ZADAULY AKERKEH YERKINOVNA

NUMERICAL SIMULATION OF A HIGH-SPEED FLOW IN A COMBUSTION CHAMBER WITH AN EXCITED JET INJECTION

ANNOTATION

of a dissertation for the degree of Doctor of Philosophy (PhD)
6D074600 - Space technology and engineering

General characteristics of the work.

This work is devoted to the numerical modeling of turbulent outflow of a disturbed supersonic fuel jet into a co-flowing supersonic air flow to control the jet injection into the combustion chamber and improve the mixing of the fuel-oxidizer mixture for the purpose of fundamental research in the field of aeromechanics problems.

One of the most important problem in aviation is the design of supersonic and hypersonic aircraft with ramjet engines, where air is used as an oxidizer. The central task of such engines is to achieve complete combustion of fuel, providing the necessary engine thrust. This is achieved by increasing the mixing speed of the fuel-air mixture.

There are various approaches to enhance the mixing of fuel and oxidizer, such as steps and cavities in front of the injected jet, steps on the upper walls of the combustion chamber, which help to obtain a developed shear layer between the fuel jet and the oncoming air flow at the inlet. However, the above-mentioned approaches increase the cost of ramjets, since the addition of new parts complicates their geometry and increases the cost.

An obstacle to improving mixing is the physical complexity of the flows under consideration, since, in addition to the three-dimensionality of the modeled turbulence, such flows include a system of shock wave interactions, as well as a wide range of emerging vortex structures.

An additional problem in formulating a numerical model using Large Eddy Simulation (LES) for the flows under consideration is also the setting of initial boundary conditions capable of generating anisotropic, inhomogeneous, three-dimensional turbulence close to real.

Currently, one of the promising approaches to improving mixing is the use of an additional deterministic disturbance imposed on the injected jet. This approach is implemented by amplitude-frequency variation of the additional forcing on the injected jet, thereby providing controlled injection of fuel into the combustion chamber. It has been well studied in subsonic jet flows, while in supersonic and hypersonic flows the problem remains poorly understood.

Thus, the above allows us to consider the studies conducted in this work as relevant problems in aerodynamics, especially in modeling and predicting three-dimensional super- and hypersonic turbulent jet flows in combustion chambers, with the aim of enhancing the mixing of the jet and flow.

The aim of this work is: numerical modeling and study of the mechanisms of intensification of mixing of an injected supersonic compressible non-isobaric jet into a supersonic coflow using a deterministic perturbation based on LES-averaged three-dimensional Navier-Stokes equations for a perfect gas.

To achieve the stated goal, **the following research objectives** were formulated:

- to develop a numerical model and perform numerical simulation of the injection of an isobaric supersonic compressible jet into a coflow with additional disturbance on the jet in order to enhace mixing.
- to perform numerical simulation of the injection of a system of non-isobaric (underexpanded) compressible supersonic disturbed jets into a coflow in order to identify the influence of the main parameters of the jet and flow on the mixing patterns, as well as to analyze the impact of additional deterministic disturbance on the growth and formation of the shear layer.

The object of the study is a spatial supersonic turbulent flow with injection of supersonic gas jets into a supersonic coflow.

The subject of the study is the numerical modeling of turbulent mixing of a gas jet injected into a supersonic coflow using the LES turbulence model.

The scientific novelty consists in the following:

- a numerical model of spatial supersonic turbulent jet injection of a perfect gas into a high-speed coflow has been formulated, which is described by three-dimensional space-averaged Navier-Stokes equations closed by the Smagorinsky model. An algorithm for numerically solving the system of equations based on the third-order ENO scheme has been presented;
- a new method for enhancing mixing of the jet with the coflow by introducing an additional deterministic disturbance at the inlet has been proposed, along with this, the range of frequencies and amplitudes of the deterministically disturbed jet leading to improved mixing under the design conditions has been determined;
- patterns of influence of the pressure ratio and Mach numbers in numerical modeling of a system of underexpanded supersonic jets in a coflow on the mechanism of formation of a shock-wave structure and its influence on the mixing zone have been established;
- parameters of deterministic disturbance were obtained, leading to enhanced mixing of the jet system with coflow.

Scientific provisions submitted for defense:

- a numerical model of a three-dimensional supersonic turbulent flow of a perfect gas jet injected into a coflow;
- a new method for enhancing the mixing of a jet with a flow by introducing a deterministic disturbance at the inlet, tested by analyzing the results of numerical modeling of supersonic compressible jet injection into a coflow;

- results of a detailed analysis of a system of non-isobaric supersonic gas jets with additional disturbance, injected into a coflow, a namely, a study of the influence of the emerging shock-wave structure on the growth of the shear layer and the formation of coherent structures using a variation of the pressure ratio, the Mach numbers of the jets and flow, as well as the frequency and amplitude variation of the deterministic disturbance.

The reliability and validity of scientific provisions, conclusions and results of the dissertation work are determined by the use of fundamental laws of conservation of mass, momentum, energy, matter in the construction of mathematical models; satisfactory agreement of numerical results with experimental data and theoretical works of other authors.

Theoretical and practical significance of the results.

The numerical model and method for solving the averaged Navier-Stokes equations developed in this work can be used to calculate three-dimensional supersonic turbulent jet flows, allowing to predict the behavior of real three-dimensional processes that occur when mixing fuel and oxidizer in the combustion chambers of ramjets.

Relationship of this work with other research works. This work was carried out within the framework of the project of the grant funding program for fundamental research in the field of natural sciences "Numerical modeling of spatial turbulent compressible flows with injection of jets and solid particles" (2018-2020, No. GR 0118PK00461).

The personal contribution of the author is that all the results presented in this work were obtained by the author himself or with his direct participation. The author participated in the formulation of the dynamic model of the problem, and also independently performed numerical calculations of all the tasks set, including verification of the mathematical and physical model, conducted a thorough and comprehensive analysis of the results obtained and came to their theoretical justification with the participation of a scientific consultant.

Work approbation. The main results of the work were reported and discussed at the following international scientific conferences: "International Scientific Conference of Students and Young Scientists FARABI ALEMI" (Almaty, Kazakhstan, April 10-12, 2018); "Traditional International April Mathematical Conference in Honor of the Day of Scientists of the Republic of Kazakhstan" (Almaty, Kazakhstan, April 3-5, 2019); "V International Scientific and Practical Conference" (Czech Republic, Karlovy Vary - Russia, Moscow, April 29-30, 2020), as well as at scientific seminars: Institute of Technical Thermodynamics, Karlsruhe University of Technology (2020, Karlsruhe, Germany); Faculty of Mechanics and Mathematics, Al-Farabi Kazakh National University (2018-2019, Almaty); Institute of Mechanics and Mechanical Engineering (2020, Almaty).

Publications.

On the topic of the dissertation, 7 works have been published, including 2 publications in scientific journals included in the list recommended by the Committee for Control in the Sphere of Education and Science of the Ministry of Education and Science of the Republic of Kazakhstan for the publication of the main results of scientific activity; 2 publications in rating scientific journals indexed by Scopus and Thompson Reuters (impact factor of at least IF=0.40); 3 publications in the materials of international conferences.

Structure and volume of the dissertation. The dissertation work consists of an introduction, five sections, a conclusion and a list of references. The work is presented on 130 pages, contains 36 figures, 8 tables.

The introduction reflects the following points: relevance, main objectives of the work, novelty, scientific and practical significance of the dissertation work, the degree of its development.

The first chapter contains an analysis of studies by various authors on the topic of the dissertation work. It contains a brief overview of works devoted to the study of turbulence modeling methods, an analysis of studies (both experimental and numerical) of turbulent jet injection into a co-flow in order to improve mixing by imposing an additional deterministic disturbance, and an overview of works on numerical modeling of non-isobaric supersonic jet injection, where additional forcing is also used to improve mixing.

The second chapter formulates a mathematical model for the problem at hand. The initial system is the averaged three-dimensional Navier-Stokes equations closed by the classical Smagorinsky model. The procedure of density averaging is performed using the continuity and Navier-Stokes equations in the x direction as an example. The main system is given in dimensionless form, where the supersonic flow parameters are taken as characteristic values, and the initial momentum loss thickness (shear layer thickness) δ_θ is taken as the smallest length scale. This chapter also provides an algorithm for solving the initial equations using a high-order ENO scheme.

In the third chapter, a numerical model is formulated using the problem of supersonic mixing layer outflow into a co-flow. Then, the numerical model is verified by comparing the obtained results with the known data of Samimmy et al. As a result of the numerical experiment conducted in this chapter, graphs for averaged turbulent characteristics were obtained, which were compared with the experimental data for five computational grids, as a result of which a satisfactory match with the experimental data was revealed, at the same time, the optimal number of nodes for the computational grid was selected. Then, graphs were obtained for the three-dimensional energy turbulent spectrum, which demonstrated the range of resolved turbulent eddies for the selected computational grid and for the specified sizes of the computational domain.

In the fourth chapter, numerical modeling is performed for the problem of supersonic compressible jet injection of a perfect gas into a co-flow with the additional deterministic disturbance. At the input, initial boundary conditions are formulated for introducing additional forcing on the jet, in order to study their effect on the formation and growth of the shear layer. As a result of the numerical modeling, graphs were obtained for various parameters for the problem of the jet injection with additional perturbation in comparison with the case of jet without additional forcing, in order to compare the obtained results. An analysis of the amplitude-frequency variation of the deterministic perturbation is also performed, as a result of which, recommendations are given for choosing the best amplitudes and frequencies that lead to more intense mixing of the jet and co-flow.

In the fifth chapter, a number of numerical experiments are carried out for the problem of injection of a system of non-isobaric supersonic jets with additional disturbance into a supersonic co-flow, as a result of which graphs were obtained demonstrating the influence of the emerging shock-wave structures on the mixing zones between the jets and the co-flow, by varying the pressure ratio parameter. The problem of injection of a system of underexpanded jets into a co-flow is also studied with variations in the Mach numbers of the jets and flow and the amplitudes of the deterministic disturbance, as a result of which conclusions are given on the selection of the most optimal conditions (parameters) for improving mixing between the jets and the co-flow.

In conclusion, the main results and conclusions obtained in the dissertation are presented.