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Rotating detonation in a ramjet engine three-dimensional modeling

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ABSTRACT

A rotating detonation engine (RDE) combustion chamber fed by hydrogen–air mixtures of different composition was modeled numerically using 3D geometry. The RDE is a new type of engines capable to create higher thrust than the traditional ones based on the combustible mixture deflagration process. The dynamical process of combustion in the RDE is more than 100 times faster than that for the classical slow deflagration combustion mode. This type of engine has a more efficient thermodynamic cycle. In numerical experiments, different combustible mixture compositions were tested, and different scenarios of the engine performance were obtained. The computational domain used a regular mesh of uniform cubic elements. The time-consuming parts of the numerical code were parallelized using the OpenMP technique. Our calculations were made at APK-5 with a peak performance of 5.5 Tera Flops.

1. Introduction

The optimization of combustion engines based on the traditional design schemes is now close to its technological limit. This forces to seek for some radically new technical solutions [1]. Within the last 20 years, there has been a considerable amount of research on developing engines using detonation waves to the point where propulsion engines are being developed and tested [2,4,5]. Several aspects of modeling detonation waves are being studied recently, not directly applied to the rotating detonation but, nevertheless important. For example, the work [6] investigates details of turbulence modeling; the work [7] studies the impact of chemical kinetics modeling on the detonation onset in a scramjet engine, and the work [8] deals with the ionization affecting pulse detonation characteristics.

Contrary to other types of detonation engines, the rotating detonation engines (RDEs) use a different approach toward ensuring the efficiency of the detonation cycle [3]. The RDEs utilize the continuous high-efficiency detonation mode to organize the combustion process in the chamber. Fuel and oxidizer are injected into the combustion chamber at one end, and one or more detonation waves propagate circumferentially at the head of combustion chamber consuming the fresh mixture. The products leave the combustion chamber from the other end with high axial speed to produce thrust [9]. Compared to pulse detonation engines (PDE's), the RDE can operate continuously once initiated, and the operating frequency is much higher than PDE. The RDE has a compact configuration, and it can operate under a wide-range of Mach-number conditions. Therefore, RDE has received a lot of attention in the propulsion research field.

In 1960's, Voitsekhovskii et al. [10] realized C_2H_2/O_2 continuous rotating detonation in a disk-shaped experimental rig. Nicholls et al. [11] performed feasibility studies of a rotating detonation wave rocket motor and realized short continuous detonation in an annular combustion chamber. Later, many researches performed experimental and numerical investigations on RDE. In 1990s, Bykovskii et al. [12–15] realized rotating detonation in annular chambers of different sizes and configurations using different kinds of fuels (hydrogen, propane, kerosene, etc). Kindracki et al. [16] experimentally investigated the parameter ranges of chamber pressure and chamber configuration, within which detonation waves can propagate stably, the authors also performed 2D numerical modeling. Zhdan et al. [17] performed two-dimensional numerical simulation of hydrogen/oxygen rotating detonation and analyzed the mechanism of detonation propagation. Liu et al. experimentally realized H_2/air rotating detonation in an annular chamber [18] and analyzed the propagation characteristics of rotating detonation wave near the operating boundary [19].

The shape of the combustion chamber, the injection details, and the nozzle effects on the engine performance were also investigated. Sun et al. [20] numerically investigated the effects of injector exit width on the RDE; they found that the mixing of

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hot detonation products and the newly injected combustible mixture could induce new detonation waves to change the propagation mode in the combustion chamber. Shao et al. [21,22] studied the effects of different nozzle configurations on the propulsive performance and found out that the Laval nozzle has some advantages over the other nozzle configurations. Chen et al. [23] used H_2/O_2 9 species and 19-step reaction mechanism to simulate the RDE flow field in order to study the effect of axial length on engine performance, and their results show that within a certain range of length variation axial length has little influence on specific impulse of the engine. Sun et al. [24] made further investigation of the effect of chamber axial length on engine performance and discussed the mechanism in detail. Tsuboi et al. [25] performed numerical simulations of three-dimensional rotating detonation engines for a hydrogen–oxygen mixture using the detailed chemistry model. They found that the effects of the grid resolution and the annular width are small on the specific impulse. The specific impulse for the two-waved RDE decreases approximately 10% than that for the one-waved RDE. Nordeen et al. [26] modified a 2D Euler simulation to include mixing factors to simulate the imperfect mixing of injected reactant streams. Contrary to expectations, mixing is shown to have a minimal impact on performance. Fievisohn and Yu [27] developed a method for modeling the steady-state internal flow field in a RDE using the shock expansion theory combined with the steady 2D isentropic method of characteristics. It has been shown that the method of characteristics (MOC) provides useful performance predictions along with conventional Euler simulations and at significantly less computational cost. Fotia et al. [28] experimentally tested the RDE with various nozzle configurations for the purpose of measuring the propulsive performance in terms of thrust and specific impulse. They found that for the nozzle to be choked, or even under a partial choke condition, stagnation pressure increase must be present in the combustor.

Levin et al. [29] considered a three-dimensional unsteady inviscid flow with a rotating detonation wave arising in an annular gap of an axially symmetric engine between coaxial cylinders. Dubrovskii et al. [30] used a separate supply of fuel and oxidizer in three-dimensional RDE simulations, which was also the first successful attempt to apply the full Navier–Stokes (N–S) equations with turbulence and micro mixing models and to directly compare the results with experiments [14]. In the work [31], the authors aimed to adopt the method of injection via an array of holes in three-dimensional numerical simulations of a rotating detonation engine. The calculation was based on the Euler equations coupled with a single-step Arrhenius chemistry model. Experimental investigations of rotating detonation engines and peculiarities of gaseous mixtures detonability in narrow channels are reflected in [32,33]. Numerical simulations of detonation initiation in hydrogen–air mixtures and back-flash phenomena in supersonic combustion were undertaken [34–36].

The aim of the present investigation is to study the peculiarities of the ignition process and transition stage towards the rotating detonation wave mode in 3D unsteady-state problem statement. The effects of different mixture compositions on the onset of rotating detonation wave mode and mean thrust are under consideration.

2. Mathematical model

The mathematical model consists of a system of differential equations of mass, momentum and energy balance, turbulence model, algebraic conditions and equations of state, initial and boundary conditions.

2.1. The balance equations

To model a multicomponent gas mixture with chemical transformations, and considering turbulence and transport, the following system of equations was used:

$$\frac{\partial \rho_k}{\partial t} + \frac{\partial}{\partial x_j}(\rho_k u_j) - \frac{\partial J_{k,j}}{\partial x_j} = \dot{\omega}_k; \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_i u_j) + \frac{\partial p}{\partial x_i} - \frac{\partial \tau_{i,j}}{\partial x_j} = 0; \tag{2}$$

$$\frac{\partial E_T}{\partial t} + \frac{\partial}{\partial x_j}\big((E_T + p)u_j\big) - \frac{\partial}{\partial x_j}(J_{T,j} + u_i \tau_{i,j}) = \dot{Q}. \tag{3}$$

In this system, ρ_k is partial density of a species k, $J_{k,j}$ are vector components of the species k diffusion flux, $\dot{\omega}_k$ is the intensity of the species k origination in chemical reactions, ρ is the gas mixture density, u_j are vector components of gas velocity, p is the mixture pressure, $\tau_{i,j}$ are the tensor components of viscous and turbulent stresses, E_T is total energy of the gas volume unit consisting of thermal, chemical, kinetic and turbulent energy, $J_{T,j}$ are vector components of the energy diffusion flux, $\dot{Q}$ is the heat flux from an external source.

The species index k ranges within $1 \dots N_C$, the coordinate indices i, j range among 1, 2, 3 with summation upon repeating indices in a term. Total we have got $N_C + 4$ equations in a 3D system, except for the turbulence modeling equations shown below. The turbulence modeling determines transport fluxes $J_{k,j}$ and $J_{T,j}$, and the stresses tensor which consists of a spherical part and of a deviator as $(-p\delta_{i,j} + \tau_{i,j})$. In case the turbulence is not modeled, p is thermodynamic pressure of gas.

2.2. Additional algebraic relationships

The gas mixture is determined by the set of species concentrations. One of possible sets is the set of partial densities ρ_k used in the equation (1); mixture density ρ is the sum of those densities. It is useful to introduce two other sets: mass shares of species, and molar densities, as:

$$\rho = \sum_{k=1}^{N_C} \rho_k, \qquad Y_k = \frac{\rho_k}{\rho}, \qquad X_k = \frac{\rho_k}{W_k}. \tag{4}$$

Here Y_k is the mass share of a species k, X_k is the molar density (molar concentration), W_k is the molar mass of a species.

The pressure p is defined as the spherical part of the stresses tensor (with the opposite sign), and it is a sum of thermal pressure $\tilde{p}$ of perfect gases mixture, and an additive corresponding to turbulent pulsations, which is modeled by means of the turbulent energy per mass unit K:

$$p = \tilde{p} + \frac{2}{3}\rho K, \qquad \tilde{p} = R_G T \sum_{k=1}^{N_C} X_k. \tag{5}$$

Total energy per volume unit E_T consists of internal energy (thermal and chemical), kinetic, and turbulent energy:

$$E_T = E + \rho\frac{u^2}{2} + \rho K, \quad u^2 = u_j u_j. \tag{6}$$

The internal energy per volume unit is calculated as:

$$E = \sum_{k=1}^{N_C} X_k E_k(T) = R_G T \sum_{k=1}^{N_C} X_k \cdot \big(\hat{H}_k(T) - 1\big). \tag{7}$$

Here, E_k is an internal energy per a species mole, $\hat{H}_k(T)$ is dimensionless enthalpy of a species containing the formation enthalpy

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