HYDROGEN-FUELED CONTINUOUS DETONATION COMBUSTORS OF DIFFERENT SCALE: THREE-DIMENSIONAL SIMULATIONS AND EXPERIMENTS

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1 Introduction

Combustion chamber with a continuous detonation was first studied by Voitsekhovskii in 1959 [1]. One of possible configurations of the continuous detonation combustor (CDC) is an annular channel formed by the walls of the two coaxial cylinders. If the bottom of the annular channel is equipped with an injector head and the other end of the channel is equipped with a nozzle, one obtains the annular jet engine. Detonative combustion in such a chamber can be arranged by starting a supply of fuel mixture through the injector head, producing a single ignition pulse for detonation initiation, and burning fuel mixture supplied through the injector head in a detonation wave continuously circulating above the chamber bottom. The detonation wave will burn the fuel mixture newly arrived in the CDC during one revolution of the wave around the circumference of the annular channel. The rotation frequency of the detonation waves in the CDC is determined by the mean diameter of the annular gap, the mean propagation velocity of the wave, and the number of waves simultaneously rotating above the bottom. The main advantages of such combustors include better propulsion performance due to pressure gain combustion [2], quasi-steady outflow of detonation products due to high frequency cycles, short combustion chamber, simple design, and a single ignition.

In 2010–2014, our research team has developed a computational technology aimed at computer-aided design of CDC for jet engines. The technology was first successfully validated against available experimental results [3] (see [4]) and then was used for the design of own large-scale hydrogen–air CDC [5]. Reported herein is the brief description of the technology, and some results of its validation against experimental data [3] and [5].

2 Continuous Detonation Combustors

2.1 Continuous detonation combustor of Lavrentyev Institute of Hydrodynamics

Schematic of the experimental CDC designed and extensively tested in Lavretiev Institute of Hydrodynamics (LIH) is reported in [3]. Figure 1 reproduces this schematic in the form of the computational domain comprising air receiver *1*, air inlet port *2*, air plenum *3*, fuel plenum *4*, CDC *5*, and outlet receiver *6* with the dimensions of basic elements. The combustor is axisymmetrical annular channel with

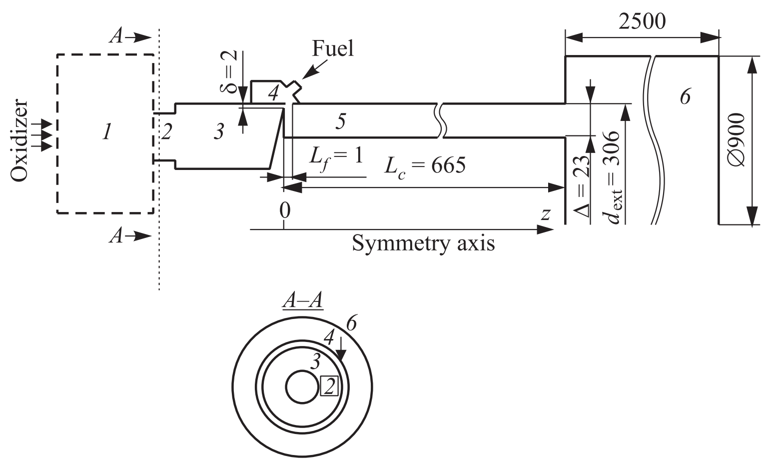
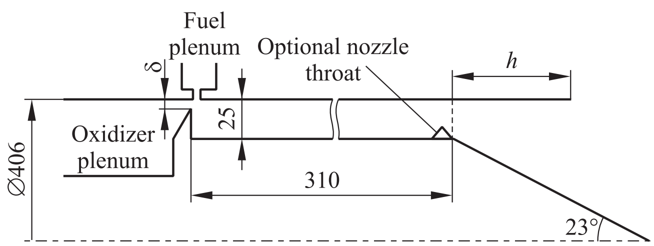


Figure 1 Continuous detonation combustor of Lavrentyev Institute of Hydrodynamics [3]. Dimensions are in millimeters

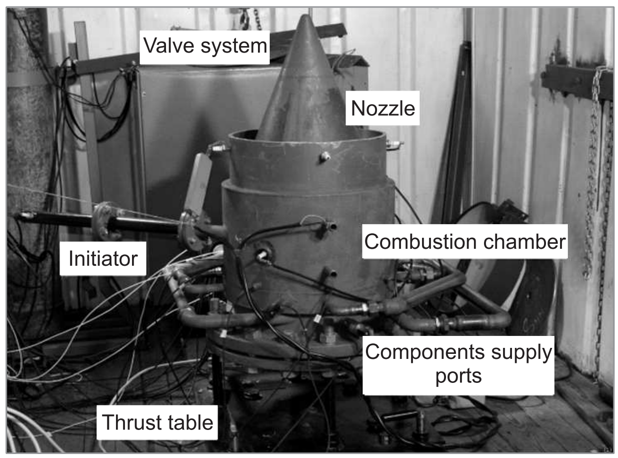
inner and outer diameters of the annular gap $d_{\text{int}} = 260$ mm and $d_{\text{ext}} = 306$ mm, respectively (width of the gap $\Delta = 23$ mm) and length $z = L_c = 665$ mm. The axial distance z is measured from the CDC bottom ($z = 0$). Between the bottom and the outer CDC wall, there is an annular gap of width $\delta = 2$ mm for supplying air from air plenum in the axial direction. Fuel (hydrogen) is supplied to the chamber from the fuel plenum in a radial direction through identical holes equally spaced around the circumference of the CDC outer wall at a distance $z = L_f = 1$ mm. The total cross-sectional area of fuel holes $S_f = 0.4$ cm^2.

2.2 Continuous detonation combustor of Semenov Institute of Chemical Physics

The outdoor experimental facility of Semenov Institute of Chemical Physics (ICP) comprises the air receiver 1.28 m^3 in volume and hydrogen receiver 0.64 m^3 in volume, both designed for the maximum overpressure up to 60 atm, fast-response ($\sim$ 100 ms) valve system with the manifold diameter of 40 mm allowing for the total mass flow rate of fuel components up to 10 kg/s, water cooled CDC, control system, and data acquisition system. Figure 2 shows the schematic and photograph of the CDC [5]. The CDC is the annular combustion chamber with the outer diameter of 406 mm and height of 310 mm. The annular gap width is 25 mm. Air is supplied to the CDC oxidizer plenum through four side tubes of round cross section connected to the outer CDC wall tangentially, so that the butt end of the CDC is closed. From the plenum, air flows axially into the combustion chamber through the sharp-edge annular air-inlet slit of width δ. Hydrogen is supplied to the CDC fuel plenum attached to the outer wall and enters the combustion chamber through 240 radial holes 1 mm in diameter equally distributed along the circumference at a distance of 1 mm above the air-inlet slit. The CDC is equipped with a detonation initiator, a tube 26 mm in diameter and 600 mm long with inlet ports for fuel (hydrogen) and oxidizer (air), two automotive spark plugs and 400-millimeter long Shchelkin spiral ensuring reliable deflagration-to-detonation transition inside the tube and detonation transmission into the annular gap of the CDC. The initiator tube is attached to the CDC tangentially at a distance of 150 mm above the air-inlet slit and has its own feed system



(*a*)



(*b*)

Figure 2 Continuous detonation combustor of Semenov Institute of Chemical Physics [6]: (*a*) main dimensions in millimeters; and (*b*) photograph

for the supply of fuel mixture components. The far end of the CDC is open to the atmosphere via the outlet nozzle with a conical center body and removable outer extension of length h. The half-angle of the cone is 23°. The CDC is installed vertically on a thrust table in a compartment with the removable roof.

The data acquisition system comprises 16 ionization probes with power supply unit, 4 low-frequency and 3 high-frequency pressure transducers all connected to the personal computer via an analog-to-digital converter. The ionization probes are installed in the outer CDC wall in two lines: axial line with 9 probes and circumferential line with 7 probes plus one common probe. Low-frequency pressure transducers are mounted in the supply manifolds of oxidizer and fuel, as well as in the oxidizer and fuel plenums of the CDC and are used for monitoring time histories of air and hydrogen pressure. High-frequency pressure transducers are used to measure local instantaneous static pressure in the air plenum and in two locations of the combustion chamber. The records of ionization probes allow obtaining information on the detonation propagation velocity and direction, detonation wave height, the number of detonation waves, simultaneously rotating in the CDC, and many other specific features of the phenomenon. Processing of the records by scaling the level of signal in terms of greyscale allows "visualization" of the flow. The detonation propagation velocity can be also obtained based on the records of high-frequency pressure transducers mounted in the combustion chamber. Thrust is measured by the calibrated strain gauge (load cell) installed underneath the thrust table and connected to the data acquisition system.

The experimental procedure is as follows. After activation by an analog switch, the control system successively activates the air and hydrogen valves of the CDC and the valves in the initiator feed system. The delay time of hydrogen valve activation is 200 ms. Thereafter, upon 200 ms, the control system activates ignition in the initiator tube resulting in deflagration-to-detonation transition and transmission of a detonation wave from the tube to the annular gap of the CDC followed by the establishment of the operation mode with one or several detonation waves continuously circulating above the circumferential row of hydrogen holes. The CDC operation time preset in the control system is usually limited by 2 s (without water cooling) and results in several thousand rotations of the detonation waves in the annular gap. The operation is terminated by successive deactivation of the hydrogen and air valves.

3 Numerical Simulations

3.1 Mathematical model

The physicochemical processes in the CDC were simulated using the mathematical model described elsewhere [4]. Here, we limit ourselves to a brief description of its main features. The flow of a viscous compressible gas in the CDC was described using the three-dimensional time-dependent Reynolds-averaged Navier–Stokes, energy, and species conservation equations for a multicomponent mixture. The turbulent fluxes of species, momentum, and energy were modeled within the framework of the standard k–ε turbulence model. Given that all physicochemical processes in the CDC occur in a very short time, the contribution from the frontal (laminar and/or turbulent) combustion to the chemical sources in the equations of conservation of energy and components of the mixture was neglected. The contributions of these reactions to the indicated bulk chemical sources were determined using the particle method (PM). The most important advantage of the PM is its ability to accurately determine the rates of chemical reactions in a turbulent flow without invoking any hypothesis about the influence of turbulent fluctuations of the temperature and concentrations of the reactants on the mean rate of the reaction. In the PM algorithm, the instantaneous local states of a turbulent reacting flow are represented as a set of interacting (Lagrangian) particles. Each particle has its individual properties: the position in space, three velocity components, volume, density, temperature, mass fractions of chemical components, and statistical weight, which is used to determine the mean values of the variables over the ensemble of particles. For each particle, the system of equations of conservation of mass of the species, momentum, and energy is solved; the flux (transfer) terms are calculated using the classic models of linear relaxation to the mean. The equations of the model were closed by the caloric and thermal equations of state of a mixture of ideal gases with variable specific heats, as well as by the initial and boundary conditions. All the thermophysical parameters of the gas were considered variable.

3.2 Computational approach

Numerical solution of the governing equations of the problem was carried out using the coupled algorithm "Semiimplicit method for pressure-linked equations (SIMPLE) – Monte-Carlo method" [4]. The chemical sources were calculated by an implicit scheme with an internal time step of integration. The coupled algorithm was previously used to simulate flame acceleration and deflagration-to-detonation transition in smooth tubes and in tubes with obstacles, as well as to solve the problems of shock-initiated autoignition and preflame ignition in confined spaces. In all cases, satisfactory agreement between the results of calculations and experiments were observed. In addition, this algorithm was used to solve the problem of the limits of existence of detonation in the CDC operating on homogeneous hydrogen–air mixture.

In the present work, fuel and oxidizer were hydrogen and air which are supplied separately to the CDC. The oxidation of hydrogen was described by a single-step reaction scheme:

$$H_2 + H_2 + O_2 = H_2O + H_2O\,. \tag{1}$$

In the Arrhenius expression for the rate of this reaction, the preexponential factor and the activation energy were taken dependent on the mixture equivalence ratio and pressure P. Their values were obtained by fitting the functional dependencies of the induction period on pressure, temperature, and equivalence ratio to the dependences obtained by a validated detailed kinetic mechanism of hydrogen oxidation [6]. The fitting is made for wide ranges of pressure (from 0.5 to 80 atm), temperature (900–2000 K), and equivalence ratio (from 0.2 to 5.0). Because reaction (1) does not take water dissociation into account, the heat of reaction (1) was modified to make the calculated Chapman–Jouguet detonation velocity for stoichiometric hydrogen–air mixture consistent with its thermodynamic value ($\approx$ 1970 m/s).

Computational domains comprised a CDC (either LIH or ICP) attached to large inlet and outlet receivers to avoid the influence of open boundary conditions on the operation process. The total number of computational cells was usually 5 to 10 million. The computational cells were compressed towards the CDC bottom with the minimum cell size of 0.2 mm.

The boundary conditions for the average flow velocity, pressure, temperature, turbulent kinetic energy and its dissipation rate, and mean concentrations of chemical components on the solid walls of a CDC were set using the formalism of wall functions on the assumption that the walls are isothermal at 293.15 K, impermeable, and noncatalytic, with no-slip properties. The inlet boundary conditions for air and hydrogen streams were taken in the form of fixed values of pressure, temperature, turbulent kinetic energy and its dissipation rate, and the mass fractions of air and fuel, respectively. The outlet boundary condition was set at the boundaries of the outlet receiver in the form of von Neumann condition, grad$(P) = 0$. The rest of the variables were extrapolated to these boundaries from the computational domain. Special calculations demonstrated that the specified boundary conditions at the outlet receiver boundaries produced no effect whatsoever on the solution. Calculations were performed using message passing interface (MPI) and up to 300 CPUs.

The calculation procedure was started with purging the CDC with air and hydrogen to form a 10–15-centimeter-thick active layer of hydrogen–air mixture over the CDC bottom. Then, the procedure of detonation initiation was performed. This procedure implied rapid burning of particles located in the initiator region, a limited-size area in the active layer. The combustion of the particles rapidly raised the pressure in the initiator region, thereby forming an initiating shock wave.

4 Comparison of Calculations with Experiments

4.1 Continuous detonation combustor of Lavrentyev Institute of Hydrodynamics

To directly compare the results of calculations with experiments [3], calculations for the CDC of LIH were performed for air inlet pressure of 22.5 atm and hydrogen inlet pressure of 37 atm.

Figure 3 shows predicted time histories of static pressure at various CDC points: at a point on the outer wall at $z = 40$ mm (Fig. 3*a*) and at a point on the inner wall at $z = 40$ mm (Fig. 3*b*).

In addition, Fig. 4 shows instantaneous distributions of static pressure, static temperature, and flow Mach number vs. azimuthal angle φ along the outer and inner wall and along the circumference in the middle of annular gap at $z = 665$ mm (CDC exit) at time 7.1 ms, when steady-state mode of continuous-detonation combustion is already established in the CDC.

Comparison of Figs. 3*a* and 3*b* shows that the detonation pressure peak on the CDC outer wall is significantly (more than by a factor of 3) higher than on the inner wall, which is caused by the diffraction of a detonation wave at the compressive (outer) and expansive (inner) walls of the cylindrical annulus. Despite static pressure tends to even

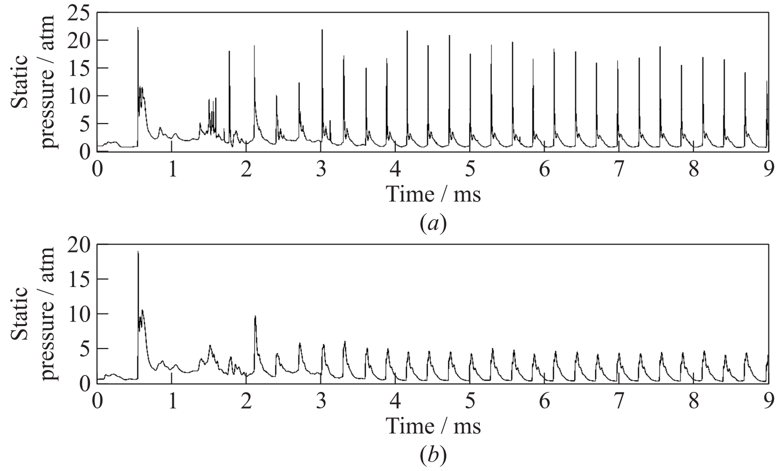


Figure 3 Calculated time histories of static pressure in different CDC points: (a) at a point located on the outer wall at $z = 40$ mm; and (b) at a point located on the inner wall at $z = 40$ mm

out across the annular gap with distance z from the CDC bottom (see Fig. 4a), the distributions of other flow parameters remain essentially nonuniform till the CDC exit (see Figs. 4b and 4c). This fact indicates that physical and chemical processes in the annular CDC are essentially three-dimensional, and the use of flat two-dimensional approximation is not justified in general. In addition, Fig. 4c shows that the flow at the CDC exit is not supersonic as is often assumed in two-dimensional numerical simulations. Wide regions with subsonic flow exist even in the middle of the annular gap, whereas near the inner and outer CDC walls, the flow is seen to be always subsonic.

Analysis of Figs. 3 and 4 and other results of calculations shows that the CDC steadily operates in the mode with two detonation waves simultaneously rotating in one direction above the CDC bottom. The maximum height of the active layer of hydrogen–air mixture directly in front of each of the detonation wave is 120 mm. The time-averaged static pressure in the CDC at $z = 100$ mm is 1.6 atm. The steady state mass flow rates of air and hydrogen are 3.4 and 0.107 kg/s. These results correspond well with the experimental data [3].

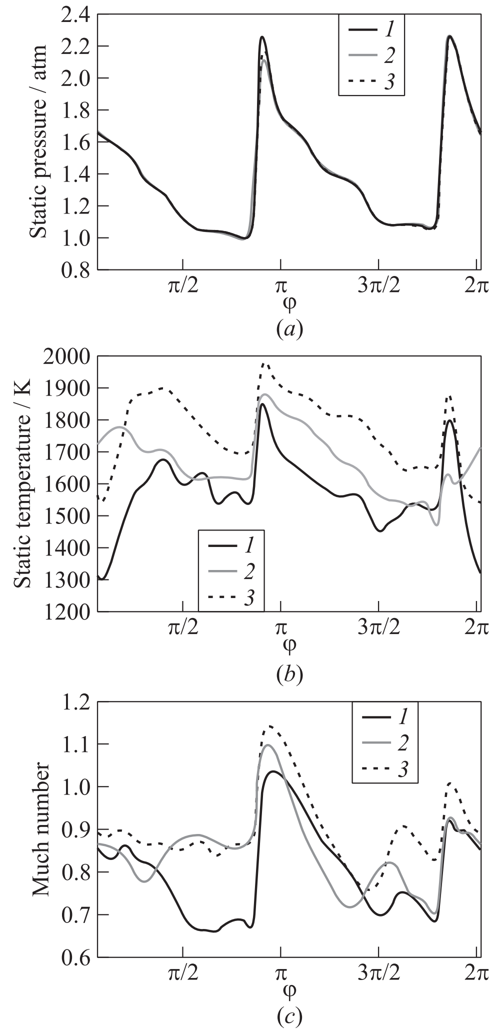


Figure 4 Instantaneous distributions of static pressure (*a*), static temperature (*b*), and flow Mach number (*c*) vs. azimuthal angle φ along the outer (*1*) and inner (*2*) walls, and along the circumference in the middle of annular gap (*3*) at $z = 665$ mm, at time 7.1 ms when steady-state mode of continuous-detonation combustion is already established in the CDC

4.2 Continuous detonation combustor of Semenov Institute of Chemical Physics

To directly compare the results of calculations with experiments [5], calculations for the CDC of ICP were performed for air inlet pressure of 4 atm and hydrogen inlet pressure of 18 atm.

Figure 5 shows the predicted snapshots of temperature, static pressure, mass fraction of hydrogen, and flow Mach number near the outer wall of the CDC operating in the continuous detonation mode with one detonation wave. The snapshots in Fig. 5 correspond to time instant 7.65 ms after ignition.

Some specific features of the flow pattern in the CDC are worth mentioning. First, the reaction zone behind the propagating detonation wave is highly nonuniform (Fig. 5*a*) and exhibits strong transverse shock

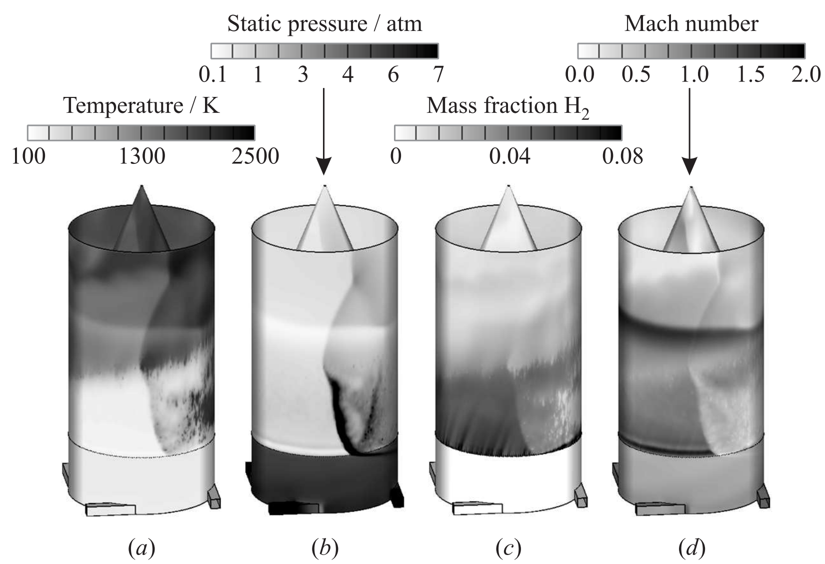


Figure 5 Predicted snapshots of temperature (*a*), static pressure (*b*), mass fraction of hydrogen (*c*), and flow Mach number (*d*) near the outer wall of the CDC operating in the continuous detonation mode with one detonation wave at air and hydrogen supply pressures of 4 and 18 atm. Detonation propagates from right to left. Time: 7.65 ms after ignition

waves (Fig. 5*b*). Second, the mixture composition in front of the propagating detonation is highly nonuniform (Fig. 5*c*). Third, an intense bow shock penetrates in the air manifold (see Fig. 5*b*) but this bow shock does not induce the backflow of reactive mixture and detonation products in the air manifold (see Figs. 5*c* and 5*a*). Fourth, the height of the detonation wave is about 200–220 mm, i. e., about 8–9 times the gap width (25 mm) (see Figs. 5*a* and 5*b*). Finally, the flow of detonation products becomes supersonic slightly above the detonation wave, passes through the Mach disk, and becomes subsonic but highly nonuniform in the outlet nozzle (see Fig. 5*d*). The latter indicates that the nozzle in the CDC is not optimized.

Figure 6 compares the predicted (point) detonation rotation frequency in the CDC with the experimental curve for similar initial and boundary conditions in terms of the air and hydrogen supply pressures (4 and 18 atm). The calculated mass flow rates of air and hydrogen in the CDC at these conditions are 6.4 and 0.26 kg/s, respectively, which corresponds within 5% to the experimental values. The overall mixture composition is hydrogen-rich with the fuel–air equivalence ratio of 1.4. Both in calculations and in experiment, the operation mode with one rotating detonation wave with a very similar rotation frequency (1460–1490 Hz) is obtained. This rotation frequency corresponds to the detonation propagation velocity 1860 m/s which is close to the thermodynamic detonation velocity in the stoichiometric hydrogen–air mixture ($\sim$ 1970 m/s) but is somewhat lower than the thermodynamic detonation velocity for fuel-rich hydrogen–air mixture with the equivalence ratio of 1.4 ($\sim$ 2065 m/s) due to obviously incomplete reaction and momentum/energy losses.

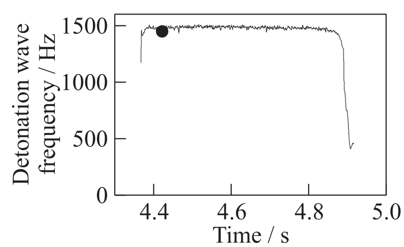


Figure 6 Predicted (point) and measured (curve) [5] frequencies of detonation rotation in the CDC with air and hydrogen supply pressures of 4 and 18 atm

Figure 7 compares the predicted thrust level (point) of the CDC with the measured thrust curve in the same computational and experimental runs as in Fig. 6. Note that Fig. 7 shows the full thrust produced

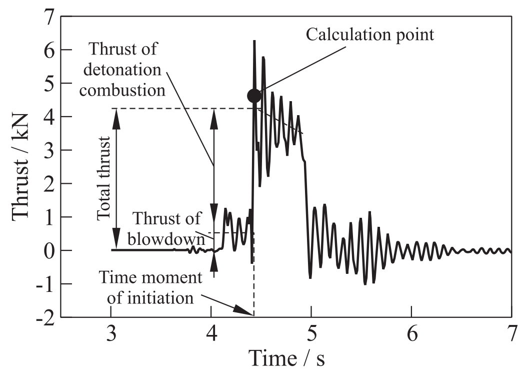


Figure 7 Predicted (point) and measured (curve) [5] thrust produced by the CDC with air and hydrogen supply pressures of 4 and 18 atm

by both air and hydrogen blowdown process and by a detonative combustion. As is seen, the predicted thrust level of 4.5 kN agrees within 7% with the measured value of ~ 4.3 kN at the onset of detonative combustion in the CDC. Note that the calculations were made for the fixed values of static pressures of air and hydrogen in manifolds, whereas in the course of the experiment, these values slightly decayed resulting in the decrease of thrust (see the descending dashed line in Fig. 7). Note also that in the calculations, the thrust was determined as the integral pressure force acting on all rigid surfaces of the CDC, i. e., viscous forces were not taken into account. The account of viscous friction at rigid walls will inevitably decrease the predicted thrust level but not much.

5 Concluding Remarks

The computational technology for computer-aided design of jet engines operating on continuously rotating detonations has been validated against experiments with two large-scale hydrogen–air CDCs of outer diameters 306 and 406 mm and total mass flow rate of fuel mixture up to 7 kg/s. Computational predictions in terms of different qualitative and quantitative features (existence of the detonation mode, mass flow rates of air and hydrogen, detonation wave velocity and height, the number of simultaneously rotating detonation waves, the height of the detonation wave, mean flow parameters in the CDC, thrust, etc.) were directly compared with experimental data. It appeared that the computational technology taking into account finite-rate chemistry of hydrogen oxidation and turbulence–chemistry interaction provides excellent agreement with experimental data and can be used for design optimization aimed at the improvement of CDC propulsion performance.

Acknowledgments

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