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NUMERICAL MODELING OF TURBULENT HEAT EXCHANGE IN THE COMBUSTION CHAMBERS OF GAS-TURBINE PLANTS WITH THE USE OF THE FLUENT PACKAGE

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The processes of combustion in the combustion chamber of a gas-turbine plant are numerically modeled using the Fluent CFD package. A detailed comparison of the obtained calculation results and the data of bench tests has been made.

The combustion chamber of a gas-turbine plant represents a complex engineering device characterized by a set of the physicochemical processes taking place: nonstationary gas dynamics, turbulent combustion of different types of fuels, heat and mass exchange, and formation of the oxides NO_x, CO, and others. In designing combustion chambers, one primarily uses different experimental benches, which determines the high cost of their manufacture and testing. This work seeks to model three-dimensional processes of combustion in a combustion chamber with the use of modern computer-aided-engineering (CAE) technologies and high-performance multiprocessor systems. The numerical modeling has been carried out with the use of a heavy Fluent gasdynamic package. The mathematical model has been developed based on the combustion chamber of a GTE-150 gas-turbine plant (LMP Public Corporation), for which detailed results of the physical experiment are available. In the course of the work, we have calculated the turbulent combustion of a gaseous fuel (natural gas) with allowance for radiative heat exchange.

A general view of the experimental compartment for testing the GTE-150 full-scale plasma tube on the large-scale bench on the All-Russia Heat Engineering Scientific-Research Institute (HEI) is given in [1]. The plasma tube of the combustion chamber and the gas collector are installed in the outer casing, which consists of two off-axial cylindrical shells. Although the experimental compartment does not model in full measure the supply of air from the compressor to the combustion chamber in the GTE-150 circuit, the diameters of these shells have been selected from the conditions of ensuring the calculated values of the mass-mean velocities in the nominal regime: 10–12 m/sec at the inlet to the portion in the case of flow about the gas collector and 35–40 m/sec in the annular channel. Air for combustion is supplied via a front device and four rows of holes located on the first four shells. Nine belts of holes have been made at the junctures of the shells for cooling the plasma tube. The mixer of the plasma tube is nonsymmetric: with two holes of diameter 0.08 and 0.09 m each respectively. The experimental compartment was investigated using special measuring equipment. The flow rates of the air and the natural gas were determined with the use of normal sharp-edge orifice plates. The pressure of the air in the fuel-conveying system was measured with standard spring-element pressure gauges. Four tubes for measuring the dynamic head were installed on the initial portion of the annular channel to evaluate the uniformity of the velocity field entering the front part. With the aim of studying the process of burnout, we sampled the combustion products for analysis in four cross sections of the plasma tube and determined the composition of the products using a Gazokhrom chromatograph and an OPCA apparatus. The concentration of nitrogen oxides was measured by the chemical method on a Beckman-951 device.

The experimental compartment was tested at nondesign pressures of 0.15 to 0.2 MPa; therefore, in the course of investigating the basic characteristics of the chamber, we maintained the volumetric flow rates, the air pressure at the inlet to the connecting cylinder, and the excess air coefficients characteristic of the operating and start-up conditions of the combustion chamber in the GTE-150 circuit. At the same time, the investigations were carried out in a wide range of variation of the indicated basic parameters and their combinations: inlet temperature of the air 333–593

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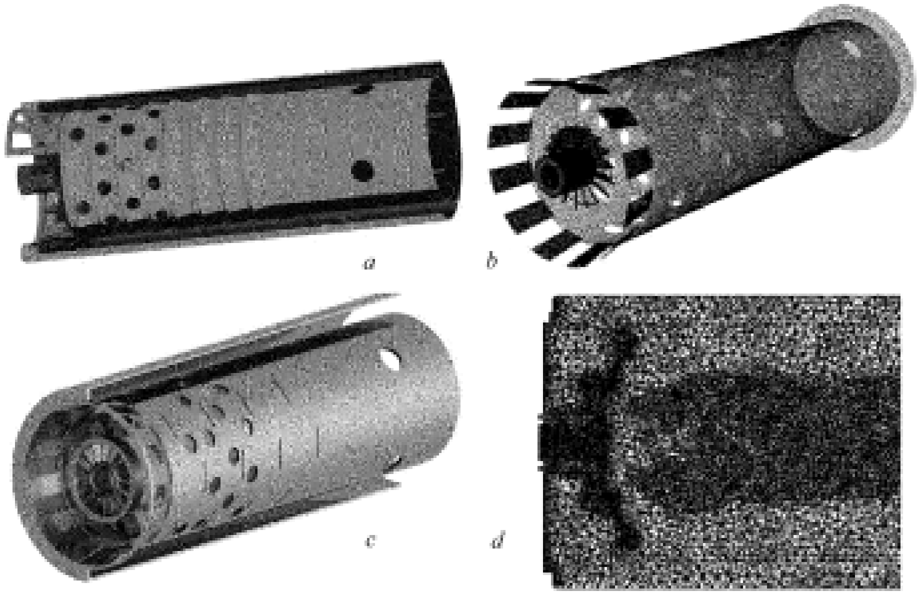

Fig. 1. General view of the experimental bench (a), mathematical analog of the combustion chamber (b), computational grids on washed surfaces (c), and computational grid in the longitudinal section of the chamber (d).

K, excess air coefficient 2.5–20, mass-mean velocities in the holes of the plasma tube 30–90 m/sec, and temperature of the gases behind the chamber 473–1473 K.

A general view of the experimental bench is presented in Fig. 1a and a mathematical analog of the combustion chamber is shown in Fig. 1b. The analog is a diagrammatic representation of the combustion chamber of a GTE-150 gas-turbine plant with the following geometric assumptions: to ensure the passage of the required flow rate of air some holes of the cooling system of the flue tube were replaced by a block of slots with an equivalent area. The computational grid (Fig. 1c and d) was constructed in the Fluent preprocessor and is structureless with tetrahedral elements. We note that use was also made of grids adapted to the field of static temperature. The number of elements varied within 0.9–1.5 mln. Using the finite-volume factorized method, we solved the Reynolds-averaged system of Navier–Stokes steady-state equations (RANS). To close them we employed the k–ε turbulence model with allowance for low-Reynolds effects [2, 3] (k–ε realizable [4]) with standard wall functions. To charge the density of the mixture we selected the volume-weighted mixing law [4]. The mixture's heat capacity varies according to the mixing law [4]. For all components of the mixture we selected the piecewise-polynomial law of change of the heat capacity. The coefficients were taken from [5].

For radiative heat exchange we employed the R-1 model [6, 7]. It is solved with a low consumption of computer time and has been especially developed for applications with combustion where the optical path is large ($\alpha L > 1$). Moreover, R-1 is easily used in the case of complex geometry. The absorption coefficient α was prescribed as a function of the local concentrations of H_2O and CO_2, the optical path, and the total pressure. Model R-1 is the simplest case of the more general R-N model that is based on expansion of the radiation intensity in a series of spherical harmonics [6, 7].

As a combustion model we selected the eddy breakup model of Spalding [7, 8]. However, it has the following drawbacks:

(1) it cannot predict the formation of intermediate components and dissociation effects and, as a consequence, leads to an overstatement of the temperature field;

(2) it is unable to correctly reproduce physical phenomena that depend on a detailed chemical kinetics, such as ignition and quenching;

(3) it is computation-intensive, i.e., one solves $N - 1$ differential equations of transfer for the components involved in the combustion mechanism (CH_4, O_2, CO_2, H_2O, and N_2).

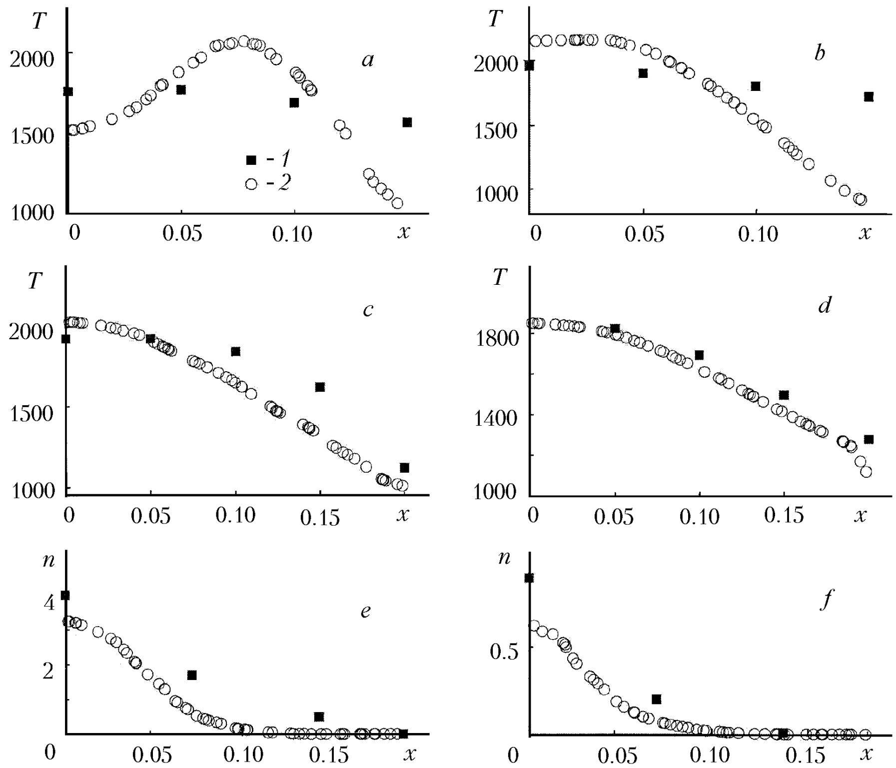

Fig. 2. Comparison of experimental and calculated data on the static temperature in four cross sections of the combustion chamber [a) $X = 0.25$, b = 0.35, c = 0.45 and d) 0.5] and on the concentration of methane in the first two cross sections (e, f): 1, 2) experimental and calculated data.

Despite the drawbacks, the model is simple and widespread and assumes global determination of the mechanism of combustion of methane. We employed air as the working gas and methane as the gaseous fuel. In the work, we employed two mechanisms: a one-step mechanism ($CH_4 + 2O_2 = CO_2 + 2H_2O$) and a two-step mechanism ($CH_4 + 1.5O_2 = CO + 2H_2O$; $CO + 0.5O_2 = CO_2$).

In the zones of air and fuel supply, we prescribed the flow rate, the total temperature, the static pressure, the intensity of turbulence (we selected a 5% turbulence), the scale (hydraulic diameter), and the mass fractions of the components. "Soft" boundary conditions were observed at the outlet of the combustion chamber.

Numerical modeling was carried out in the nondesign regime of operation of the GTE-150 gas-turbine plant [1]. Use was made of the schemes of first and second orders of approximation of convective terms of the equations, the PRESTO! discretization scheme for pressure [4, 9], and the SIMPLEC algorithm of pressure correction [4, 9].

We carried out the numerical modeling with the use of a parallel version of the Fluent package based on the cluster of the Center of High-Performance Computational Cluster Technologies at St. Petersburg State Polytechnic University. The average time of calculation of one variant was 10–12 h of computer time. Figure 2a–d compares the numerical and experimental data (experiment of the HEI [1]) on the static temperature in four cross sections of the combustion chamber. Their comparison for the concentration of methane in the first two cross sections of the plasma tube is made in Fig. 2e and f. It has shown that a correct qualitative picture of the flame structure was obtained in the numerical predictions. The disagreement between the calculated and experimental data for the first two cross sections in Fig. 2a and b is attributable to both the drawbacks of the selected model of combustion and the crudeness of the grid.

A satisfactory, on the whole, agreement between the results of the numerical modeling and the available experimental data enables us to draw the conclusion on the correctness (for engineering calculations) of the developed mathematical models and the adequacy of employment of the Fluent package for prediction of the characteristics of complex gasdynamic processes, including those of combustion.

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NOTATION

x, longitudinal coordinate measured from the beginning of the combustion chamber, m; *X*, cross section located perpendicularly to the *x* axis; *k*, energy of turbulent pulsations, m^2/sec^2; ε, dissipation rate of turbulent energy, m^2/sec^3; *L*, characteristic dimension of the combustion chamber, m; α, absorption coefficient, 1/m; *N*, number of components of the gas mixture; *T*, temperature, K; *n*, concentration of methane, %.

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