EXPERIMENTAL STUDIES OF A LARGE-SCALE HYDROGEN–AIR CONTINUOUS DETONATION COMBUSTOR

S. M. Frolov\textsuperscript{1,2,3}, V. S. Aksenov\textsuperscript{1,2,3}, P. A. Gusev\textsuperscript{3}, V. S. Ivanov\textsuperscript{1,2}, S. N. Medvedev\textsuperscript{1,2}, and I. O. Shamshin\textsuperscript{1,2,3}

\textsuperscript{1}Center for Pulse Detonation Combustion
Moscow, Russia

\textsuperscript{2}N. N. Semenov Institute of Chemical Physics
Russian Academy of Sciences
Moscow, Russia
e-mail: smfrol@chph.ras.ru

\textsuperscript{3}National Research Nuclear University
“Moscow Engineering Physics Institute” (NRNU MEPhI)
Moscow, Russia

Advanced air-breathing 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. The main theoretical benefit is a considerable gain in their propulsion efficiency [1].

Three-dimensional calculations of the operation process in air-breathing continuous detonation combustor (CDC) reported in [2] indicate that the gain in total pressure in such a combustor could attain 14\%–15\% provided the annual gap for the air flow 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 (DW).

The objective of the work briefly 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 CDC propulsion performance.
1 Experimental Facility and Procedure

Figure 1 shows the schematic of the open-air 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 flow cross section 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.

Figure 1 Experimental facility

Figure 2 shows the schematic and photograph of the CDC. 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; 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
Continuous Detonations

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 $\delta$. 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

Figure 2 Continuous detonation combustor: (a) main dimensions; and (b) photograph. Dimensions are in millimeters
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 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 $23^\circ$. In order to increase pressure in the annular combustion chamber, the provision is made for mounting an optional shaped obstacle directly upstream the cone for blocking the cross section of the gap up to 50%. The CDC is installed vertically on a thrust table in a compartment with the removable roof.

The control system provides digital control over the operation of air and hydrogen valves, detonation initiator, as well as data acquisition and safety systems. The control system consists of a laptop, a digital control module, and a digital signal amplifier.

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 probe is designed to detect and measure the electrical conductivity of the medium in the combustion chamber. The probe is the needle isolated from the housing and introduced by the exposed end into the annular gap of the CDC. The other end of the needle is soldered to a shielded cable connected to the data acquisition system. 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 (see sketches (a) and (b) in Fig. 3). Low-frequency CURANT DI 6 MPa 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 PCB 113B24 pressure transducers are used to measure local instantaneous static pressure in the air plenum and in two locations of the combustion chamber (30 and 255 mm above the air-inlet slit). Due to high-temperature conditions in the combustion chamber, the corresponding pressure transducers were mounted outside the CDC outer wall and communicated with the combustion chamber through short branch tubes 2 mm in diameter.
Thrust is measured by the calibrated strain gauge (load cell M500) installed underneath the thrust table and connected to the data acquisition system. The maximum measured force of the gauge is 50 kN.

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 DW from the tube to the annular gap of the CDC followed by the establishment of the operation mode with one DW or several DWs 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 DWs in the annular gap. The operation is terminated by successive deactivation of the hydrogen and air valves.

Figure 3 shows the example of registration of the operation process in the CDC with one DW by the ionization probes of axial (a) and circumferential (b) lines. The records allow obtaining information on the detonation propagation velocity and direction, DW height, 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 demonstrated in Fig. 4. Here, the maximum brightness corresponds to the maximum level of the signal, whereas dark regions correspond to the minimum level of the signal. Thus, one can clearly distinguish the detonation front and the contact surface between detonation products and fresh fuel mixture and to determine the height of the DW and the time interval of inflow blockage by high-pressure detonation products. Also, one can readily determine the velocity and direction of DW propagation, detonation rotation frequency, and the number of DWs, simultaneously rotating in the CDC. The number of DWs is obtained based on the measured propagation velocity of the DW and its rotation frequency. For example, if the characteristic detonation propagation velocity is \(\sim 1800 \text{ m/s}\) (determined from the slope in Fig. 4b) and the detected rotation frequency is 1.5 kHz, then the CDC operates in the mode with one DW (the rotation frequency of 1.5 kHz is obtained by dividing the propagation velocity by the length of the mean circumference in the annual gap, 1.2 m). If the detected rotation frequency is about 3, 4.5, or 6 kHz, then the CDC operates with
Continuous Detonations

two, three, or four DWs, respectively, once the detonation propagation velocity does not change. The detonation propagation velocity can be also obtained based on the records of high-frequency pressure transducers mounted in the combustion chamber. The error of determining the detonation velocity from the pressure record is estimated as 1%.

2 Experimental Results

In this section, the experimental results obtained for the CDC with \( \delta = 2, 5, \) and 15 mm, \( h = 0 \), with/without conical centerbody, and at different values of nozzle blockage \( \beta \), air overpressure in the oxidizer plenum \( P_{\text{air}} \), hydrogen overpressure in the fuel plenum \( P_{\text{hyd}} \), and the initial total mass flow rate of fuel mixture \( G \) will be discussed. Note that in the course of a single experiment, the total mass flow rate gradually decreases by not more than by 10% as compared to \( G \).

Table 1 lists some representative test cases discussed below.

<table>
<thead>
<tr>
<th>Test</th>
<th>( \delta ), mm</th>
<th>Exit cone</th>
<th>( \beta ), %</th>
<th>( P_{\text{air}} ), atm</th>
<th>( P_{\text{hyd}} ), atm</th>
<th>( G ), kg/s</th>
<th>Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>+</td>
<td>50</td>
<td>14.0</td>
<td>17</td>
<td>7.5</td>
<td>4 DW*</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>+</td>
<td>0</td>
<td>13.0</td>
<td>18</td>
<td>6.7</td>
<td>2 DW**</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>-</td>
<td>0</td>
<td>13.0</td>
<td>18</td>
<td>6.7</td>
<td>2 DW</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>+</td>
<td>50</td>
<td>13.0</td>
<td>18</td>
<td>6.7</td>
<td>2 DW</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>+</td>
<td>50</td>
<td>3.7</td>
<td>14</td>
<td>5.8</td>
<td>2 DW</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>+</td>
<td>0</td>
<td>3.5</td>
<td>17</td>
<td>5.4</td>
<td>2/1 DW***</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>+</td>
<td>0</td>
<td>4.0</td>
<td>15</td>
<td>6.8</td>
<td>1 DW***</td>
</tr>
<tr>
<td>8</td>
<td>15</td>
<td>+</td>
<td>50</td>
<td>1.0</td>
<td>14</td>
<td>5.8</td>
<td>Pulse</td>
</tr>
</tbody>
</table>

*Mode with four DWs.
**Mode with two DWs.
***Transient mode with two and one DWs.

2.1 Operation mode with four detonation waves in the continuous detonation combustor with 2-millimeter air-inlet slit

Figure 5 shows the “visualization” of a part of the operation process in the CDC and the time history of the detonation rotation frequency for the case with \( \delta = 2 \) mm, \( \beta = 50\% \), \( P_{\text{air}} = 14 \) atm, \( P_{\text{hyd}} = 17 \) atm,
**Figure 5** Operation of CDC with 4 DWs in Test 1

**Figure 6** Static pressure records at positions 1 to 3 in the CDC operating with 4 DWs in Test 1
and $G = 7.5$ kg/s (Test 1 in Table 1). In this case, after detonation initiation, there is a relatively long period of transient operation followed by the establishment of the operation mode with four DWs, as the measured rotation frequency is close to the value determined based on the measured detonation velocity (dashed horizontal line denoted “4 DW”). The detected height of the DWs is estimated as 50–70 mm.

Figure 6 presents a small segment of static pressure records at positions 1 to 3 in the CDC (see insert in Fig. 6) for the same test as in Fig. 5. It is seen that the static pressure in the combustion chamber changes periodically and sharply due to periodic arrival of a DW at position 2. Static pressure fluctuations in the air plenum (position 1) and at the nozzle exit (position 3) do not exceed $\pm 0.1$ atm and $\pm 1$ atm, respectively.

2.2 Operation mode with two detonation waves in the continuous detonation combustor with 2- and 5-millimeter air-inlet slit

Removal of nozzle blockage ($\beta = 0$) at $\delta = 2$ mm results in the establishment of the operation process with two DWs (Tests 2 and 3 in Table 1).

Figure 7 shows the “visualization” of a part of the operation process in the CDC and the time history of the detonation rotation frequency for the case with $\delta = 2$ mm, $\beta = 0$, $P_{\text{air}} = 13$ atm, $P_{\text{hyd}} = 18$ atm, and $G = 6.7$ kg/s (Test 2 in Table 1). In this case, after detonation initiation, there is a relatively long period of transient operation followed by the establishment of the operation mode with two DWs, as the measured rotation frequency is close to the value determined based on the measured detonation velocity (dashed horizontal line denoted “2 DW”). It is interesting that the DWs are continuously separated from each other by the distance which is shorter than the half of the annular gap circumference. The detected height of the DWs is estimated as 100–130 mm.

Widening of the air inlet slit from $\delta = 2$ to 5 mm and placement of nozzle blockage with $\beta = 50\%$ also results in the establishment of the operation process with two DWs (Tests 4 and 5 in Table 1).

Figure 8 presents a small segment of static pressure records at positions 1 to 3 in the CDC (see insert in Fig. 8) for the case with $\delta = 5$ mm,
$\beta = 50\%$, $P_{\text{air}} = 13$ atm, $P_{\text{hyd}} = 18$ atm, and $G = 6.7$ kg/s (Test 4 in Table 1). It is seen that the static pressure in the combustion chamber changes periodically and sharply due to periodic arrival of a DW at position 2. Static pressure fluctuations in the air plenum (position 1) and at the nozzle exit (position 3) do not exceed $\pm 0.1$ atm and $\pm 0.7$ atm, respectively.

**Figure 7** Operation of CDC with 2 DWs in Test 2
Figure 8 Static pressure records at positions 1 to 3 in the CDC operating with 2 DWs in Test 4

Figure 9 Transient CDC operation with 2 and 1 DWs in Test 6
2.3 Transient operation with two and one detonation waves in the continuous detonation combustor with 5-millimeter air-inlet slit

Figure 9 shows the “visualization” of a part of the operation process in the CDC and the time history of the detonation rotation frequency for the case with $\delta = 5$ mm, $\beta = 0$, $P_{\text{air}} = 3.5$ atm, $P_{\text{hyd}} = 17$ atm, and $G = 5.4$ kg/s (Test 6 in Table 1). In this case, after detonation initiation, the CDC first operates in the mode with 2 DWs and then abruptly turns to the mode with 1 DW, as the measured rotation frequencies are close to the values shown by dashed horizontal lines “2 DW” and “1 DW” determined based on the measured detonation velocities. The detected height of the DWs is estimated as 200 mm in the mode with 1 DW and 100 mm in the mode with 2 DWs. The transition from “2 DW” to “1 DW” operation mode is likely caused by the gradual decrease in the total mass flow rate of fuel components.

2.4 Operation mode with one detonation wave

Figure 10 shows the “visualization” of a part of the operation process in the CDC and the time history of the detonation rotation frequency for the case with $\delta = 5$ mm, $\beta = 0$, $P_{\text{air}} = 4$ atm, $P_{\text{hyd}} = 15$ atm, and $G = 6.8$ kg/s (Test 7 in Table 1). In this case, after fast detonation initiation, the CDC operates in the mode with 1 DW, as the measured rotation frequency is close to the value determined based on the measured detonation velocity (dashed horizontal line denoted “1 DW”). The detected height of the DW is estimated as $\sim 200$ mm.

Figure 11 presents a small segment of static pressure records at positions 1 to 3 in the CDC (see insert in Fig. 11) in the same test. It is seen that the static pressure in the combustion chamber changes periodically and sharply due to periodic arrival of a DW at position 2. Static pressure fluctuations in the air plenum (position 1) and at the nozzle exit (position 3) do not exceed $\pm 0.7$ atm and $\pm 0.5$ atm, respectively.

2.5 Operation mode with intermittent detonations

At large air-inlet slits $\delta$, a new operation mode of the CDC was observed. Figure 12 shows the “visualization” of a part of the operation process in the CDC and the time history of process frequency for the
case with $\delta = 15$ mm, $\beta = 50\%$, $P_{\text{air}} = 1$ atm, $P_{\text{hyd}} = 14$ atm, and $G = 5.8$ kg/s (Test 8 in Table 1). In this case, after detonation initiation, the operation mode with intermittent reaction waves resembling detonations (pulse mode) is established in the CDC. It is seen in the “visualization” picture obtained from the records of ionization probes in the circumferential line that bright regions (i.e., regions with high electric conductivity) appear simultaneously in the entire cross section of the annular gap and propagate downstream and upstream periodically with the mean measured frequency of 1000 Hz. Analysis of Fig. 12 indicates that the reaction wave originates periodically at the CDC exit and
Figure 11 Static pressure records at positions 1 to 3 in the CDC operating with 1 DW in Test 7.

Figure 12 Operation of CDC with intermittent longitudinal reaction waves resembling detonations in Test 8.
propagates downstream at the absolute velocity of \( \sim 1000 \text{ m/s} \) in the fresh fuel mixture (see arrows in the “visualization” picture). Thereafter the hot combustion products are convected downstream at the mixture purging velocity of about 300 m/s. Note that a similar mode of intermittent longitudinal reaction waves treated as detonations was observed in [3] in the disk-shaped CDC.

### 2.6 Thrust measurements

Figure 13 shows the results of thrust measurements in 3 tests (Tests 1 to 3 in Table 1) with the air-inlet slit \( \delta = 2 \text{ mm} \). Curve A corresponds to Test 3 without exit nozzle, i.e., without conical center body. Curves B and C correspond to Tests 2 and 1, respectively. Clearly, the comparison of curves A and B shows that the conical centerbody increases the thrust by a factor of 2: from 2.2 to 4.4 kN. Furthermore, the comparison of curves C and B shows that the blockage of the CDC exit by the shaped obstacle with \( \beta = 50\% \) increases the thrust from 4.4 to 6.5 kN.

All thrust curves A, B, and C exhibit three characteristic regions. Region I corresponds to the purging stage when fuel components are purged through the CDC. First (at \( \sim 0.6 \text{ s} \) in Fig. 13), the air valve activates airflow and then (at \( \sim 0.8 \text{ s} \) in Fig. 13), the hydrogen valve activates hydrogen flow through the CDC. Region II corresponds to CDC operation in the detonation mode. Mixture ignition in the initia-

![Thrust measurements in Tests 3 (A), 2 (B), and 1 (C)](image)

**Figure 13** Thrust measurements in Tests 3 (A), 2 (B), and 1 (C)
Figure 14 Thrust measurement in Test 5 with the highest value of fuel-based specific impulse (∼ 3000 s)

tor tube is triggered at ∼ 1 s followed by detonation transmission in the CDC. Region III corresponds to the quenching stage. First (at ∼ 1.4 s in Fig. 13), the hydrogen valve deactivates hydrogen supply to the CDC and then (at ∼ 1.7 s in Fig. 13), the air supply valve deactivates air supply to the CDC.

It is seen that the CDC produces thrust at all three stages. For estimating the net thrust produced by the CDC, one has to extract the thrust produced at the purging stage (∼ 0.5 kN) from the thrust produced at stage II. Thus, the maximum net thrust in Fig. 13 is ∼ 6 kN.

Figure 14 shows the thrust curve in one of the tests (Test 5 in Table 1) with (currently) the highest value of fuel-based specific impulse. In this test, the net thrust of ∼ 5 kN was produced at \( G = 5.8 \text{ kg/s} \) with the partial mass flow rate of hydrogen 0.17 kg/s. Thus, the fuel-based specific impulse in this test is close to ∼ 3000 s.

3 Concluding Remarks

A large-scale 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 from 2 to 15 mm leads to a decrease in the number of DWs simultaneously circulating in the combustor from four
Continuous Detonations

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 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.

Further work will be focused on replacing hydrogen with a hydrocarbon fuel.

Acknowledgments

This work was partly supported by the Program No.26 “Combustion and explosion” of the Russian Academy of Sciences.

References