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Brief Communications

An experimental study of formation of stabilized oblique detonation waves in a combustor

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ABSTRACT

This study reports the first experiments of a large-scale hydrogen-fueled oblique detonation engine model conducted in a hypersonic wind tunnel. The stabilization characteristic of oblique detonation wave, the specific combustion mode and the corresponding flow structures are emphasized. Results show that by adjusting the geometry of the combustor in different tests, two stabilized oblique detonation combustion modes relevant to the two theoretical branches of oblique detonation at a given wedge angle, referred to as the strong oblique detonation mode and the weak oblique detonation mode, respectively, are consequently implemented in the combustor.

1. Introduction

By replacing the traditional diffusion combustion with detonation combustion through holding a stabilized oblique detonation wave (ODW) in the combustor, oblique detonation engine (ODE) has attracted more and more attention in the development of air-breathing hypersonic propulsion systems recently [1]. Stabilization of ODWs in the combustor is one of the important prerequisites for the successful application of ODEs in hypersonic flights [2, 3]. It has been demonstrated, through experiments (for example, Refs. [4–6]) and numerical simulations (for example, Refs. [7–10]), that it is easy to stabilize an ODW over an isolated wedge, cone, or sphere. However, stabilizing an ODW in a space-confined ODE combustor is one kind of supersonic/hypersonic reactive internal flow problems involving shock/detonation reflection on walls, shock/detonation–shock/detonation interaction, shock/detonation–boundary layer interaction and the consequent boundary layer separation, etc. [11, 12], which, however, has been poorly investigated, especially by experiments. Furthermore, affected by the numerous factors mentioned above, the flow structures of ODW in the combustor would be quite complex and the combustion mode could be changed accordingly. In this paper, experimental tests of a large-scale ODE model in the JF-12 hypersonic wind tunnel in the Institute of Mechanics, Chinese Academy of Sciences [13] are reported, and special emphases are given to the experimental demonstration of stabilized ODWs in the ODE combustor, the specific detonation combustion modes and the corresponding flow structures.

2. Experimental methodology

Figure 1 shows the photograph of the tested ODE model mounted in the test section of the JF-12 wind tunnel, and its geometry is detailed in Fig. 2. The ODE model, which is about 2.2 m in length, 0.6 m in height and 0.6 m in width, is mainly composed of four parts: fuel injectors, inlet, combustor and nozzle. Three parallel strut-injectors (denoted as A, B and C in Fig. 2a, respectively) are employed to pre-inject hydrogen fuel into the core airflow (through sonic transverse jets) in the leading front of the single-stage external compression inlet. The detailed shape (the cross-section) of each strut-injector is depicted in Fig. 2b. On each strut-injector, fifteen injection holes (indicated by the short green lines in Fig. 2c) with a diameter of 1 mm are staggeredly distributed along the middle lines of its upper and bottom surfaces, and the injection area has a span of 0.28 m. The hydrodynamic diameters of other flow paths in the gas supply system were chosen to be large enough to ensure that the sonic throat is exactly located at the exit of each injection hole; thereafter, the mass flow rate of hydrogen can be uniquely controlled by the pressure of the supplied gas (stored at normal temperature). The combustor is in the shape of a rectangular straight channel, which is 0.0765 m in height and 0.4 m in width. The length of the upper wall of the combustor (denoted as the length of the combustor, L_c) is adjustable by moving

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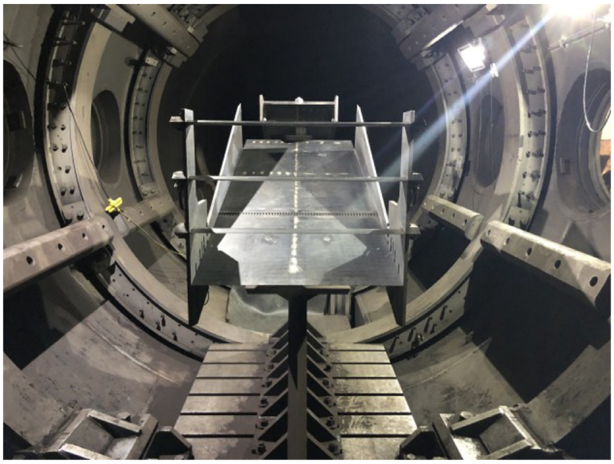


Fig. 1. A photograph of the tested ODE model mounted in the test section of the JF-12 wind tunnel [3].

Table 1
Test conditions and fuel jet setup.

Test No.	No. 20190705	No. 20190710
Freestream total temperature	3525 K	3377 K
Freestream total pressure	2.45 MPa	2.26 MPa
Freestream Mach number	6.6	6.6
Combustor length, L_c	0.26 m	0.41 m
Strut-injectors used	A	A, B
H_2 mass flow rate	19.6 g/s	36.7 g/s

Table 2
Summary of the measured oblique shock/detonation angles.

Test	OSW	ODW
No. 20190705	46.8°	83.8°
No. 20190710	47.8°	53.2°

it upstream, while it is fixed at 0.2 m for the lower wall. Moreover, the combined combustor and nozzle structure is at an inclined angle of −15°, while the single-stage inlet is 15°-inclined to the freestream direction, implying a deflection angle of 30° for the high-speed mixture flowing into the combustor from the inlet.

Two tests corresponding to two different oblique detonation modes by setting different combustor lengths and adopting different strut-injectors, referred to as No. 20190705 and No. 20190710, respectively, are reported in this paper. The corresponding test conditions and fuel jet setups are listed in Table 1. The global equivalence ratios of the high-speed fuel-air mixture flowing into the combustor in these two tests, estimated by numerical simulations, are about 0.8 and 1.0, respectively. Measurement methodologies include high-speed schlieren photography and wall pressure and heat flux measurements in the combustor. A total of twenty-eight piezoresistive pressure transducers was installed along the central lines of the upper and lower walls of the combustor and nozzle, while a total of thirty-three chromel-constantan (E-type) coaxial thermocouples with a diameter of 1.4 mm was distributed along the lines that are 0.01 m away from the central lines of the upper and lower walls.

3. Results and discussion

3.1. *Strong oblique detonation mode (Test No. 20190705)*

Figure 3a shows a schlieren photograph of the flow field in the combustor in this test. No obvious premature combustion of the high-speed fuel-air mixture occurs before entering the combustor, while fast and violent combustion with bright light emission happens in the combustor, resulting in the formation of complex flow structures. The formed flow structures and the corresponding combustion state are observed to remain stabilized in the combustor during the whole effective tunnel test time (> 50 ms).

A non-reactive oblique shock wave (OSW) with a shock angle of 46.8° (relative to the inlet flow, as summarized in Table 2) is first induced by the combustor's upper wall. In another aspect, from the brightness difference of the combustion flow field, a large separation zone (lSZ) can be easily identified right after the leading edge of the lower wall of the combustor. As a result, a non-reactive separation shock wave (SSW) forms at the leading edge. Under the interaction of the OSW and SSW, Mach reflection happens and a

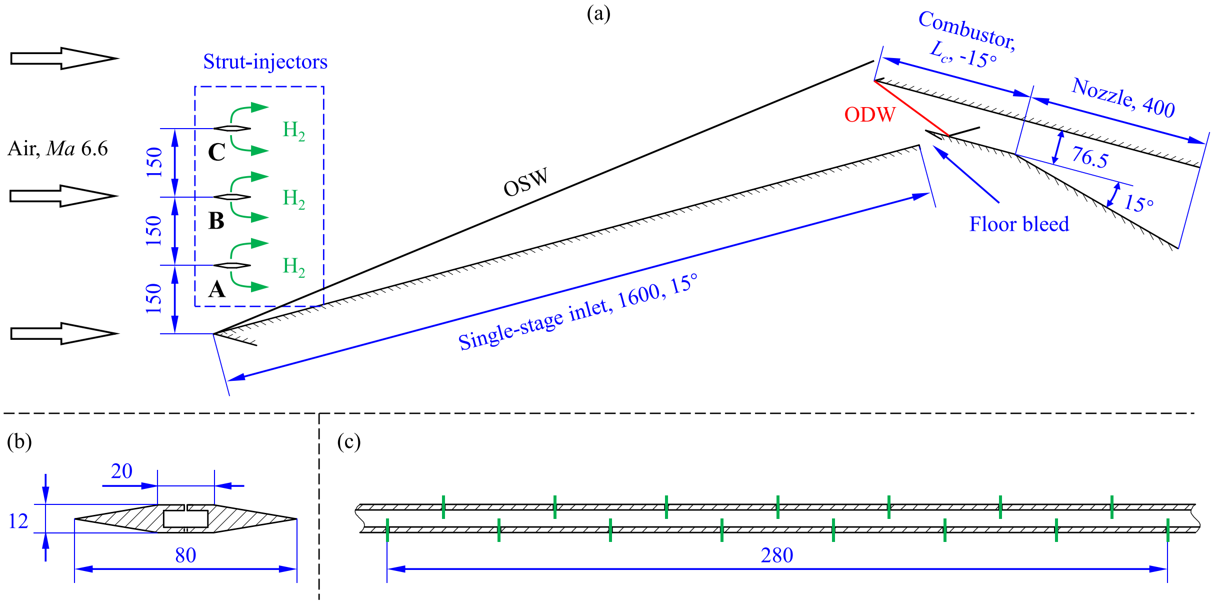


Fig. 2. Geometry of the designed ODE model (dimensions in mm): (a) global side view, (b) side view of the cross-section of one strut-injector, and (c) front view of the cross-section of one strut-injector.

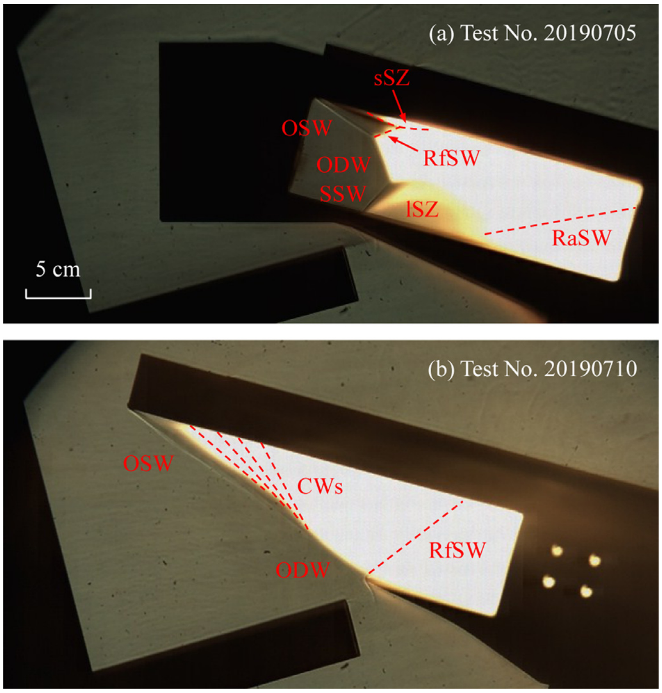


Fig. 3. Schlieren photographs of the flow field in the ODE combustor in two different tests.

Mach stem with a measured inclined angle of 83.8° (see Table 2) consequently forms in the middle of the combustor (in the height direction). From its tightly coupling with combustion, this oblique Mach stem is identified as an ODW with a large oblique detonation angle close to 90°.

Theoretically, similar to OSW, there are two potential solutions of ODW for a given wedge angle, namely the weak ODW solution with a smaller oblique detonation angle and the strong ODW solution with an oblique detonation angle generally close to 90°. Therefore, as a matter of fact, the ODW in the present test corresponds to the strong solution of ODW, and the relevant combustion mode is referred to as the strong oblique detonation mode.

Additionally, a reflected shock wave (RfSW) observably forms from the upper triple point, and it reflects on the upper wall, which can be identified by the obvious peaks located at about 0.08 m from the leading edge in the pressure and heat flux distributions along the upper wall (see Fig. 4). A small and flat boundary layer separation zone (sSZ) forms near the reflection point of the RfSW as observed in the schlieren photograph, leading to that the pressure or heat flux jump of this RfSW increases in a relatively moderate matter (spanning from 0.04 m to 0.08 m) and is not as abrupt as a traditional shock wave. Moreover, a reattachment shock wave (RaSW) relevant to shock wave–boundary layer interaction forms at the end of the lSZ and reflects on the upper wall, which can also be identified by the peaks of pressure or heat flux located at about 0.3 m from the leading edge along the upper wall and at about 0.1–0.12 m from the leading edge along the lower wall. All these flow structures are similar to those obtained via numerical simulations [14–16].

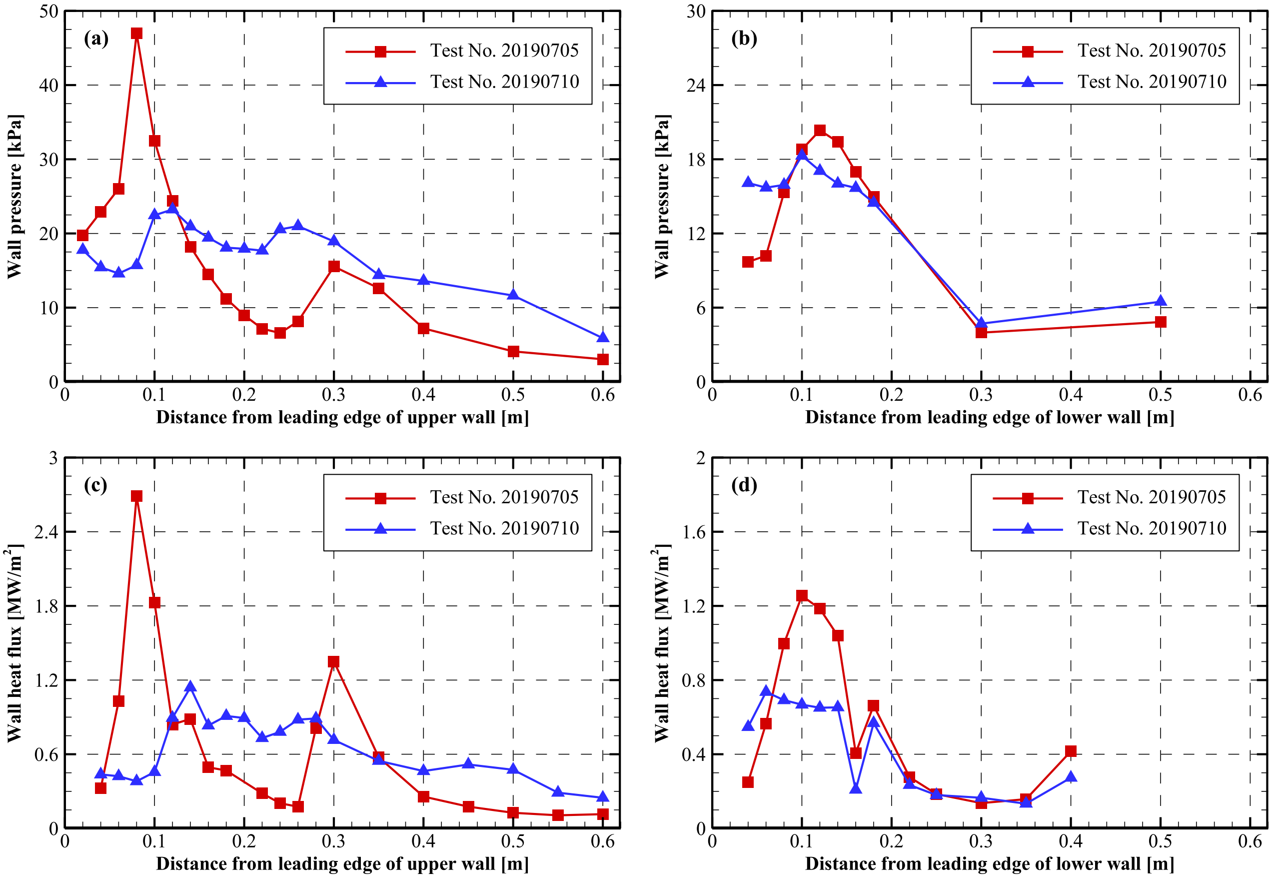
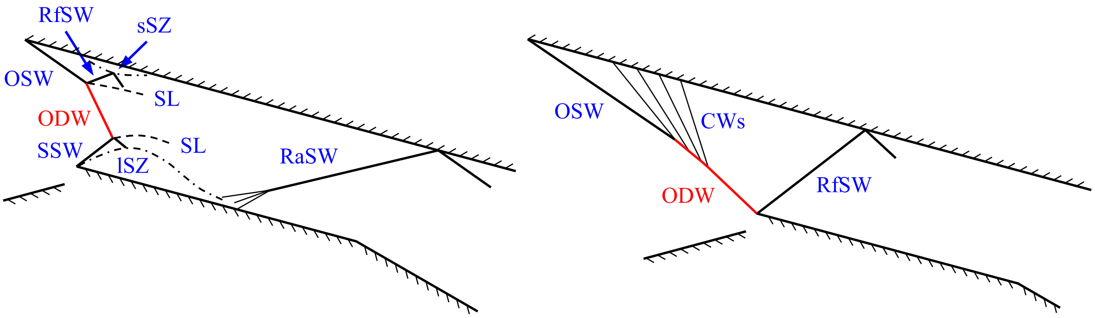


Fig. 4. Wall pressure and heat flux distributions in the ODE combustor and nozzle in different tests: (a) pressure along the upper wall, (b) pressure along the lower wall, (c) heat flux along the upper wall and (d) heat flux along the lower wall.



(a) Strong Oblique Detonation Mode **(b) Weak Oblique Detonation Mode**

Fig. 5. Schematics of the flow structure of different stabilized oblique detonation combustion modes in the ODE combustors.

3.2. Weak oblique detonation mode (Test No. 20190710)

Figure 3b shows another schlieren photograph of the flow field in the combustor. There is also no observable premature combustion in the inlet. When the high-speed fuel-air mixture flows into the combustor, an OSW forms over the leading edge of the upper wall again. Induced by this OSW, this mixture is then fast burnt and bright light emits simultaneously. The shock front and the flame formed in the combustor also remain stabilized during the test.

A loose coupling of the flame and the shock front is observed in the upper part of the combustor with an obvious separation between them, and the shock angle of the OSW at this location slightly increases to about 47.8° compared to that of the OSW (about 46.8°) in the test of No. 20190705 (see Table 2). This increase of OSW angle results from the combustion happening downstream. Referring to the traditional smooth OSW–ODW initiation structure [9, 10], a series of compression waves (CWs) would generate through combustion behind the OSW, which can be identified by the rapid increases of pressure and heat flux at around 0.06–0.12 m along the upper wall (see Fig. 4).

In the middle part of the combustor, the flame front apparently distorts and evolutes to upstream relative to the OSW due to the convergence of these CWs, and it finally couples with the shock front tightly in the lower part of the combustor, forming a traditional tightly coupled ODW with an inclined angle of about 53.2°. Notably, the oblique detonation angle of 53.2° in the present test is greater than the oblique shock angle of 46.8° and is significantly smaller than that of the strong oblique detonation combustion mode (83.8°) as observed in the test of No. 20190705, implying that the presently observed ODW exactly corresponds to the theoretical weak solution of oblique detonation. Therefore, the present combustion mode is referred to as the weak oblique detonation mode.

When the formed ODW reacts at the leading edge of the lower wall in the present test (see Fig. 3b), the pressure and heat flux levels near the leading edge along the lower wall increase (see Figs. 4b and 4d), as compared to those in the test of No. 20190705. As a result, a RfSW forms from the leading edge of the lower wall and subsequently reflects on the upper wall of the combustor, leading to the occurrence of the second peak of pressure and heat flux at about 0.26 m on the upper wall (see Figs. 4a and 4c).

4. Conclusions

In this study, two tests of a large-scale ODE model in the JF-12 hypersonic wind tunnel, with different fuel mass flow rates and different combustor geometries, are reported for the first time. Results show that there is no obvious premature combustion of the fuel-air mixture occurring in the inlet, and violent stable combustion of this mixture is then induced by the shock waves formed in the combustor. Two stabilized oblique detonation combustion modes, namely the strong oblique detonation mode and the weak oblique detonation mode, are realized in the combustor. The detailed flow structures of these two stabilized oblique detonation combustion modes can be schematically summarized in Fig. 5 (SL denotes slip line). The stabilization characteristic of ODWs within the engine combustor under realistic flight conditions is demonstrated feasible experimentally, which is important to performance optimization of ODEs in the next stage.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] P. Wolański, Detonative propulsion, Proc. Combust. Inst. 34 (1) (2013) 125–158.
[2] Q. Liu, D. Baccarella, T. Lee, Review of combustion stabilization for hypersonic airbreathing propulsion, Prog. Aerosp. Sci. 119 (2020) 100636.
[3] Z. Jiang, Z. Zhang, Y. Liu, C. Wang, C. Luo, Criteria for hypersonic airbreathing propulsion and its experimental verification, Chin. J. Aeronaut. 34 (3) (2021) 94–104.
[4] J. Verreault, A.J. Higgins, Initiation of detonation by conical projectiles, Proc. Combust. Inst. 33 (2) (2011) 2311–2318.
[5] J.D. Sterling, E.B. Cummings, K. Ghorbanian, D.T. Pratt, T.H. Sobota, N.J. Brock, M.S. Brown, J. Segall, P.A. DeBarber, Oblique detonation wave studies in the Caltech T-5 Shock Tunnel Facility, in *Proc. 8th AIAA International Space Planes and Hypersonic Systems and Technologies(1998)*, Paper No. 98-1561.
[6] Z. Lin, J. Zhang, J. Zhou, Design of high-enthalpy premixed supersonic heater and experimental study of oblique detonation, *43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit (2007)*, Paper No. 2007-5009.
[7] G.X. Xiang, X. Gao, W.J. Tang, X.Z. Jie, X. Huang, Numerical study on transition structures of oblique detonations with expansion wave from finite-length cowl, *Phys. Fluids*32 (2020) 056108.
[8] Z. Ren, B. Wang, G. Xiang, L. Zheng, Effect of the multiphase composition in a premixed fuel-air stream on wedge-induced oblique detonation stabilisation, J. Fluid Mech. 846 (2018) 411–427.
[9] Y. Zhang, Y. Fang, H.D. Ng, H. Teng, Numerical investigation on the initiation of oblique detonation waves in stoichiometric acetylene–oxygen mixtures with high argon dilution, Combust, Flame 204 (2019) 391–396.
[10] H. Teng, C. Tian, Y. Zhang, L. Zhou, H.D. Ng, Morphology of oblique detonation waves in a stoichiometric hydrogen–air mixture, J. Fluid Mech. 913 (2021) A1.
[11] X. Cai, J. Liang, R. Deiterding, Y. Mahmoudi, M. Sun, Experimental and numerical investigations on propagating modes of detonations: detonation wave/boundary layer interaction, Combust. Flame 190 (2018) 201–215.
[12] G. Xiang, Y. Zhang, X. Gao, H. Li, X. Huang, Oblique detonation waves induced by two symmetrical wedges in hydrogen-air mixtures, *Fuel*295 (2021) 120615.
[13] Z. Jiang, Experiments and development of Long-test-duration Hypervelocity Detonation-driven Shock Tunnel (LHDst), *52nd Aerospace Sciences Meeting*, 2014.

[14] Z. Zhang, K. Ma, W. Zhang, X. Han, Y. Liu, Z. Jiang, Numerical investigation of a Mach 9 oblique detonation engine with fuel pre-injection, *Aerosp. Sci. Technol.*105 (2020) 106054.

[15] Z. Zhang, C. Wen, W. Zhang, Y. Liu, Z. Jiang, Formation of stabilized oblique detonation waves in a combustor, Combust. Flame 223 (2021) 423–436.

[16] Y. Fang, Z. Zhang, Z. Hu, Effects of boundary layer on wedge-induced oblique detonation structures in hydrogen-air mixtures, Int. J. Hydrogen Energy 44 (2019) 23429–23435.