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Brief Communication

Experimental demonstration of forced initiation of kerosene oblique detonation by an on-wedge trip in an ODE model

Xin Han[a,b], Yunfeng Liu[a,c,*], Zijian Zhang[d,**], Wenshuo Zhang[a,c], Chaokai Yuan[a], Guilai Han[a], Zonglin Jiang[a,c]

[a] Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China
[b] School of Aerospace Engineering, Xiamen University, Xiamen 361102, China
[c] School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China
[d] Department of Aeronautical and Aviation Engineering, The Hong Kong Polytechnic University, Hong Kong, China

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ABSTRACT

The first free-jet experiment of a kerosene-fueled oblique detonation engine, conducted in a large-scale hypersonic shock tunnel, is reported in this paper. A novel initiation-control technique using a small on-wedge trip is proposed to overcome the initiation issue of oblique detonation waves (ODWs) encountered when liquid hydrocarbon fuel is used. The results show that the kerosene-fueled ODW fails to initiate within the length-limited combustor without the trip but is successfully initiated when the trip is used, which demonstrates the effectiveness of the proposed initiation-control method. The feasibility of kerosene-fueled oblique detonation propulsion technology is also demonstrated.

Novelty and significance statement The feasibility of liquid-hydrocarbon-fueled oblique detonation propulsion technology was demonstrated by performing free-jet shock tunnel experiments of a kerosene-fueled oblique detonation engine. To address the initiation issue of oblique detonation waves encountered when liquid hydrocarbon fuel such as kerosene is used, a novel but simple initiation-control technique was proposed and experimentally validated. Stabilized oblique detonation waves were implemented in the combustor, and the detailed flow structures of different oblique detonation combustion modes were clarified. The proposed technique and the results provide significant reference to the future development of oblique detonation engines.

1. Introduction

Benefiting from the high heat-release rate of detonation waves, a short combustor is one of the advantages of using an oblique detonation engine (ODE) as a hypersonic air-breathing propulsion system [1,2]. On the other hand, the natural initiation of an oblique detonation wave (ODW) typically transitions from a nonreactive oblique shock wave (OSW; see Fig. 1) [3], and the corresponding initiation length is highly dependent on the inflow parameters and the chemical kinetic characteristics of the fuel/air mixture [4]. Liquid hydrocarbon fuel, such as aviation kerosene, is easy to store, has a high volumetric energy density and can serve as a coolant in onboard regenerative-cooling thermal management systems; thus, it is an ideal fuel option for powered hypersonic vehicles. However, under the same conditions (i.e., the same equivalent ratio, pressure and temperature), the ignition delay time of a gaseous-kerosene/air mixture is at least one order of magnitude larger than that of a hydrogen/air mixture [5,6], which would be worse if the multiphase processes of liquid kerosene such as breakup, atomization and evaporation are taken into consideration [7]. As a result, an ODE fueled by liquid kerosene might suffer from initiation issues compared to a hydrogen-fueled ODE; that is, the initiation length of the ODW might be so large that the ODW fails to initiate within the length-limited combustor. Therefore, some initiation-control techniques are always necessary for the reliable operation of kerosene-fueled ODEs. This paper reports the first free-jet experiment of a large-scale kerosene-fueled ODE conducted in the JF-12 hypersonic shock tunnel at Institute of Mechanics, Chinese Academy of Sciences [8], during which a novel forced-initiation technique of using a small on-wedge trip is demonstrated as well.

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* Corresponding author at: Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China.
** Corresponding author.
E-mail addresses: liuyunfeng@imech.ac.cn (Y. Liu), zijzhang@polyu.edu.hk (Z. Zhang).

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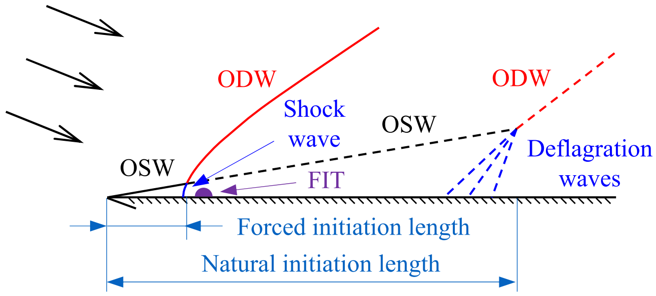

Fig. 1. Schematic of the natural initiation of an ODW (dashed lines) and forced initiation by an FIT (solid lines).

2. Forced-initiation trip

According to the well-reported abrupt initiation structure (see the dashed lines in Fig. 1), an ODW is typically initiated through an interaction between the primary OSW and some convergent combustion waves (i.e., the deflagration waves) induced by the high temperature and pressure behind the OSW [3,4]. This spontaneous process is sensitive to the temperature and pressure as well as the chemical kinetic characteristics of the combustible mixture, leading to quite different initiation lengths under different conditions. Inspired by the effects of deflagration waves on ODW initiation, Han et al. [9] first proposed setting a small on-wedge trip (referred to as a forced-initiation trip, FIT) inside the induction zone to generate a shock wave to interact with the primary OSW in advance to control the initiation of the ODW at a specific location despite the flow conditions (see the solid lines in Fig. 1). The effectiveness of this technique on the initiation of hydrogen/air ODWs was validated numerically by Xiang et al. [10]. The size of the FIT compared to the scales of the combustor is expected to be small [9,10], and hence, its negative effects (such as pressure penalties) on the overall performance of the engine (if the ODW is successfully initiated) are considered limited. This study mainly focuses on the experimental demonstration of the effectiveness of an FIT on detonation initiation, whereas the optimizations regarding its size and location require further parametric studies.

3. Experimental methodology

The ODE model tested (see Fig. 2) is modified from a previous hydrogen-fueled model [11]. The key modification involves the fuel injectors. Two parallel strut-injectors (denoted as A and B in Fig. 2a) are mounted in the leading front of the engine inlet to pre-inject kerosene into the core airflow. To ensure good initial atomization, 20 injection holes with a diameter of 0.3 mm and a spanwise interval of 20 mm are uniformly distributed along the central line of each surface of each strut-injector (see Fig. 2b). Such an injection configuration is expected capable of providing a uniform fuel distribution in the spanwise direction before the mixture flowing into the combustor [12]. The liquid kerosene is stored in a cylinder at normal temperature, and its injection is driven by high-pressure nitrogen gas via a piston and is controlled by a fast-acting solenoid valve. The mass flow rate of kerosene by each strut-injector is uniquely controlled by the injection pressure based on pretest calibration data. The FIT employed is a semicylinder with a radius of 5 mm and is mounted 50 mm downstream from the leading edge of the combustor's upper wall (see Fig. 2c and d). Notably, such parameters of the FIT were determined based on Ref. [9], but they are still tentative before experiments. More details of the modified ODE model can be found in Han et al. [13].

Three tests using different combustor lengths and strut-injectors with or without FIT are reported. The detailed test conditions and setups of the fuel jet and FIT are summarized in Table 1. Different setups of the fuel jet are associated with different capturing areas of different combustor configurations [11,13]. Chinese RP-3 aviation kerosene [6] is used. The kerosene injection pressure is approximately 0.92–0.94 MPa, and the calibrated mass flow rate on each strut-injector is approximately 100 g/s. The nominal fuel equivalent ratio evaluated using an assumed freestream area of 0.15 × 0.6 m^2 (height × width) per strut-injector (i.e.,

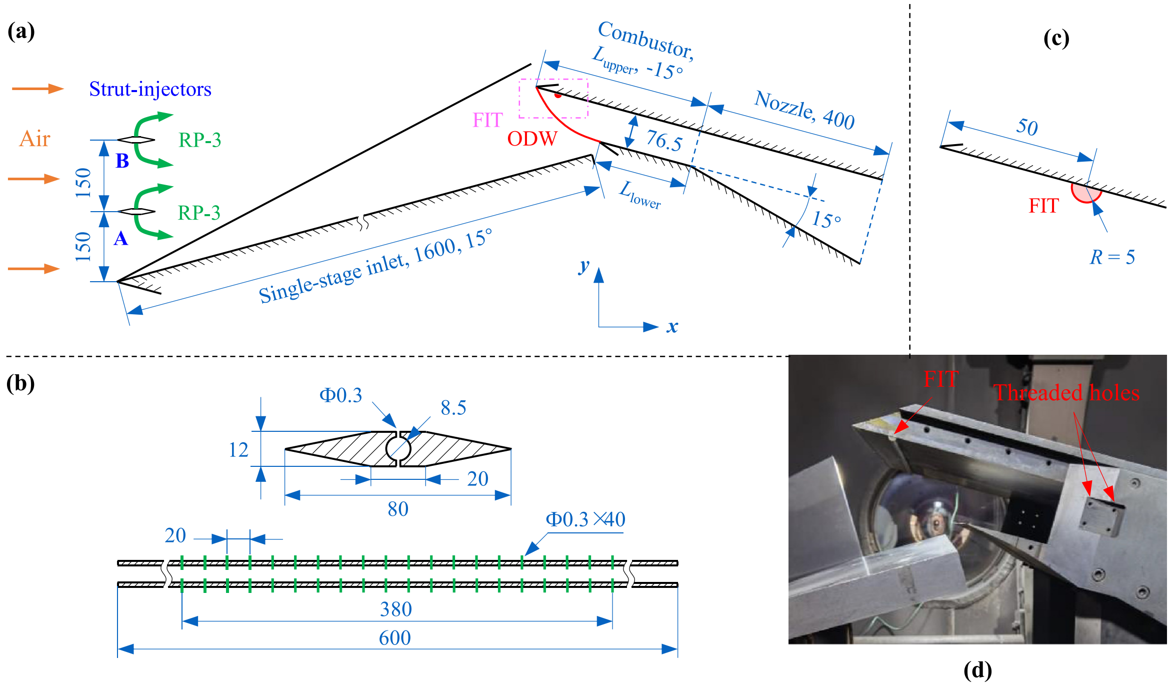

Fig. 2. (a) Detailed geometry of the ODE model, (b) detailed geometry of the strut-injector, (c) installation location of the FIT, and (d) photograph of the FIT and combustor configuration used in test No. 20220110. The coordinate origin is set at the leading edge of the combustor's lower wall. Dimensions are in mm.

Table 1
Test conditions and setups of the fuel jet and the FIT.

Test No.	No. 20220114	No. 20220110	No. 20220105
Freestream total temperature (K)	3799	3865	3867
Freestream total pressure (MPa)	3.78	4.08	4.09
Freestream static temperature (K)	474	484	485
Freestream static pressure (Pa)	768	829	839
Freestream velocity (m/s)	2857	2884	2884
Freestream Mach number	6.55	6.54	6.53
Length of combustor's upper wall, L_{upper} (mm)	360.5	360.5	660.5
Length of combustor's lower wall, L_{lower} (mm)	200	200	600
Strut-injectors used	A, B	A, B	A
Kerosene injection pressure (MPa)	0.92	0.92	0.94
Kerosene mass flow rate (g/s)	200	200	101
Use of FIT	No	Yes	Yes
Detonation initiation	No	Yes	Yes

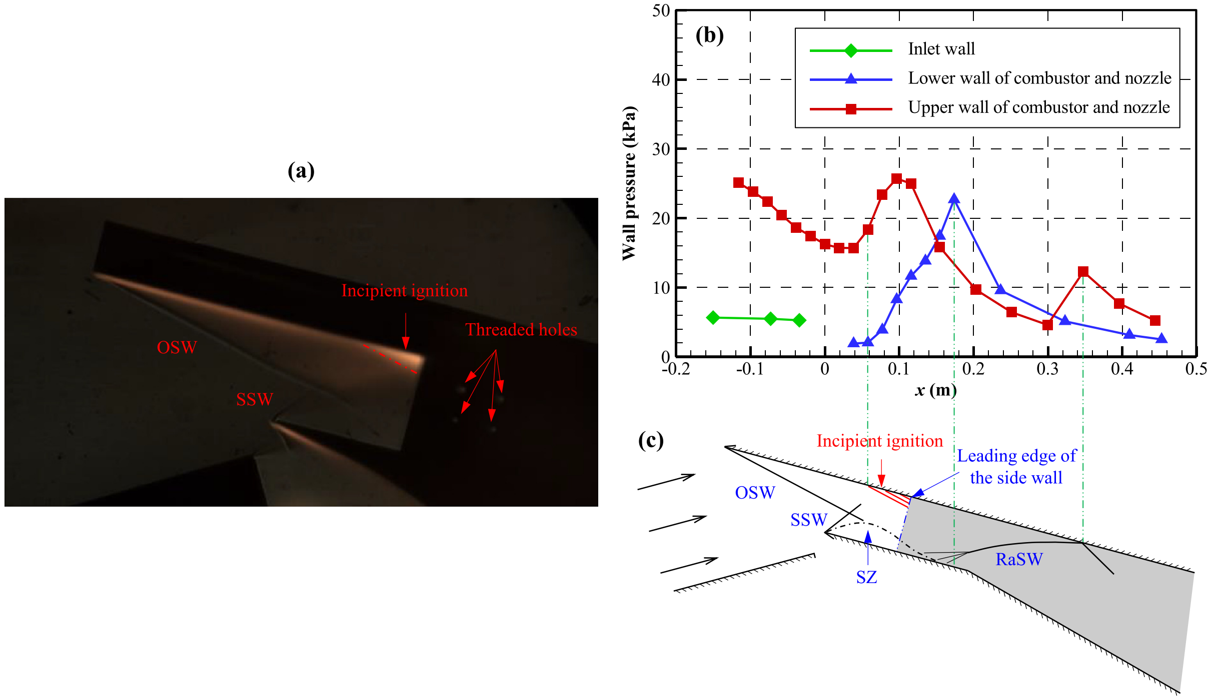

Fig. 3. (a) A schlieren photograph of the combustor, (b) the mean wall pressure distributions along the central lines of the inlet, combustor and nozzle, and (c) a schematic of the flow structures in the combustor in test No. 20220114.

such amount of freestream air is assumed to be mixed with the fuel out of one strut-injector in the inlet) and an RP-3 surrogate model ($C_{11.13}H_{21.79}$) [14] is approximately 0.95. High-speed schlieren photography is conducted to directly identify detonation initiation and stabilization within the combustor, and complementarily, wall pressure measurements are carried out along the central lines of the inlet, combustor and nozzle (see Tables S1–S3 in the Supplementary Materials). The effective test times of the three tests are approximately 50–60 ms.

4. Results and discussion

4.1. Detonation-initiation failure without an FIT (Test no. 20220114)

In this test, the FIT is not mounted in the combustor. As shown in Fig. 3a, an OSW forms from the leading edge of the upper wall after the kerosene/air mixture flows into the combustor. Due to the large ignition delay time of the kerosene/air mixture, no significant combustion is observed behind the OSW. Only very weak combustion with faint light emission occurs in the hot boundary layer along the upper wall. Far downstream of the OSW, incipient ignition of the core flow with slightly brighter light emission can be identified near the top-right corner of the visible region of the combustor. The leading boundary (see the dash-dotted line in Fig. 3a) of this light-emission area has an inclination angle similar to that of the OSW, which is consistent with the ignition feature of an ODW within the induction zone [4]. Moreover, a gradual increase in the upper-wall pressure can be observed from approximately $x = 0.04$ m to 0.1 m (see Fig. 3b), which is additional evidence of ignition near this corner.

However, the wall pressure distributions remain at a low level, without any significant peaks related to detonation initiation, throughout the combustor compared to the other two tests described later, implying that this incipient ignition ultimately fails to form an ODW within the combustor. No bright light emission can be identified at the four threaded holes on the sidewall in Fig. 3a. (Bright light emissions can be identified at these holes in a successful initiation test, as shown in Fig. 4a.) In summary, no detonation initiation is observed in this test.

In addition, a separation shock wave (SSW) is observed at the leading edge of the combustor's lower wall (see Fig. 3a). This SSW interacts with the OSW, and consequently, a regular reflection pat-

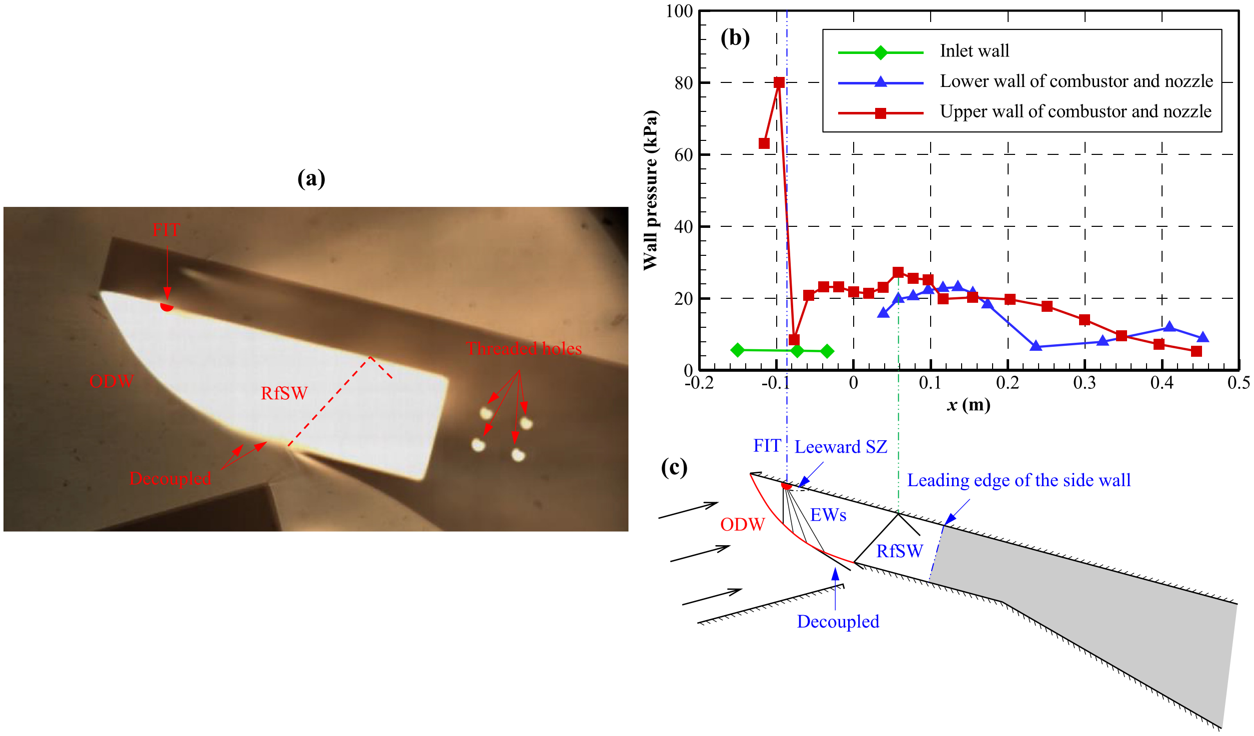

Fig. 4. (a) A schlieren photograph of the combustor, (b) the mean wall pressure distributions along the central lines of the inlet, combustor and nozzle, and (c) a schematic of the flow structures in the combustor in test No. 20220110. The ends of the annotated dashed lines in (a) correspond to either the leading edge of the lower wall or the measured pressure peak on the upper wall as in (c).

tern is formed. In Fig. 3b, two other wall pressure peaks can be identified at approximately $x = 0.17$ m on the lower wall and $x = 0.35$ m on the upper wall, which correspond to the formation of a reattachment shock wave (RaSW) behind the leading-edge separation zone (SZ) on the lower wall and its reflection downstream of the upper wall. The flow structures in the combustor in this test are schematically summarized in Fig. 3c, aligning with the x-coordinate in Fig. 3b. (Similar aligning is performed in Figs. 4 and 5.)

4.2. Successful detonation initiation with the FIT: mode 1 (Test no. 20220110)

An FIT is mounted on the upper wall of the combustor to force detonation initiation in this test (see Fig. 2d). After the high-speed kerosene/air mixture flows into the combustor, fast and violent combustion with bright light emission occurs under the effects of the FIT (see Fig. 4a). It is hard to distinguish the OSW and the upstream boundary of the combustion zone in the schlieren photograph, implying a tight coupling between the OSW and the flame, i.e., the formation of an ODW. The formed ODW is attached and curved from the leading edge of the upper wall towards downstream. Decoupling of the flame and the OSW is observed near the leading edge of the lower wall. The inclined angle of the curved ODW with respect to the incoming flow in the inlet varies from 77.5° at the upper-wall leading edge to 47° before decoupling. Notably, the curved nature of this ODW as well as its decoupling results from the expansion waves (EWs) emitted from the FIT. The flow structures are observed to remain stabilized in the combustor during the effective test time (see Fig. S1 in the Supplementary Materials).

As shown in Fig. 4b, a high-pressure zone forms between the leading edge of the upper wall and the FIT. As a result of the expansion effects of the EWs, both the upper-wall and lower-wall pressures downstream of the FIT, from approximately $x = -0.06$ m to 0.2 m, appear with a relatively lower but uniform level inside the straight combustor. At approximately $x = -0.08$ m, a further lower-pressure zone is observed on the upper wall immediately downstream of the FIT, which results from the formation of a leeward SZ behind the FIT. All these features are consistent with those of hydrogen-fueled ODWs with forced initiation by an FIT observed in previous numerical simulations [9,10]. In addition, another pressure peak is observed at approximately $x = 0.06$ m on the upper wall, which results from the reflection of a reflected shock wave (RfSW) forming from the leading edge of the lower wall (see Fig. 4a and c).

4.3. Successful detonation initiation with the FIT: mode 2 (Test no. 20220105)

In this test, a detonation combustion mode transition [11] is implemented by retracting the leading edge of the upper wall downstream by 100 mm. Additionally, the nozzle is removed, and the upper and lower walls of the combustor are both extended downstream by 400 mm. With the use of the FIT, a curved ODW is also formed in the combustor, but the flow structures are more complex (see Fig. 5a and c). An OSW is formed between the leading edge of the upper wall and the ODW. An SSW is formed at the leading edge of the lower wall. As a result of the interaction between the ODW and the SSW, Mach reflection occurs, and a Mach stem (MS, which can also be identified as a strong ODW as in Ref. [11]) is formed. Notably, most of the dark burned-out regions on the schlieren window glass (see Fig. S2 in the Supplementary Materials) were caused in previous tests (not reported here). The flow structures formed in the combustor also remain stabilized during the test (see Fig. S3 in the Supplementary Materials).

In addition to the high-pressure zone formed upstream of the FIT (see Fig. 5b), there are three other pressure peaks at approx-

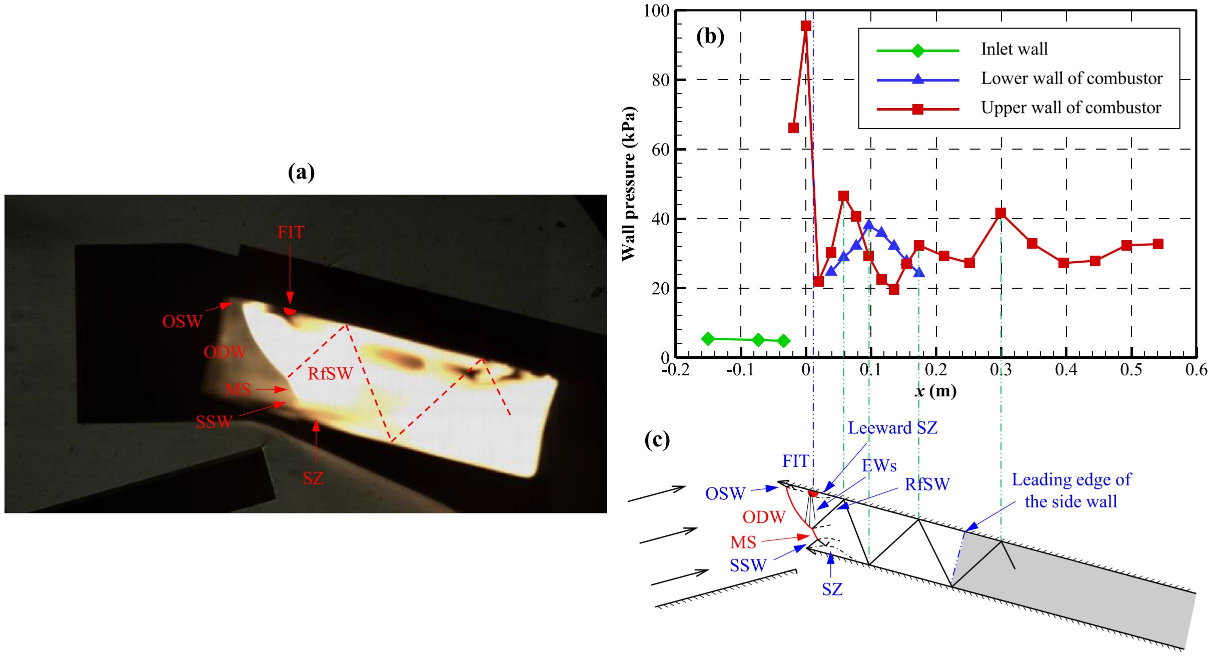

Fig. 5. (a) A schlieren photograph of the combustor, (b) the mean wall pressure distributions along the central lines of the inlet and combustor, and (c) a schematic of the flow structures in the combustor in test No. 20220105. The ends of the annotated dashed lines in (a) correspond to either the triple point or the measured pressure peaks on the walls as in (c).

imately $x = 0.06$, 0.18 and 0.3 m on the upper wall of the combustor and one at approximately $x = 0.1$ m on the front part of the lower wall. These pressure peaks actually correspond to the multiple reflections of an RfSW between the combustor walls (see Fig. 5a and c), which is emitted from the triple point between the ODW and the MS.

5. Conclusions

In this study, three free-jet tests of an RP-3 kerosene-fueled ODE model conducted in the JF-12 hypersonic shock tunnel are reported for the first time. The effects of a proposed initiation-control technique, i.e., the use of an FIT, are emphasized. The results show that without using the FIT, detonation of the kerosene/air mixture fails to initiate in the length-limited combustor, while an ODW is successfully initiated with the use of the FIT. Two stabilized oblique detonation combustion modes with different flow structures are implemented by using different combustor geometries and fuel setups in different tests. The effectiveness of the FIT on detonation initiation as well as the feasibility of kerosene-fueled oblique detonation propulsion technology is experimentally demonstrated.

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.

CRediT authorship contribution statement

Xin Han: Data curation, Formal analysis, Writing – original draft. **Yunfeng Liu:** Methodology, Data curation, Formal analysis, Writing – original draft. **Zijian Zhang:** Methodology, Data curation, Formal analysis, Writing – original draft. **Wenshuo Zhang:** Data curation. **Chaokai Yuan:** Data curation. **Guilai Han:** Data curation. **Zonglin Jiang:** Data curation.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.combustflame.2023.113102.

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