INFORMATION

Authors' contribution. A.V. Kostyukov — general supervision of the work, writing the text of the manuscript, approval of the final version; A.G. Valeev — development of the test rig, modeling of flow and combustion processes in the combustion chamber, conducting an experiment; A.A. Dementiev — test rig making, editing the text of the manuscript; creating images; processing experimental data. Authors confirm the compliance of their authorship with the ICMJE international criteria. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work.

Competing interests. The authors declare that they have no competing interests.

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ДОПОЛНИТЕЛЬНАЯ ИНФОРМАЦИЯ

Вклад авторов. А.В. Костюков — общее руководство работой, написание текста рукописи, утверждение финальной версии; А.Г. Валеев — разработка стенда, моделирование процессов течения и горения в камере сгорания, проведение эксперимента; А.А. Дементьев — изготовление стенда, редактирование текста рукописи, создание изображений; обработка экспериментальных данных. Авторы подтверждают соответствие своего авторства международным критериям *ICMJE* (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией).

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Источник финансирования. Авторы заявляют об отсутствии внешнего финансирования при проведении исследования.

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