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ORIGINAL RESEARCH ARTICLE

Investigation of the parameters influence of the oxy-fuel burner and the test bench parameters on the deviation of the model similarity criterions from the full-scale values

Sergey Osipov, Ivan Komarov, Olga Zlyvko, Timofey Karev*, Maxim Oparin

Department of Innovative Technologies for High-Tech Industries, National Research University "Moscow Power Engineering Institute", 111250 Moscow, Russia

*** Corresponding author:** Timofey Karev, karevTP@mpei.ru

ABSTRACT

The article presents the results of a study of the workflow parameters influence in the full-scale and model burners of the combustion chamber oxy-fuel combined cycle on the deviation of similarity criteria from full-scale values. The variable parameters are the pressure and velocity of the fluid under model conditions, as well as the power of model and full-scale burners. The supercritical parameters of the working fluid in the cylindrical sections of the combustion zone at a pressure of 30 MPa and a temperature of 1570 °C were taken as full-scale conditions. In this paper, the dependences of the deviations of hydrodynamic and thermophysical similarity criteria on the speed and pressure of the combustion products of an oxygen-fuel mixture with carbon dioxide in the working zone of the test bench for burners are obtained. The parameters of the working fluid and the power of model burners are obtained, at which the values of the criteria deviations are minimal.

Keywords: carbon dioxide combustion chamber; diluent; test bench; burner device; similarity criteria

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1. Introduction

Currently, the majority of electricity is generated by burning fossil fuels at thermal power plants (TPPs). Combustion products of the fuel-air mixture, mainly greenhouse gases, are released into the environment during the TPP operation, thereby contributing to an increase in their concentration in the Earth's atmosphere[1]. Adoption of prior-art technologies for capturing carbon dioxide at thermal power plants means an increase in the cost of electricity generated[2–4]. As an alternative, oxyfuel electricity generation can be used to reduce harmful emissions[5,6]. Unlike conventional power units, oxyfuel power generators (OFPG) almost does not pollute the atmosphere with emissions due to the closed-loop Brayton cycle, the use of oxygen as a fuel oxidizer, and the disposal of carbon dioxide removed from the cycle[7]. One of the most efficient units operating on the basis of oxyfuel technology is the Allam cycle unit[8].

A change in the component composition and thermodynamic parameters of the working medium relative to the conventional operating conditions of a gas turbine unit predetermines a change in the nature of the combustion process. In the combustion chamber (CC) of the oxyfuel power generator (OFPG), the combustion of natural gas with oxygen occurs in a CO_2 diluent at a pressure of approx. 300 bar, which greatly differs from the conventional combustion chambers of gas turbine units, where the air serves as a diluent[9,10]. Specifics of the arrangement of mixing and combustion processes necessitate an experimental study of methane combustion in the O_2 and CO_2 medium.

In the publication[11,12], Toshiba demonstrated an installation for testing the combustion chamber of an oxygen-fuel energy complex operating on the Allam cycle with a capacity of 5 MW at a pressure of 300 bar. The authors observed stable flame behavior and operability in a wide range of equivalence coefficients and the percentage of O_2–CO_2 oxidizer from 16 to 44% of the mass fraction of O_2 with an equivalence ratio from 0.89 to 0.92. The test time was 263 seconds. The temperatures of the metal in the combustion chamber were close to their predicted values by the authors of the study. The temperature of the combustion products at the outlet of the combustion chamber reached 1400 °C. Verification of the results was carried out by comparing the metal temperature with the results obtained by analytical dependencies and the temperature of combustion products under experimental conditions, relative to those calculated in the CANTERA software package[13].

In a publication devoted to the study of oxyfuel combustion in a CO_2 medium, tests were carried out at a pressure of 1 to 10 bar for burner capacities from 10 to 100 kW. In stabilization modes, flame stability at the burner outlet was higher, but there was a possibility of flashback and overheating of the burner in V-shaped flame mode. M-shaped flames with combustion in the outer recirculation zones are safer in terms of burner integrity and have been observed in modes between attached and raised V-shaped flames. The limit of flame stabilization by the oxygen concentration of 31.7% was determined for capacity range from 10 to 40 kW. Exceeding the concentration directed the flame into the burner. With increasing pressure, the residence time in the chamber increased by 5 times, but this does not lead to a decrease in CO emissions[14].

The publication[15] shows the temperature levels of combustion products in a mixture of $CH_4/CO_2/O_2$ depending on the equivalence ratio at its values from 0.458 to 0.5.

Validation of the results of numerical modeling was carried out by the velocity gradient at extinction for a mixture of CH_4/Air relative to experimental data[16].

The study[17] is devoted to the experimental dependencies of the ignition delay of a methane-air mixture at an equivalence ratio of 0.5 and a pressure of up to 450 atm in the temperature range from 1200 to 1700 K. Validation of the ignition delay determined by the GRI-Mech 3.0 mechanism[18] was carried out relative to its experimental values.

Publications devoted to experimental studies of the combustion of methane with oxygen in the CO_2 medium of oxyfuel power generators provide no information about the deviation of the model similarity criteria from the full-scale ones. The creation of an experimental bench that allows testing burner devices at supercritical parameters and capacities over 1 MW requires large financial costs. Process conditions demand higher standards of safety. Reducing costs can be achieved by testing under conditions different from the full-scale ones, when the fluid pressure is lower and the similarity in the flow of gas dynamics processes and heat and mass transfer processes is ensured. The described similarity of conditions is possible if the similarity criteria are met[19,20].

The following are conventionally taken as the main criteria that determine the conditions for mixing components, their movement through the combustion chamber and flame propagation[21]:

1) Euler's criterion, Eu;
2) Schmidt number, Sc;
3) Froude number, Fr;
4) Reynolds number, Re;
5) Prandtl number, Pr;
6) Lewis number, Le;

7) Mach number, M.

A brief description,the physical meaning of the similarity criteria, and the calculation formulas are given in **Table 1**.

Table 1. Criteria for similarity of combustion processes.

Criterion	Formula	Physical meaning
1) Euler's criterion. where p is the pressure, Pa; p is the density, kg/m^3; v is the velocity, m/s	$Eu = \frac{p}{\rho \cdot v^2}$,	A typical case—the gas is affected by pressure and inertia forces Eu is a value proportional to the ratio of pressure forces to inertia forces.
2) The Schmidt Number, where v is the kinematic νviscosity, m^2/s; D is the diffusion coefficient, m^2/s.	$Sc = \frac{\nu}{D}$,	Characterizes the relative role of molecular processes of transfer of the amount of motion and transfer of the impurity mass by diffusion The value of Sc shows how much momentum is transferred more efficiently than substance
3) Froude's criterion, where v is the characteristic velocity scale (gas velocity), m/s; g is the acceleration of gravity, м^{m2}/s; d is the characteristic size (diameter), m	$Fr = \frac{v^2}{g \cdot d}$,	The gas is affected by gravity, pressure and inertia. Fr is a value proportional to the ratio of the forces of inertia to the forces of gravity
4) The Reynolds number	$Re = \frac{v \cdot d}{\nu}$	Gas is affected by the forces of viscosity, pressure, and inertia. Reis a value proportional to the ratio of the viscosity forces to the inertial forces.
5) Prandtl number, where c_p specific heat capacity, kJ/ (kg $*$ K), k-thermal conductivity W/(m $*$ K)	$Pr = \frac{\nu \cdot \rho \cdot c_p}{k}$,	The Prandtl number is considered as a measure of similarity between the temperature and velocity fields.
6) Mach number where c is the speed of sound in the medium, m/s	$\mathrm{M} = \frac{v}{\mathrm{c}}$,	the Mach number takes into account forces elastic forces. It is a measure of the ratio of the flow velocity and the velocity of propagation of elastic deformations
7) The Lewis number	$Le = \frac{Sc}{Pr}$	The Lewis number (or Lewis-Semenov number) can be considered as a quantitative measure of the similarity of the temperature and concentration distributions in the flame front.

Some of the criteria may be excluded from consideration, or the requirements for the degree of their implementation may be reduced. So, when determining the parameters of the experimental bench for studying burner devices (BD) of the OFPG combustion chambers, it is possible to exclude the Froude number from consideration since the forces of gravity during the movement of gases are insignificant.

The publication is devoted to determining the dependence of deviations of the model similarity criteria from the full-scale ones at different capacities of the corresponding burner devices. The influence of parameters of the medium in the bench working area on the deviation of the model similarity criteria from the full-scale ones is studied.

There is no information in open literature sources about the values of similarity criteria in oxygen-fuel combustion chambers with supercritical parameters of the working medium, as well as recommendations on the selection of similarity criteria that must be taken into account when developing experimental stands for studies of model combustion chambers with reduced relative to the full-scale parameters of oxyfuel components. This article presents the results of studies of deviations of similarity criteria in model combustion chambers from full-scale values at different capacities of combustion chamber burners and experimental parameters. The relevance of this article and the novelty of the results presented are justified by the formulated recommendations on the choice of a unit power of a full-scale combustion chamber, at which the minimum deviation of similarity criteria in a model combustion chamber relative to full-scale conditions will be ensured.

2. Determination of similarity criteria values in OFPG combustion chamber

The bench working area parameters must be selected taking into account the similarity criteria determined in the full-scale combustion chamber. The results of a three-dimensional numerical simulation of a combustion chamber with a capacity of 105 MW were adopted as full-scale conditions[22]. The simulation was carried out in the Ansys Fluent solver. The mass flow rates of methane, carbon dioxide, and an oxidizer mixture consisting of 82 wt.% CO_2 and 18 wt.% oxygen are set as boundary conditions. **Figure 1** shows the temperature field in the longitudinal section, obtained as a result of simulation under the initial conditions described in the publication.

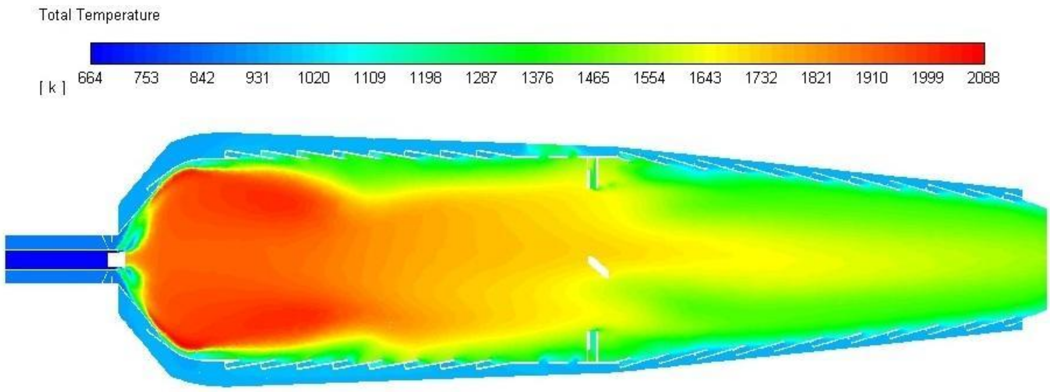

Figure 1. Combustion chamber temperature field of 105 MW to determine similarity criteria.

The similarity criteria were determined along the length of the combustion chamber in its transverse sections of the cylindrical part, spaced at intervals of 50 mm. In these sections, the main thermodynamic and thermophysical parameters of the medium are determined. Speeds and temperatures were averaged over the mass flow in each of them. Further, the value of the similarity criteria was determined in each of the sections. The arithmetic mean value for the cylindrical part is adopted as the corresponding criterion in full-scale conditions. The average temperature value was obtained by averaging the temperatures in all sections of the chamber combustion zone. The values of other similarity criteria are obtained similarly. **Table 2** shows the values of the similarity criteria and the main parameters of the working medium in the combustion chamber used for their calculation in some sections.

Table 2. Main parameters of 105 MW combustion chamber under full-scale conditions.

l, m	ρ, kg/m^3	$F_ж$, m^2	v_{gas}, m/s	T, °C	Re, 10^6	Eu, 10^4	Sc	Pr	Le	M, 10^{-3}
0.2	70	0.14	5.99	1647	2.558	1.42	0.853	0.714	1.194	8.7
0.35	70	0.14	5.96	1629	2.550	1.41	0.859	0.714	1.202	8.6
0.5	73	0.14	5.73	1572	2.615	1.36	0.845	0.715	1.183	8.4
0.65	75	0.14	5.60	1516	2.654	1.33	0.854	0.715	1.194	8.3
0.8	77	0.14	5.46	1481	2.713	1.28	0.847	0.716	1.184	8.2
Average value	-	-	-	1570	2.623	1.36	0.852	0.715	1.191	8.4

3. Studies of the influence of the parameters of the working flow of the experimental bench on the deviation of the model Reynolds numbers relative to the full-scale values

Initially, the influence of pressure and speed of the medium in the experimental bench working area on the deviation of the model Reynolds number ΔRe, % from the full-scale value was studied. The value of 186 kW is adopted as the capacity of the model burner device. **Figure 2** shows the dependence of the deviation of the Reynolds number in the cylindrical part of the full-scale combustion chamber on the medium conditions in the bench working area.

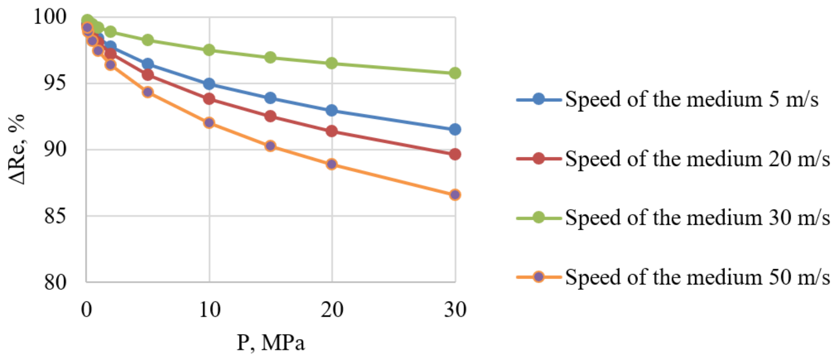

Figure 2. Deviation of model Reynolds number obtained at experimental BD capacity of 186 kW from value obtained in full-scale conditions at BD capacity of 105 MW.

The analysis results showed that an increase in the pressure and speed of the medium in the bench working area leads to a decrease in the deviation of the model Reynolds number from the full-scale value. In the selected range of speeds and pressures, the deviation of the model Reynolds number from the full-scale value is 86.6%–99.7%. Since the air speed at the BD outlet in conventional combustion chambers of gas turbine units is max. 50 m/s, it was decided to reduce the Reynolds number deviation by reducing the value of the full-scale Reynolds number through a reduction in the unit capacity of the burner devices[23].

The combustion chamber of the SGT-800 turbine[24] was adopted as a prototype for determining the unit thermal capacity of burner devices. The thermal capacity of the SGT-800 gas turbine unit combustion chamber, equal to 103.5 MW, is provided by thirty burner devices with 3.45 MW capacity each. The similarity criteria in the combustion chamber at a constant fuel mixture composition and a unit capacity of burner devices reduced to 3.5 MW were determined under the assumption of a constant bulk temperature in each of the sections. The similarity criteria values for a 3.5 MW burner device were determined by the method described above for a 105 MW CC. **Table 3** shows average values of the similarity criteria at a reduced burner device capacity of 3.5 MW.

Table 3. Similarity criteria values at 3.5 MW unit capacity of full-scale burner devices.

Re, 10^6	**Eu, 10^4**	**Sc**	**Pr**	**M, 10^{-3}**	**Le**
0.479	1.355	0.852	0.714	8.4	1.191

The results of the study at a constant temperature showed that reducing the unit capacity of the burner device to 3.5 MW and maintaining the capacity of the model BD equal to 186 kW reduced the range of deviation of the model Reynolds number from the full-scale value from 86.6%–99.7% to 26.6%–98.0% (**Figure 3**). It is possible to achieve the minimum deviation of the model Reynolds number from the full-scale value equal to 26.6% with the capacity of the model and full-scale BD equal to 186 kW and 3.5 MW, respectively, if the pressure of the medium is equal to 30 MPa and the speed is 50 m/s in the experimental bench working area.

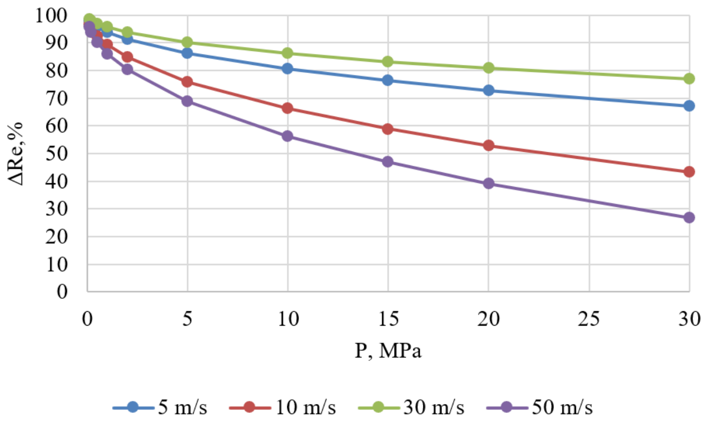

Figure 3. Deviation of model Reynolds number obtained at BD capacity of 186 kW from value obtained in full-scale conditions at BD capacity of 3.5 MW.

To determine the possibility of carrying out model tests of the burner device at lower pressures, it was decided to study the influence of the model burner device capacity on the deviation of the model Reynolds number from the full-scale value obtained in a combustion chamber with a unit capacity of 3.5 MW. **Figure 4** shows the results of a study of the influence of pressure and speed of the medium in the bench working area at BD capacities of 500 and 800 kW on the deviation of the model Reynolds number from the full-scale value obtained for full-scale BDs with a unit capacity of 3.5 MW.

An analysis of the results shows that with an increase in the model BD capacity, the deviation of the model Reynolds number from the full-scale value decreases, and it becomes possible to test the burner device at a pressure below 30 MPa and ensure an acceptable deviation in Reynolds number. For example, with a model BD capacity of 800 kW, a pressure of 10 MPa and a speed of 50 m/s of the working medium in the bench working area, the deviation of the model Reynolds number from the full-scale value will be 9.3%.

4. Studies of the influence of the parameters of the working flow of the experimental bench on the deviation of the Euler criterion relative to the full-scale values

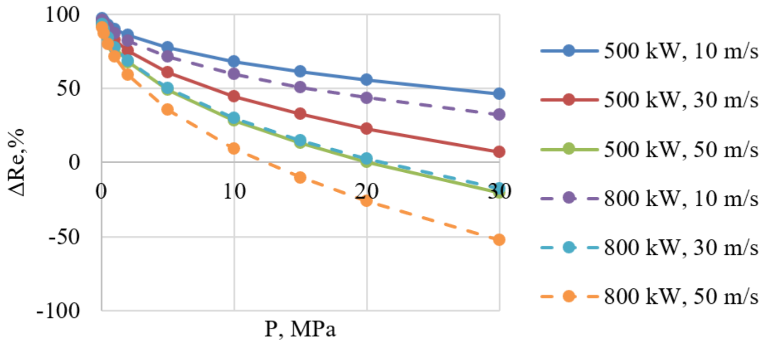

Figure 4. Deviation of model Reynolds number obtained at different capacities of experimental bench BDs from value obtained in full-scale conditions at BD capacity of 3.5 MW.

Further, the influence of pressure and gas flow rate under bench conditions on the deviation of Euler's criterion from full-scale conditions was studied. The study was carried out for the model burner device capacities of 186 kW, 500 kW, 800 kW and the full-scale BD capacity of 3.5 MW. The study results showed that the criterion value does not depend on the burner device capacity, since the change in volume flow is not taken into account in the calculation formula that determines Euler's criterion values (1). **Figure 5** shows the dependence of the influence of the pressure and speed of the medium in the cylindrical part of the working area on the deviation of the model Euler's criterion value from the full-scale value ΔEu, %.

$$Eu = \frac{P}{\rho \cdot v^2}, \quad (1)$$

where,

P—pressure, Pa;

ρ—density, kg/m^3;

v—speed, m/s.

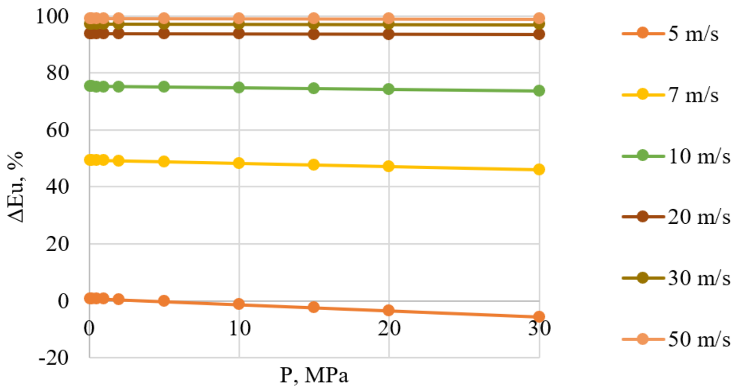

Figure 5. Dependence of model Euler's criterion deviation from full-scale value at different speeds and pressures of medium.

The study results showed that Euler's criterion is practically insensitive to changes in the pressure of the medium in the experimental bench working area. For example, with an increase in pressure from 0.1 MPa to 30 MPa, the deviation of the model Euler's criterion value from the full-scale value was up to 5%. However, a change in the speed of the medium in the experimental bench working area at constant pressure leads to a significant change in the Euler number value. For example, an increase in the speed of the working medium from 5 m/s to 50 m/s at a pressure of 10 MPa led to a change in the model Euler number from its full-scale value from 1.3% to 99%. At a pressure of 10 MPa and a speed of 50 m/s of the working medium in the bench working area, the deviation of the model Reynolds number from the full-scale value was 9.3%. Accordingly, it is impossible to ensure the minimum deviation of the model values from the full-scale values of the Reynolds numbers and the Euler's criterion for the same parameters of the medium in the experimental bench working area. In order to ensure the minimum value of ΔEu at a pressure of 10 MPa, it is necessary to reduce the speed in the experimental bench working area to 5 m/s.

5. Studies of the influence of the parameters of the working flow of the experimental bench on the deviation of the Schmidt, Prandtl and Lewis model numbers relative to the full-scale values

The values of the deviations of the Schmidt, Prandtl and Lewis numbers do not depend on the speed of the gases or the capacity of the burner device. The influence of pressure change on the listed criteria is insignificant due to its absence in the calculation formulas (2, 3, 4).

$$Sc = \frac{\nu}{D}, \quad (2)$$

$$Pr = \frac{\nu \cdot \rho \cdot c_p}{k}, \quad (3)$$

$$Le = \frac{Sc}{Pr}, \tag{4}$$

where,

ν—kinematic viscosity, $м^2$/s;

D—diffusion coefficient, $м^2$/s;

c_p—specific heat capacity, kJ/(kg · K),

k—thermal conductivity W/(m · K).

Table 4 shows the results of studying the influence of the working medium pressure on the deviations of the Schmidt, Prandtl and Lewis criteria in a model 800 kW BD from full-scale conditions with a BD capacity of 3.5 MW. For the entire range of pressures in the bench working area, the values of the criteria are in the range of 14.76% to 14.94% for the Schmidt number, from 0.07% to 0.14% for the Prandtl number, and 16.04% for the Lewis number, which indicates an acceptable level for ensuring similarity in the entire considered range of pressures of the medium in the experimental bench working area.

Table 4. Determination results for deviation of Schmidt, Prandtl and Lewis number values under model conditions from full-scale values obtained by numerical simulation of processes.

P, MPa	ΔSc, %	ΔPr, %	ΔLe, %
30.0	14.76	0.068	16.04
20.0	14.87	0.060	16.04
15.0	14.90	0.101	16.04
10.0	14.93	0.128	16.04
5.0	14.94	0.139	16.04
2.0	14.94	0.139	16.04
1.0	14.94	0.138	16.04
0.5	14.94	0.138	16.04
0.2	14.94	0.136	16.04
0.1	14.94	0.136	16.04

Thus, when determining the parameters of the medium in the experimental bench working area and its geometric parameters, foremost, it is necessary to determine the deviation of the model values from the full-scale values of the Reynolds number and the Euler's criterion. Conducting experimental studies of the combustion of CH_4 with O_2 in a CO_2 medium does not allow for the minimum deviation of the model values of these criteria from full-scale conditions at the same working medium parameters and burner device capacity. It is necessary to carry out studies at different speeds of the medium in the bench working area, which is possible with a decrease in the consumption of components, leading to a decrease in capacity.

6. Conclusion

Based on the results of numerical modeling of combustion processes in a carbon dioxide combustion chamber of the Allam cycle operating at a pressure of 30 MPa, a temperature of 1481 to 1647 °C and a total mass flow rate of 48.8 kg/s of combustion products, the values of similarity criteria are determined: Reynolds numbers, Euler criteria, Schmidt numbers, Prandtl and Lewis in its cylindrical cross sections parts of the burning zone. The obtained values of similarity criteria can be used to determine the parameters of experimental stands for testing oxygen-fuel combustion chambers under model conditions.

It is determined that the similarity criteria indicated above are most sensitive to the power of the burner device and the Reynolds number. It is established that the unit power of a full-scale gas generator in an oxygen-fuel COP should be no more than 3.5 MW for the possibility of experimental research of combustion processes under model conditions to ensure a deviation of the model Reynolds number from the full-scale value of no more than 10%. As model conditions, we assume that the power of the full-scale gas generator is up to 1 MW and the pressure of the working flow is not more than 15 MPa.

The parameters of the experimental stand that provides testing of model oxygen-fuel combustion chambers are determined if the model similarity criteria deviate from the full-scale ones (no more than 10% by the Reynolds number, 1.3% by the Euler criterion, 15% by the Schmidt number, 0.2% by the Prandtl number, and no more than 17% by the Lewis number):

—the power of the model burner device is not less than 800 kW if the power of the full-scale burner device is not more than 3.5 MW;

—the pressure of the medium in the working area of the experimental stand is not less than 10 MPa.

The recommendations obtained by the authors can be used in designing an experimental base for conducting studies of model oxygen-fuel combustion chambers.

Author contributions

Conceptualization, IK and SO; methodology, IK; software, MO; validation, MO, and TK; formal analysis, SO; investigation, TK; resources, TK; data curation, MO; writing—original draft preparation, TK; writing—review and editing, OZ; visualization, OZ; supervision, SO; project administration, SO; funding acquisition, OZ. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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