NUMERICAL INVESTIGATION OF MIXTURE FORMATION IN A ROTATING DETONATION ENGINE AND ITS INFLUENCE ON ENGINE OPERATION MODES

S. M. Frolov[1–3], V. A. Smetanyuk[1,2], V. S. Ivanov[1,2], and B. Basara[4]

[1]N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences
4 Kosygin Str., Moscow 119991, Russian Federation
e-mail: smfrol@chph.ras.ru

[2]Scientific Research Institute for System Analysis Russian Academy of Sciences
36-1 Nakhimovskii Prosp., Moscow 117218, Russian Federation

[3]National Research Nuclear University MEPhI (Moscow Engineering Physics Institute)
31 Kashirskoe Sh., Moscow 115409, Russian Federation

[4]AVL LIST GmbH
1 Hanz List Pl., Graz 8020, Austria

The computational technology jointly developed by the N. N. Semenov Federal Research Center for Chemical Physics and AVL LIST GmbH and validated in [1–3] is used for simulating the operation process in a Rotating Detonation Engine (RDE) with an annular combustor and with separate supply of fuel (natural gas (NG)) and oxidizer (gaseous oxygen) shown in Fig. 1. The technology is based on the coupled Finite Volume – Joint Velocity-Scalar Probability Density Function (PDF) approach suggested in [4] and implemented in [5]. The corresponding PDF equation is solved by the Monte Carlo (MC) method using lagrangian MC particles. Special attention in the study is paid to turbulent and molecular mixing of fuel and oxidizer and its effect on the RDE operation process.

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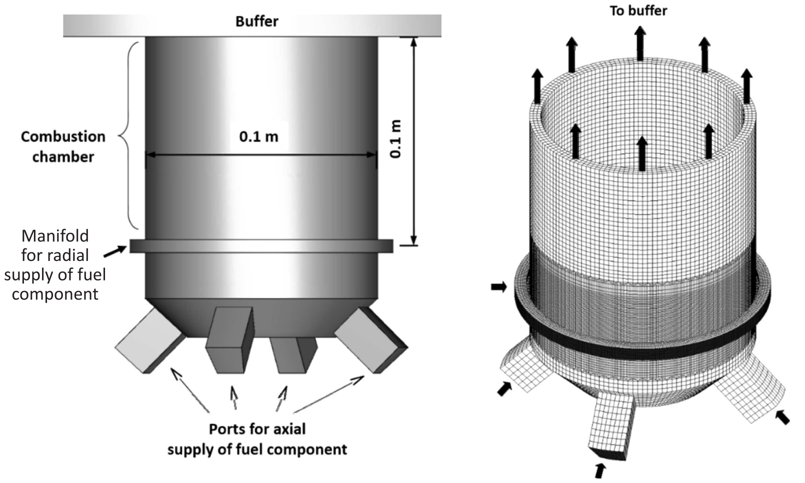

(*a*) (*b*)

Figure 1 Rotating detonation engine: (*a*) geometry; and (*b*) computational grid

Two different schemes of fuel and oxidizer supply are considered at fixed values of their mass flow rates (0.07 kg/s of NG and 0.28 kg/s of oxygen). In the first, "direct," scheme, the oxidizer is supplied axially through the annular slot, whereas the fuel is supplied radially through the belt of multiple distributed holes in the outer wall of the combustor. In the second, "inverse," scheme, the oxidizer and fuel replace each other while their mass flow rates are kept fixed. Such a replacement is shown to lead to restructuring of the operation process: the mode with three equidistant detonation waves (DWs), each ~6 mm high, rotating over the fire head of the RDE at a tangential velocity of ~2200 m/s, is replaced by the mode with a single DW, ~15 mm high, rotating at a tangential velocity of ~2400 m/s, which is the indication of approaching the marginal operation conditions.

Figure 2 compares the PDFs of the local instantaneous fuel-to-oxygen equivalence ratio Φ in the premixed gas "pockets" directly ahead of the DW front in the RDE of direct and inverse schemes obtained during one revolution of a DW in the both cases. The PDFs

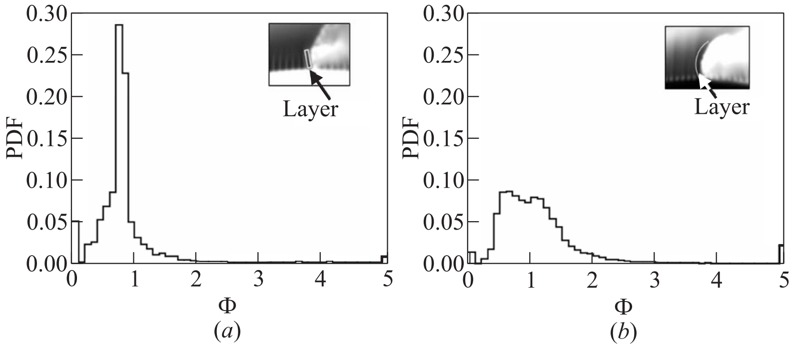

Figure 2 Particle-based PDFs of the true fuel-to-oxygen equivalence ratio Φ in the premixed gas "pockets" directly ahead of the DW front in the RDE of direct (a) and inverse (b) schemes

include only MC particles located in a thin layer ahead of the detonation front shown in the inserts of Figs. 2a and 2b. The thickness of this layer in the tangential and azimuthal directions is 2 and 5 mm, respectively, whereas its height is taken equal to the corresponding height of the DW. The PDFs are constructed for Φ ranging from 0 to 5 with the interval of 0.1. For the sake of simplicity, all MC particles with the mass fractions of methane and oxygen less than 0.025 and 0.1, respectively, are considered to consist only of the combustion products and are conditionally attributed to the interval $\Phi = 0 \ldots 0.1$. All MC particles with $\Phi > 5$ are conditionally attributed to the interval $\Phi = 4.9 \ldots 5.0$. The PDFs are normalized by the total mass of MC particles in the layer. Despite the resultant PDFs are somewhat dependent on the choice of the layer thickness, the chosen value of 2 mm provides enough statistics (over 10^5 MC particles) for making qualitative conclusions on the thermochemical state of the flow ahead of the detonation front.

As follows from Fig. 2, the PDFs are bell-shaped with some dominating values of Φ. The probability densities of finding MC particles with pure oxygen ($\Phi = 0$) and pure NG ($\Phi = \infty$) tend to zero. In the RDE of direct scheme, over 50% of mixture mass is mixed on the molecular level with $\Phi = 0.7 \ldots 0.9$ (see Fig. 2a). The mass fraction of the premixed fuel-rich gas with $\Phi > 1$ is only about 10%, while the mass fraction of combustion products (peak at $\Phi = 0 \ldots 0.1$) is about 5%. In the RDE of inverse scheme, premixed gas "pockets" with $\Phi = 0.5 \ldots 1.5$ dominate and the mass fraction of fuel-rich gas is considerably larger than in the RDE of direct scheme. The mass fraction of combustion products (peak at $\Phi = 0 \ldots 0.1$) is less than 2%, i.e., considerably lower than in the RDE of direct scheme. It is interesting that in the RDE of inverse scheme, the mass fraction of the premixed gas "pockets" with near-stoichiometric composition ($\Phi \approx 1.0$) is larger than in the RDE of direct scheme. This fact together with the finding that the fuel mixture is less diluted by hot combustion products could explain a higher value of the detonation velocity in the RDE of inverse scheme (2400 vs. 2200 m/s). Also, the operation mode with a single DW in the RDE of inverse scheme provides both a longer residence time for fuel and oxidizer in the RDE and, therefore, their longer mixing time as compared to the mode with three DWs in the RDE of direct scheme. This could explain a larger height of the DW in the RDE of inverse scheme. Nevertheless, the difference in the operation modes in the RDE of inverse and direct schemes indicates that the general quality of turbulent and molecular mixing of the fuel components in the RDE of inverse scheme is worse than in the RDE of direct scheme.

In general, the results obtained mean that the performance characteristics of RDEs are largely determined by the organization of turbulent and molecular mixing of fuel components in the region of rotation of one or more DWs. With the given mass flow rates of fuel components, there should exist the optimal conditions for delivering them to the RDE which ensure the greatest efficiency of the operation process.

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