Numerical investigation of the operating process in an annular detonation chamber of low diameter

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Abstract. Burning in unsteady rotating detonation waves is one of the ways of operating process organization in future aircraft engines. However, a minimum combustion chamber diameter in which the unsteady rotating detonation process can be actualized is a significant limitation of such engines. A possibility of hydrogen-air mixture burning in an annular chamber with a diameter of 78 mm is shown in this paper using methods of three-dimensional computational fluid dynamics. The geometry of the chamber and the modes of its operation were selected, and the influence of the total pressure of air at the inlet was studied. At the pressure of 32 bar, the mass flux in the critical section of the aerodynamic nozzle was 7349.2 kg/(s·m²). It is shown that in a rotating reference frame in which the detonation wave is at rest, streamlines come to the wavefront almost at right angles. This fact allows making simple estimates of the fresh mixture parameters in front of the wave. Comparison with the detonation parameters in a premixed hydrogen-air mixture in the tube showed that the velocity of the detonation wave in the chamber is 0.65-0.74 of the Chapman-Jouguet detonation velocity, and its height is approximately equal to the characteristic size of the cellular structure of the detonation.

1. Introduction
One of the promising directions in modern high-speed aircraft designing is the development of ramjet engines with combustion in continuously rotating detonation waves (rotation detonation engines, RDE). Although the comparison of the thermodynamic efficiency of classical ramjets and engines with detonation combustion still requires discussion [1-3]. One of the advantages of RDEs is the possibility to shorten the combustion chamber (CC) length provided good enough mixing of fuel and oxidizer. At the same time, the RDE CC has a significant limitation, which is not inherent in the ramjet CC, namely, the minimum diameter at which the continuous rotating detonation (CRD) can be implemented.

So, in [4] it is reported that when using air as an oxidizer, the diameter of the CC equal to 100 mm was insufficient, and detonation combustion of the mixtures was carried out in the CC with a diameter of 306 mm. It was also shown [5] that the two-dimensional mathematical model of RDE with a premixed fuel-air mixture and the boundary conditions described in [6] does not allow estimating the effect of the physical dimensions of CC on the existence of detonation.

In [4], the existence region of the CRD in the hydrogen-air mixture was determined at mass flux in the CC $j_c = G/F_c$ ranging from 60 to 110 kg/(s·m²), where $G$ is the total mass flow rate (MFR), $F_c$ is the CC cross-section area. The feasibility of CRD in CC with a diameter of less than 100 mm at large values of $j_c$, flow structure, and characteristics of the operating process were numerically studied in this work.

Tasks were solved in a three-dimensional definition, with separate fuel and oxidizer supply.
2. Problem formulation
Combustion chambers with a diameter of 78 mm, which were connected to aerodynamic nozzles with smooth generatrices, were considered (figure 1). Initially, as in [4], the fuel injectors were located in the cylindrical part of the CC (this design variant is not shown in the diagram). But this led to strong pressure growth in this area, a strong relief of the DW in the direction of the critical section, to a decrease in air flow and, as a result, to the attenuation of the DW. Therefore, it was decided to place the fuel injectors in the conical part of the central body (CB), and significantly reduce the length of the cylindrical one.

Further, as in [7], a position of the fuel supply point was chosen, at which a stable mode of CRD was ensured. The Mach number of the air flow in front of the injectors was 2.5. At that, 32 spray injectors 1.1 mm in diameter were arranged in one belt. Their number and diameter were selected in such a way that the height of the fuel jet was at least a half CC gap, and a sufficiently uniform concentration field was provided as close to the feed point as possible. At the same time, the maximum pressure in the fuel collector and air flow did not exceed 100 bar and 4.5 kg/s, respectively.

Figure 1 shows the final installation diagram.

![Figure 1. General scheme of the model. Dimensions are in mm.](image)

The total air and fuel temperatures $T_a^*$ and $T_f^*$ were 300 K. The total inlet air pressure $p_a^*$ was varied, and the total fuel pressure $p_f^*$ was selected according to $p_a^*$ and the excess air coefficient $\alpha$, the outlet pressure was 1 bar.

3. Calculation method
The flow calculations were carried out in a three-dimensional formulation using the program package developed in CIAM for integrating the complete averaged system of Navier-Stokes equations for a reacting mixture of compressible gases with variable thermophysical properties [8,9]. A one-parameter turbulence model vt-90 [10] was used. The unsteady problem was solved numerically by the method based on the implicit scheme of S.K. Godunov with an increased order of accuracy in spatial coordinates.

To calculate the substances formation rates, the kinetics model of chemical reactions of the H$_2$-O$_2$ mixture [11] was used. The software package with this kinetic mechanism was tested in the simulation of various experiments, including mixing and combustion in supersonic flows of fuel and oxidizer [12].

The Chapman-Jouguet (CJ) DW velocity was also found during calculating the parameters of the equilibrium composition of the hydrogen-air mixture using the algorithm described in [13].

A structured grid was built with a total volume of 1.7 million cells; the gap in the CC was 30 cells. First, the flow in the combustion chamber was calculated with fuel supply, but in the absence of combustion. The DW was initiated by setting a significant azimuthal velocity in a small flow region, which made it possible to set the initial propagation direction of the initiating shock wave (SW). The attainment of the CC steady-state operation mode was monitored by the time dependence of mass flow rates. Such dependences, calculated at $p_a^* = 15$ bar, $\alpha = 1.5$ are shown in Figure 2.

During data processing, the time-dependences of pressure was built at a point located on the surface of the CB slightly downstream of the fuel supply zone. The DW passage frequency was determined from these curves.
Figure 2. Dependences of the mass flow rate through the critical section $G_{cr}$, mass flow rate through the outlet section $G_{out}$ and static pressure at a point on physical time ($p_a^* = 15 \text{ bar}, \alpha = 1.5$).

4. The general results of the calculations
In the beginning, a calculation was conducted for $p_a^* = 32 \text{ bar}, \alpha = 1$. Figure 3 (a) shows the distribution of static pressure on the CC walls. It is clearly seen that the maximum pressure on the outer wall significantly exceeds the pressure on the inner wall, i.e. DW has a higher intensity near the outer wall. Figure 3(b) shows the field of Mach numbers on an imaginary cylindrical surface, which is equidistant from the outer wall and the central body wall in the critical section, with axis coinciding with the CS axis. It can be noted that there is a sufficiently extended subsonic region in the critical section ($x = 0$) behind the DW, i.e. the pressure drop is not supercritical, and disturbances penetrate into the subsonic part of the aerodynamic nozzle. Indeed, in this calculation, the mass flow rate did not achieve a steady-state value as in Figure 1, and was significantly less than the theoretically possible $G_{\text{theor}}$ for given $p_a^*$, $T_a^*$ and $F_{cr}$ (see table 1).

Figure 3. The field of static pressure on the outer wall and the CB (a), and the field of Mach numbers on the cylindrical surface (b) for $p_a^* = 32 \text{ bar}, \alpha = 1$.

At $p_a^* = 32 \text{ bar}, \alpha = 1.5$, the fuel consumption was decreased, the DW intensity and the pressure in the chamber were decreased as well so that the pressure drop became supercritical, and the air flow increased, almost reaching the theoretically possible value.

Further, at a constant $\alpha = 1.5$ $p_a^*$ decreased stepwise to a value of 5 bar. In this case, the propagation frequency of the DW $f$ and their velocity $D$ (see Table 1) did not decrease monotonically as $p_a^*$ decreased, in contrast to the experiment [4]. At $p_a^* = 5 \text{ bar}$ the influence of atmospheric pressure at the outlet became...
significant, as in [14], subsonic regions appeared downstream of the DW. But the pressure drop in the aerodynamic nozzle still remained supercritical. In [4] the CRD mode for a hydrogen-air mixture in a CC with a conical central body was obtained within the range of mass fluxes in the CC changed from \( j_{c_{\min}} = 60 \) at \( \alpha = 1.25 \) to \( j_{c_{\max}} = 110 \text{ kg/(s·m}^2 \) at \( \alpha = 0.83 \), and it also was noted about a positive effect of \( j_c \) increase on the stability of DW parameters. For the model shown in Figure 1, due to the almost absence of the cylindrical part of the CB, it is difficult to calculate the correct \( j_c \), because \( j_{c_{\min}} \) and \( j_{c_{\max}} \) were recalculated for the critical section taking into account the fuel supply and geometry of the CC (CC gap \( \Delta = 2.3 \text{ cm} \), critical section gap \( \delta = 2 \text{ mm} \), CC diameter \( d_c = 306 \text{ mm} \)): \( j_{c_{\min}} = 658, j_{c_{\max}} = 1221 \), that is, in all the considered modes, except the mode with \( p_s^* = 5 \text{ bar} \), \( \alpha = 1.5, j_c > j_{c_{\max}} \).

It should also be noted that during CC launch several DWs appeared, but all of them except for the main one decayed.

**Table 1. Flow parameters in CC**

| \( p_s^*, \text{bar} \) | \( \alpha \) | \( f, \text{Hz} \) | \( D, \text{m/s} \) | \( D_0/D_{CJ} \) | \( h, \text{mm} \) | \( h/\alpha \) | \( G, \text{kg/s} \) | \( G_{\text{theor}}, \text{kg/s} \) | \( j_{c_r}, \text{kg/m}^2 \) |
|---------------------|--------|-------------|----------------|----------------|----------------|--------|----------------|----------------|-------------|
| 32                  | 1      | 5970        | 1195           | 0.74           | 26             | N/D    | 3.654          | 4.425          | 6193.2      |
| 32                  | 1.5    | 5348        | 1070           | 0.663          | 31             | N/D    | 4.336          | 4.425          | 7349.2      |
| 25                  | 1.5    | 5128        | 1026           | 0.651          | 35             | N/D    | 3.374          | 3.457          | 5718.6      |
| 20                  | 1.5    | 5714        | 1144           | 0.751          | 36             | N/D    | 2.67           | 2.766          | 4525.4      |
| 15                  | 1.5    | 5405        | 1082           | 0.73           | 29             | N/D    | 1.978          | 2.074          | 3535.2      |
| 10                  | 1.5    | 6061        | 1213           | 0.748          | 32             | 0.941  | 1.322          | 1.383          | 2240.7      |
| 7.5                 | 1.5    | 5682        | 1137           | 0.708          | 36             | 0.766  | 0.969          | 1.037          | 1642.4      |
| 5                   | 1.5    | 5587        | 1118           | 0.719          | 40             | 1.121  | 0.661          | 0.692          | 1120.3      |

5. DW characteristics estimation

### 5.1. Parameters of a fresh mixture

In Fig. 4, streamlines plotted against the pressure field correspond to the flow velocity components in a rotating reference frame (RF), in which the DW is at rest. It can be noticed that the streamlines enter the DW almost at right angles. This provides a basis for estimating the axial component of mixture velocity in the DW front:

\[
 u_m = Dc\tan \beta,
\]

where \( D \) is the azimuthal component of the DW velocity determined by the frequency \( f \), \( \beta \) is the angle between the plane of the DW and the vector of the instantaneous velocity of its propagation in the laboratory RF (in Fig. 4 this direction coincides with the shock wave SW2, which is formed during the interaction of the air flow with hydrogen jets).

The estimation of mixture temperature before the DW is based on the fact that the total enthalpy is preserved along the streamline in the axial direction:

\[
 T_m = T_m^* = u_m^* \gamma_m - \frac{1}{2} \frac{\mu_m}{\gamma_m} R,
\]

where \( T_m^* \) is the total temperature of the hydrogen-air mixture, equal to 300 K, \( \gamma_m \) and \( \mu_m \) are adiabatic index and molar mass of the mixture, respectively. To estimate the total pressure, the coefficient of total pressure recovery \( \sigma_{\text{SW2}} = 0.57 \) which reflects the losses arising on SW2 and during jets mixing, was preliminary calculated from the computations conducted without burning at \( \alpha = 1.5 \).

The total pressure was estimated by the formula

\[
 p_m = P_s^* \sigma \left( \frac{T_m^*}{T_m} \right)^{\gamma_m - 1}.
\]
Thus, at $p_a^* = 10$ bar, $\alpha = 1.5$ angle $\beta = 67^\circ$. According to these data, we obtain $u_m = 510$ m/s, $T_m = 198$ K, $p_m = 1.31$ bar, which agrees quite well with the three-dimensional calculation. For these parameters, it is possible to find the CJ velocity $D_{CJ}$ by calculating the equilibrium composition of the mixture. $D_0 = D / \sin \beta$ – is the velocity of the fresh mixture flowing into the DW in RF, at which the DW is at rest. $D_0 / D_{CJ}$ is given in table 1.

**Figure 4.** The pressure field in the part of the cylindrical surface, where the DW is passing; streamlines in a rotating RF associated with the DW. $p_a^* = 25$ bar, $\alpha = 1.5$

### 5.2. DW height

The DW height $h$ (see Figure 4) was measured from SW2 in the three-dimensional calculation, i.e. from the place of fuel supply. As it can be seen from Table 1, $h$ changes not monotonously and rather weakly as $p_a^*$ decreases. For some calculations for $p_m$, $T_m$, and $\alpha$, according to the experimental data [15, 16], detonation cell sizes $a$ were found. Some of $h/a$ ratios are shown in Table 1. The DW height turned out to be close to the detonation cell size.

From the height $h$ one can also estimate the axial component of the slow combustion front propagation velocity with respect to the fresh mixture. This front is adjacent to the mixture. The estimation can be done, if we assume that during one revolution of the DW the front of slow combustion moves a distance $h$ from the fuel supply zone:

$$u_{fl} = u_m - hf$$

So, for example, for $p_a^* = 10$ bar, $\alpha = 1.5$ $u_{fl} = 312$ m/s, which is already approaching the speed of sound in the mixture.

### Conclusions

A possibility of hydrogen-air mixture burning in an annular chamber 78 mm in diameter is shown in this paper using methods of three-dimensional computational fluid dynamics. The geometry of the chamber and the modes of its operation were selected, and the influence of the total pressure of air at the inlet was studied. At a pressure of 32 bar, the mass flux in the critical section of the aerodynamic nozzle was $7349.2$ kg/(s·m$^2$).

It is shown that in a rotating reference frame in which the detonation wave is at rest, streamlines come to the wave front almost at right angles. This fact allows simple estimates of the fresh mixture parameters in front of the wave to be made. Comparison with the detonation parameters in a premixed hydrogen-air mixture in the tube showed that the velocity of the detonation wave in the chamber is $0.65$-
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