Studying unsteady combustion processes that occur in an annular combustion chamber of a gas turbine engine

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Abstract. When designing low-emission combustion chambers for gas turbine engines (GTE) and power plants, determining their tolerance to high-amplitude pressure oscillations during combustion is a challenging task. This paper proposes a modified instability criterion of combustion processes, which allows us to assess the influence of design and operating parameters on the amplitude of pressure oscillations. The comparison between the modified criterion and experimental data showed that for the volume-averaged estimation of the criterion, it is necessary to use the flame front region, defined by the value of the Progress Variable parameter of the FGM combustion model in the range of 0.3-0.7.

1. Introduction

Currently, the environmental performance of gas turbine power plants is achieved mainly by the combustion of lean air-fuel mixtures. The use of this combustion technology leads to problems related to the achievement of a stable combustion process and high-amplitude pressure pulsations [1].

To achieve steady combustion, it is necessary to introduce design solutions at the preliminary design stage of the combustion chamber, which leads to a change in the entire design methodology. Nowadays, there are several methods for the calculation study of pulsating combustion in the combustion chambers of gas turbine power plants such as acoustic analysis [2], modal analysis [3], and flame dynamics simulation using LES [4]. There are also approaches that analyze the gas-dynamic flow structure. For instance, in the works of JSC "VTI" [5-6], a criterion is proposed which assesses the relative position of temperature gradient (which characterizes the flame front region) and the velocity gradient (which characterizes the location of the source of turbulent oscillations). The close arrangement of these gradients can contribute to the development of instabilities, as shown in [7].

The comparison of the values, obtained for the criterion during the post-processing of the 3D simulation results of combustion processes in a steady state solution, combined with experimental data made it possible to conclude that its value correlates with the amplitude of the oscillations that occur during combustion. Thus, the use of this criterion allows us to assess the stability of various design cases of the combustion chamber in comparison with each other. The advantage of the proposed criterion is that for its determination it is enough to have the reliable distribution of temperatures and velocities in the volume of the flame tube, which can be obtained by steady 3D simulations. The disadvantage of the
criterion and its calculation method is the need for a "manual" analysis of the gas-dynamic flow simulation results. For combustion chambers with a complex three-dimensional distribution of the flame front in the volume of the flame tube, the "manual" calculation of this stability criterion is complicated. In this paper, we propose an approach for the volume-average estimation of the stability criterion based on 3D steady state simulation results. Thus, the purpose of this paper is to develop a calculation method for the volume-average estimation of the stability criterion for an annular combustion chamber of a gas turbine power plant.

2. Methods and instruments

The subject of the study is a low-emission annular combustion chamber. The flame tube head contains 28 vane swimmers with two channels for fuel supply: supply through swirler vanes, and supply to the pilot zone. The combustion mechanism contains a partially premixed fuel-air mixture. Secondary air is supplied through one row of large holes in the outer and inner case of the flame tube [3, 8]. Experimental measurements were carried out for three modes, differing in inlet pressure and fuel distribution between the main and pilot circuits. The results of the experimental measurements are presented in Table 1. Thus, for mode №1, there are practically no oscillations, and their amplitude is about 0.09% of the inlet pressure; for mode №2, the amplitude of oscillations increases to 0.2%, and mode №3 approaches the permissible values and reaches 2.53%.

This study contains a modal analysis that determines the shape of the frequency, measured in experimental studies. The modal analysis methodology is described in [9]. A feature of the technique is that it takes into account the spatial distribution of temperature in the volume of the combustion chamber. The frequencies obtained in the modal analysis, which are closest to the measured ones, are presented in Table 1.

Calculations of combustion processes in a three-dimensional steady setting were carried out to improve the approach of the stability criterion calculation. The turbulence model used in the calculations was the Reynolds stress transport model, and the combustion model was the Flamelet Generated Manifold (FGM) [10]. Methane was used as fuel. Figure 1 shows the temperature field in the combustion chamber for the investigated modes.

Table 1. Results of the calculated and experimental study of pulsating combustion

| Mode | № | Inlet pressure, atm | Fuel in the pilot circuit, % | Measured oscillation frequency, Hz | Measured oscillation amplitude, Pa | Measured oscillation amplitude, % | Closest frequency in modal analysis, Hz |
|------|---|---------------------|-----------------------------|-----------------------------------|-----------------------------------|-----------------------------------|----------------------------------------|
|      | 1 | 19.8                | 7,32%                       | 6,6                               | 371                               | 0,029                             | -                                      |
|      | 2 | 19.8                | 7,32%                       | 296,6                             | 706                               | 0,036                             | -                                      |
|      | 1 | 19.8                | 7,32%                       | 342,8                             | 566                               | 0,029                             | 346,24                                |
|      | 2 | 20.3                | 4,59 %                      | 19,8                              | 1383                              | 0,068                             | -                                      |
|      | 3 | 20.3                | 4,59 %                      | 65,9                              | 1393                              | 0,069                             | -                                      |
|      | 1 | 20.3                | 4,59 %                      | 323                               | 1334                              | 0,066                             | 319,6                                  |
|      | 2 | 21.6                | 1,32 %                      | 418,6                             | 53897                             | 2,53                              | 434,62                                |

We proposed to carry out the estimation of the stability criterion by averaging the multiplication of the total velocity and total temperature gradients of the flow over the volume of the combustion chamber: \( \text{grad}(T) \times \text{grad}(v) \). In this case, the average should be carried out not for the entire volume of the combustion chamber, but only for the flame front region, as the main source of oscillations, while high gradients of the flow velocity and temperature can be located, for example, in the streams of the mixing zone region. Based on the results of combustion processes simulation in a three-dimensional setting, the region of the turbulent flame front can be determined by the following three parameters:

1. Progress variable (C). This scalar variable shows the completeness of the combustion process and is the main parameter of the FGM combustion model. This parameter changes from 0 to 1, so values close to 0.5 are taken as the flame front.
2 - Mass fraction of OH. The presence of the OH radical indicates intense processes of chemical reactions, which are most often associated with the flame front. Therefore, values close to the maximum are studied.

3- Product formation rate (PFR), which characterizes the rate of change of the Progress variable due to the combustion process - the source term in the transport equation Progress variable. It changes from 0 to an arbitrary value, where the maximum values correspond to the most intense combustion process.

Since each of these parameters characterizes not only the flame front but also the post-flame and pre-flame zones, it is necessary to determine the range of values that correspond only to the flame front. To determine the relevant range of each parameter, a volume corresponding to this range was separated from the computational domain. The volume-average value the multiplication of the total velocity and total temperature gradients were calculated for the obtained volume. Further, the obtained volume-average value of the criterion was compared with the experimental oscillation amplitudes.

![Figure 1. Temperature field in CC for modes: a) No. 1; b) No. 2; c) No. 3](image)

3. Results and discussion

To numerically determine the criterion for OH concentration, the following concentration ranges were considered:

- from 50 to 100% of the maximum value;
- from 30 to 100% of the maximum value;
- from 20 to 100% of the maximum value;
- from 10 to 100% of the maximum value;
- from 5 to 100% of the maximum value.

The comparison of the results of the criterion calculation for various concentration ranges with experimental data on the amplitude of oscillations is shown in Figure 2.a. The comparison is presented in relative values, normalized to their maximum values for the given concentration range. The experimental value of the oscillation amplitude is normalized to the amplitude for mode №3.

The graphs show that in the range of OH concentrations of 10–100% and 5–100%, the value of the criterion does not correlate with the experimental data. This may be due to the fact that the calculation includes
regions that are not in the flame front and do not affect the pressure oscillations. For all other ranges of OH concentrations, an increase in the value of the criterion is observed when passing from mode №1 to mode №3. Thus, when determining the criterion $\text{grad}(T)\text{grad}(v)$ by OH concentration, it is necessary to be limited to the region in which the range of OH mass concentration is from 20% (or higher) to 100% of the maximum.
4. Conclusion

The paper presents the results of developing an approach to determine the criterion of stability of processes in a combustion chamber to pulsating combustion. The proposed version of the calculation of the criterion makes it possible to obtain the numerical volume-average values of the criterion for the flame front region of the combustion chamber. In this case, the flame front is determined by the region in which the value of the Progress Variable parameter is in the range of 0.3-0.7. The acoustic modal analysis showed that the experimental frequencies correspond to a circular mode with two or one periods.

In the future, there are plans to use the proposed method to analyze the design solutions implemented in the combustion chamber of the GTE-65.1 gas turbine power plant of PJSC «Power Machines», in which the quality control of the air-fuel mixture is provided by redistributing fuel between the fuel circuits. It should be noted that the proposed approach should be supplemented by methods for determining unstable frequencies that are caused by convective transfer time (mixing) from the fuel supply to the flame front (time-lag). However, unlike the combustion chamber presented in this article, the GTE-65.1 combustion chamber is modular, which excludes the rise of circumferential modes.

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