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Large-scale hydrogen–air continuous detonation combustor

S.M. Frolov [a,b,c,*], V.S. Aksenov [a,b,c], V.S. Ivanov [a,b], I.O. Shamshin [a,b,c]

[a] Centre for Pulse Detonation Combustion, Moscow, Russia
[b] N.N. Semenov Institute of Chemical Physics, Moscow, Russia
[c] National Research Nuclear University "Moscow Engineering Physics Institute" (NRNU MEPhI), Moscow, Russia

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ABSTRACT

A large-scale continuous detonation combustor (CDC) has been designed, fabricated and tested to study the effect of different design elements on the operation process and CDC propulsion performance. It has been shown experimentally that widening of the air-inlet slit in the annular combustion chamber from 2 to 15 mm leads to a decrease in the number of detonation waves (DWs) simultaneously circulating in the combustor from four to one and, finally, to transition to the operation mode with intermittent (pulse) longitudinal reaction waves resembling pulse detonations. The number of DWs and the thrust produced by the CDC can be increased by installing a shaped obstacle at the CDC exit nozzle providing the blockage of the combustor cross section. The maximum net thrust produced by the CDC attained 6 kN at the total mass flow rate of fuel components of 7.5 kg/s, whereas the maximum fuel-based specific impulse attained ~3000 s.

Introduction

Advanced combustors operating on detonations continuously rotating in annular combustion chamber attract growing interest worldwide in view of their potential benefits as compared to existing combustors operating in a conventional deflagration mode. According to Zel'dovich [1], the main theoretical benefit of detonation combustors is a considerable gain in their efficiency. Development of hydrogen-fueled combustors of this type are, on the one hand, a good way to advance in the new technology because of high detonability of hydrogen in mixtures with both oxygen and air. On the other hand, hydrogen-fueled combustors of the new type can find numerous applications in "green" power engineering with turbo machinery and in autonomous power plants supplementing hydrogen fuel cells to cover peak electrical loads.

The idea of the combustion chamber with a continuous detonation was proposed by Voitsekhovskii [2]. One of possible configurations of the continuous detonation combustor (CDC) is an annular channel formed by the walls of 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 or a turbine vane, one obtains an annular jet engine or an annular gas turbine combustor. Detonative combustion in such a chamber can be arranged by starting a supply of fuel mixture through the

* *Corresponding author*. N.N. Semenov Institute of Chemical Physics, 119991 Moscow, Russia. Tel.: +7 495 9397228.
E-mail address: smfrol@chph.ras.ru (S.M. Frolov).
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injector head, producing a single ignition pulse for detonation initiation, and burning fuel mixture supplied through the injector head in a detonation wave (DW) continuously circulating above the chamber bottom. The DW 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 DW 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. For example, in the CDC with the mean diameter of the annular gap 300 mm operating with one or two DWs propagating at 1700 m/s the rotation frequency will attain 1.8 or 3.6 kHz. If the fuel mixture is supplied to the CDC at the mean velocity of, say, 200 m/s, the maximum thickness of the fuel-mixture layer filling the CDC will be 110 or 55 mm, i.e., complete combustion in the DWs will be attained at a very short distance. Moreover, the combustion process in CDC can be accompanied with the total pressure rise. As a matter of fact, it is shown computationally in Ref. [3] that up to 14–15% gain in total pressure can be readily attained in a CDC with low pressure loss. Thus, the main advantages of such combustors include better performance due to pressure gain combustion, quasi-steady outflow of detonation products due to high frequency cycles, short combustion chamber, simple design, and a single ignition.

Extensive experimental and computational studies of such combustors have been recently reviewed in book [4]. For several decades, the authors of [4] themselves have conducted systematic experimental and computational studies of continuously rotating detonation in annular and disk shaped combustion chambers of various designs with both fuel–oxygen and fuel–air mixtures, with gaseous and liquid fuels. During the last decade, interest in the CDC concept increased significantly: the works of American [5–7], Chinese [8,9], French [10,11], Japanese [12,13], Polish [12,14], and Russian [3,15,16] scientists have appeared to mention just a few. These papers report the results of experimental and computational studies of the CDC operation process. Experiments are performed mainly with hydrogen-containing gas mixtures. As regards computational studies, they all are based on the equations of inviscid flow (Euler equations) for homogeneous gas mixtures, except for [3,15,16] where fuel mixture components, hydrogen and air, are delivered to the CDC separately, and the operation process is modeled using Reynolds averaged Navier–Stokes equations with a stochastic turbulent micromixing model and finite-rate chemical kinetics of hydrogen oxidation.

Three-dimensional calculations of the operation process in a hydrogen – air CDC reported in Ref. [3] indicate that the gain in total pressure in such a combustor could be attained provided the annual gap for the airflow entering the combustor is sufficiently wide to minimize accompanying pressure loss. However widening of the annular gap deteriorates the operation process decreasing its domain of existence and its stability due to the loss of confinement for a detonation wave.

The objective of the work outlined in this paper is to study experimentally the effect of different CDC elements including the width of the annual gap on the operation process and propulsion performance of the CDC operating on hydrogen – air mixture.

Experimental facility and procedure

Fig. 1 shows the schematic of the outdoor experimental facility. It 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 (~100 ms) valve system with the tubing of 40 mm allowing for the total mass flow rate of fuel components up to 7.5 kg/s, water cooled CDC, control system, and data acquisition system.

Fig. 2 shows the schematic (a) and photograph (b) of the CDC. The CDC is the annular combustion chamber with the outer diameter of 406 mm and length of 310 mm. The annular gap width is 25 mm, so the length of the medium circumference in the gap is about 1.2 m. 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 of 1 mm in diameter equally distributed along the circumference at a distance of 1 mm downstream the air-inlet slit. The number of holes (240) and their diameter (1 mm) are chosen based on the preliminary computational fluid dynamic studies [16]. 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 independent automotive spark plugs and 400-mm long Shchelkin spiral ensuring reliable deflagration-to-detonation transition inside the tube and detonation transmission into the annular gap of the CDC. Two spark plugs are used to ensure ignition in case of misfire. The energy deposited by each spark plug is 0.1 J. The initiator tube is attached to the CDC tangentially at a distance of 150 mm downstream the air-inlet slit and has its own feed system 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 (spike nozzle) and removable outer extension of

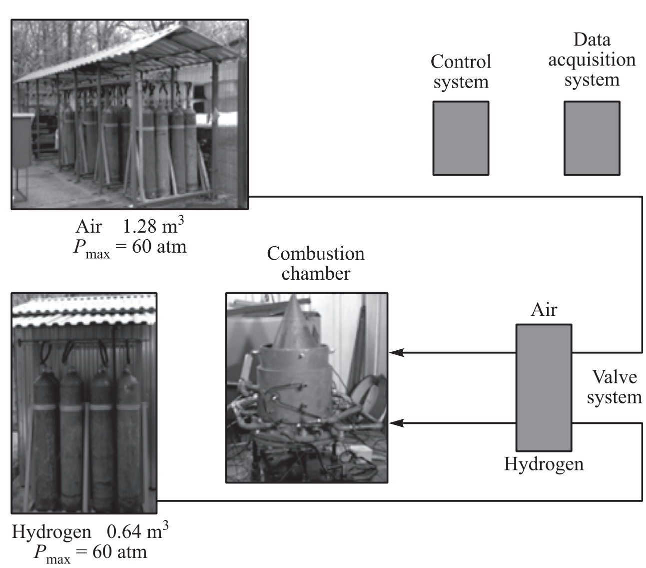

Fig. 1 – Experimental facility.