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Standing oblique detonation for hypersonic propulsion: A review

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ABSTRACT

Standing oblique detonation is a unique pressure-gain combustion phenomenon for hypersonic ramjet propulsion, and its research has been related with supersonic combustion in scramjet engines since its births, for example, absent treatment in its early stage and re-consideration in recent decades. Standing oblique detonations and supersonic combustion share the same features of supersonic chemically-reacting flows, and can be considered as different flow development stages. Combustion instability in a chemically-reacting flow is reviewed first to identify its fundamental mechanisms, and the upstream-propagating shock wave is identified as one of intrinsic characteristics and taken as the key problem for developing hypersonic ramjet propulsion. Critical conditions for the standing oblique detonation are summarized as a theoretical base for standing oblique detonation ramjet engines. Three key parameters are included, that is, the maximum heat that can drive local flow states from supersonic to sonic after combustion, the critical inflow Mach number of combustors, at which supersonic combustion becomes stable, and the critical wedge angle at which a standing oblique detonation can be initiated. The evolution of the standing oblique detonation is reviewed by placing emphasis on its complex wave structure that was found to develop via three stages, that is, shock-induced initiation, the decaying stage and the fully-developed stage. Finally, progress in experimental research is reviewed with detailed discussions on stabilization of the standing oblique detonation, experimental methods and development of adequate test facilities. In conclusion, the stable operation of hypersonic ramjet propulsion is a critical issue to approach its engineering application, and the standing oblique detonation ramjet engine is recommended as a promising candidate, deserving more attention in the future.

1. Introduction

Hypersonic flight is one of the most challenging research topics for decades [1–3] and a most pressing issue must be air-breathing engine development. The turbojet engine working well for low supersonic flight cannot be operated properly in hypersonic vehicles and two key issues limit its extension. The first issue is gas dissociation in combustion chambers because the airflow is at a high static temperature state after inlet compression. The second one is large inflow compression loss, that is, the inlet compression from hypersonic to subsonic speeds can induce significant mechanical energy loss of the freestream flow. Therefore, the scramjet engine concept was proposed to solve the two issues [4,5] and the oblique detonation engine appeared also at the same time as a kind of supersonic combustion modes for hypersonic ramjet propulsion [6,7].

Two new engine concepts can be dated from 1935 when René Leduc of France issued a patent on a piloted aircraft propelled with a ramjet engine. Interest in the ramjet engine began toward the end of World War II at a time when the turbojet was being accepted as an effective means of obtaining higher flight speeds, but it was also felt that the ramjet propulsion may be a next step for attaining still higher flight speeds. The inflow compression loss could be reduced with shock compression and the combustion could be organized in high-speed flows. In the 1950's [6,7] supersonic combustion ramjets and standing oblique detonation ramjets were proposed to avoid gas dissociations in subsonic combustion, only one persisted and survived, that of the diffusive burning scramjet in the 1965 to 1970 time period. With this singular exception it appears most of the interest in the standing oblique detonation hypersonic propulsion ceased [8,9].

Scramjet engines are an attractive research topic for decades, and "supersonic combustion" was accepted to describe flow physics in the scramjet combustor. There are many books and scientific research papers that reported research on supersonic combustion and scramjet engines, including numerical simulations, wind tunnel experiments, and even flight tests [4,5,10–14]. However, there are still no practical scramjet engines for aerospace. By recalling progress on supersonic combustion and scramjet engines, Yu and Fan reported two important

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issues from their experimental research, that is, inadequate engine thrust and the unstable combustion at high equivalent ratios [15]. Jiang demonstrated that unstable combustion was found to be induced by spontaneous combustion waves and can lead to scramjet engine choking, resulting in inlet unstart [16]. Actually, the low engine thrust is also closely related with the low limitation of useable equivalent ratios. These are two aspects of one problem, that is, the combustion instability of chemically-reacting flows. This provides motivation for reconsidering standing oblique detonation (SOD).

The concept of standing oblique detonation ramjet (sodramjet) engines has received little attention for decades due to the dominance of the scramjet engine from 1960 to 1980, as a potential candidate for hypersonic ramjet propulsion, the sodramjet engine differs markedly from the scramjet engine in its combustion mode. The compression process in the scramjet engine is carried out to high pressures and high temperatures that are required for diffusive auto-burning in the combustor, i.e. at flight Mach numbers of 5–7 to the combustor inflow Mach numbers of 2–3. The SOD compression process is moderate and carried out to relatively low pressures and temperatures, with the shock component of the oblique detonation process supplying the additional large compression as well as the corresponding high temperatures required for the rapid combustion portion. In turn, the combustion immediately behind the oblique shock wave provides a certain amount of chemical energy to make this leading shock wave of an oblique detonation be constant, resulting in a self-sustainable detonative process [8,17]. For the sodramjet in which the oblique detonation is applied to replace the diffusion-dominated combustion in scramjets, it is a huge step jump in the combustion mode from the diffusive burning to shock-induced combustion. moreover, the standing oblique detonation also belongs to supersonic chemically-reacting flows, and the shock/-combustion interaction and combustion instability are their common mechanisms.

The sodramjet engine concept was reconsidered in the late 1980's and its position in the flight regime of airbreathing hypersonic propulsion has been delineated. Morrison theoretically demonstrated that the sodramjet is of high-power density with short combustor length and simple engine structure, and can be operated stably for a wide range of flight Mach numbers from 6 to 16 [8,9]. The specific impulse calculated by Ostrander et al. at the same flow condition is also much higher than the scramjet engine [18]. Comparison of the total pressure, entropy and exergy at combustor outlets was completed by Yuan et al. showing that the performance of the SOD mode is the best among the supersonic combustion modes and its entropy increase at the nozzle outlet is also the lowest [19].

In order to make an oblique detonation stationary, many studies had been dedicated to the detailed structure of the detonation front and its evolution. The standing oblique detonation is shown to develop via three stages, namely, shock-induced initiation at its early stage, a detonation-decaying stage from the overdriven state to C-J sate, and the fully-developed stage where transverse shock waves exist such as freely-propagating detonation waves [20–23]. Yi et al. reported their numerical study on detonation wave propagation in a confined supersonic flow and found that the upstream-propagating detonation becomes stronger with a supersonic incoming flow [24]. The average pressure and temperature of the detonation front were found to be approximately proportional to the incoming flow Mach number while the detonation velocity is inversely proportional to the Mach number [25].

A standing oblique detonation originating from a sharp cone or wedge can be stationary but it may no longer stand if the flow is in a confined flow passage. Regarding the standing oblique detonation in a simplified ramjet passage, the oblique detonation initiation and its stabilization were investigated by considering influences from boundary layer development [26–28]. It was found that the blunt wedge plays an important role in SOD initiation and the boundary layer also had obvious effects on SOD initiation transition patterns. With some flow control methods, the stabilized oblique detonation in ramjet combustors was demonstrated both numerically and experimentally [29,30]. The fuel pre-injection into the core of airflow in the inlet is found to be acceptable for the sodramjet engines, and hypersonic mixing can be enhanced by the baroclinic effect of oblique shock waves, and the incipient expansion of fuel jets and the intensive momentum exchange can result in a well-mixed core flow before entering the combustor.

Three critical criteria for the standing oblique detonation were proposed to identify key parameters for determining hypersonic ramjet propulsion stability [16,31]. The first parameter is the maximum heat that can drive local flow states from supersonic to sonic during combustion. The second is the critical inflow Mach number at which supersonic combustion becomes stable. This parameter indicates a balance point between the total chemical reaction heat and the inflow kinetic energy. The last criterion is the critical wedge angle at which the standing oblique detonation can be initiated by the oblique shock wave that is just strong enough to trigger chemical reaction. A full-scale sodramjet engine model was tested with the JF-12 hypersonic flight-duplicated shock tunnel and the design concept of the oblique detonation engine was well demonstrated [32,33]. Experimental data showed that the standing oblique detonation in the sodramjet engine is stable and controllable, and the engine test model had operated steadily and continuously for about 50 ms.

By summarizing the important research progress achieved on standing oblique detonation, this paper is dedicated to the following aspects: (1) instability of supersonic chemically-reacting flows and generation of the upstream-propagating shock wave; (2) critical conditions for the standing oblique detonation at which the sodramjet engine can be operated steadily; (3) evolution of the standing oblique detonation in a confined space; (4) experimental visualization and demonstration of the standing oblique detonation. These four aspects may not include all the key physical issues for understanding the standing oblique detonation, but could be the significant ones being worthy of attention in the future. In the following discussions on each aspect, emphases are put on the problem identification, mechanism exploration, result remarking and research prospects from the author's viewpoint.

2. Instability of supersonic chemically-reacting flows

Both standing oblique detonation and supersonic combustion belong to a family of supersonic chemically-reacting flows. Sodramjet engine development benefits from a wealth of scramjet research since it is believed that organizing combustion in supersonic flows is an effective means to reduce inflow compression loss and avoid high-temperature gas dissociations. A big project was launched in the USA in the late 1980s and early 1990s to build a hypersonic vehicle that is powered mostly by a scramjet engine to fly into orbit around the earth [34,35].

Scramjet research received a huge push and has rapidly spread worldwide since then. Free-piston driven shock tunnels were commissioned and became the first high-enthalpy ground test facility in the world, being capable of simulating the range of flight speeds required for scramjet development and measuring performance characteristics of the scramjet engine [36–38]. Understanding of supersonic chemically-reacting flows benefit much from the facility development. A great milestone was reached by the X-43A flight test and the airframe-integrated engine worked well in actual flights at Mach numbers of 7 and 10. The engine thrust was sufficient to overcome the vehicle drag and provided positive acceleration. The progress is huge and the flight test became a turning point in hypersonic propulsion research [14,39–41]. However, the critical matter of utmost concern for this type of air-breathing hypersonic engines is that the net engine thrust is still not as large as expected as has been demonstrated also by both the flight tests and ground experimental data [15,40,41]. This concern is closely related with instability of hypersonic chemically-reacting flows.

2.1. Inlet unstart at high equivalent ratios

For production of engine thrust, one of the important issues is the engine operational stability resulting from unsteady combustion in supersonic flows. A large number of experiments on stable combustion limits has been carried out. Yu and Fan's experimental data for the inlet flow Mach number of Ma = 2.5 at a total pressure of $P_0 = 1.01 \pm 0.04$ MPa are presented in Fig. 1 for discussion [15]. In their experiments, both hot ethylene and supercritical kerosene were applied for different stagnation temperatures. Fuel injection occurred upstream of the cavity. Fig. 1 shows that the stable combustion region related with both the equivalence ratio and the stagnation temperature is located between the low limit of 0.2 and the upper limit of 0.65. The higher the total temperature, the higher the two limits become. From the figure, it is easy to understand that the low equivalence ratio leads to flame extinction because the combustible gas mixture is too lean to maintain any continuous flame. However, it is a bit confusing that inlet unstart will happen when the equivalence ratio is higher than the upper limit, resulting in flameout. For example, the equivalence ratio must be lower than 0.6 to avoid inlet unstart at a total temperature of 1200 K. This situation had been recognized widely but the mechanism underlying flame instability at high equivalence ratio is still in need of further investigation. Moreover, the highly-compressed inlet flow cannot react fully with fuels to release the maximum value of chemical reaction energy so that the engine thrust would be significantly limited because of the total pressure loss incurred during the inflow compression, being quite a large percentage of the kinetic energy of hypersonic free-stream flows.

Inlet unstart at high equivalence ratios can result in the engine surging that had been demonstrated with a long test duration shock tunnel and the corresponding experiment was reported briefly by Ju and in the 2015 annual review of Aerospace American [42] with detailed discussions presented later by Jiang [31]. The frequency of the engine surge is about 200 Hz. It is understood that the upstream-propagating shock wave is getting stronger and stronger as the continuously-released chemical reaction heat becomes higher and higher. Finally, the Mach number of the upstream-propagating shock wave becomes higher than the inflow Mach number and the inlet falls in unstart state when the shock is spat out of the inlet, resulting in unsteady operation of scramjet engines. The underlying mechanism for the unsteady operation is the shock/combustion interaction.

2.2. Shock/combustion interaction

Considering acoustic waves in chemically-reacting flows, Oh et al. [43] and Choi et al. [44] numerically simulated combustion oscillations in a scramjet engine combustor. Strong unsteady flow characteristics exist due to flow disturbances generated by boundary layer instability triggered by its interactions with shock waves. The flow disturbances induced by the flame-holder, override those induced by the shock/-boundary layer interactions. Transverse fuel jets can penetrate deeply into the cross-flow to enhance the mixing with air, but may be triggered into unstable states by the flow disturbances generated from shear layer development or the flame holder. The flame holder is considered as a source of flow disturbances from the transverse jet oscillation, fuel/air mixing enhancement, and flame-holding improvement. When combustion takes place throughout the flow passage, a Mach reflection develops above fuel injectors due to the upstream propagating compression waves in the local subsonic region, resulting in a strong pressure fluctuation on the upper wall. As an extreme case of the Mach reflection wave enhancement, thermal choking will occur in the combustor, which leads to the inlet unstart.

Fig. 2 shows instantaneous temperature fields at 5 ms from two cases with and without reacting flows. The combustion-induced flow instability is quite obvious by comparing the two results [44]. Although the initial conditions are the same, combustion drives the standing oblique shock wave to move forward, as shown in Fig. 2(b), which may result in inlet unstart that will lead to engine operational failure. From this figure, it is also observed that acoustic waves are produced in the combustor, propagate upstream and interact with shock waves standing in the inlet. The resultant flow oscillations in the inlet diffuser either propagate upstream in the form of shock waves or are transported downstream with the mean flow in the form of vorticity and entropy waves, which further reinforces unsteady flow motions in the combustor. A feedback loop is, thus, established between the inlet and the combustor. In extreme cases, the upstream-propagating shock wave may be disgorged out of the inlet due to large flow fluctuations, resulting in a catastrophic engine failure. The feedback loop phenomenon is supported with interaction between the upstream shock and acoustic waves in a supersonic inlet diffuser, and considered to be a dominant mechanism underlying start and unstart processes of the inlet. Shock/combustion interaction is the key mechanism in the chemically-reacting flow and the oblique detonation is also one of interaction results [48].

Considering shock/combustion interaction, Sislian et al. classified hypersonic ramjet propulsion into three types, namely the supersonic combustion ramjet (scramjet), the shock-induced combustion ramjet

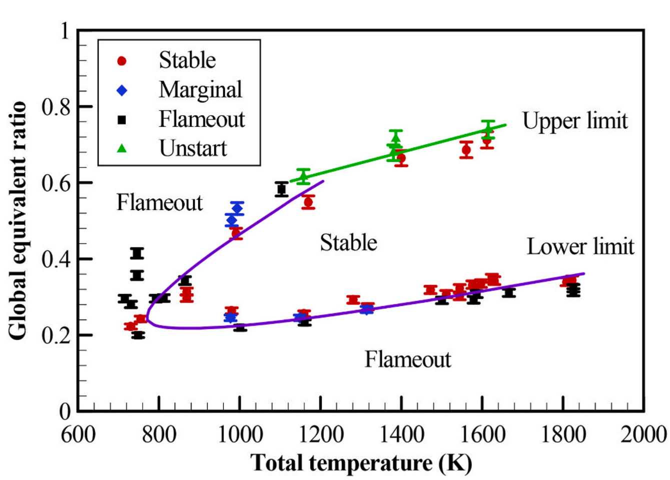


Fig. 1. Stable combustion limit at condition of supercritical fuel injection at the cavity upstream for $Ma = 2.5$ and $P_0 = 1.01 \pm 0.04$ MPa [15].

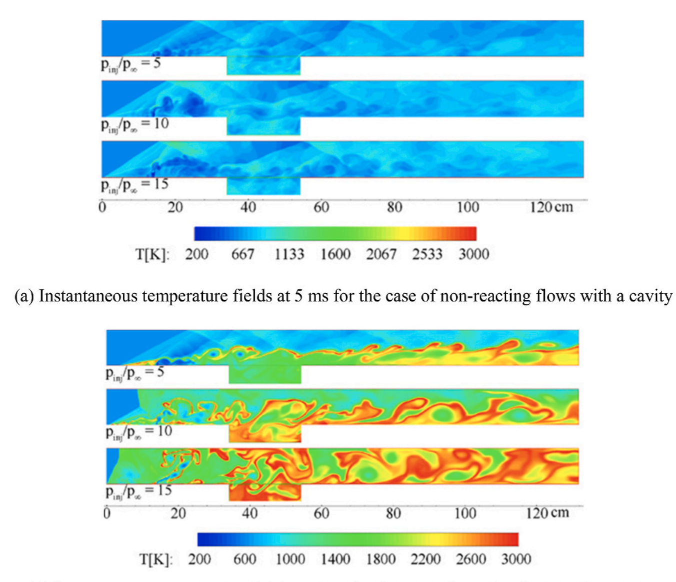


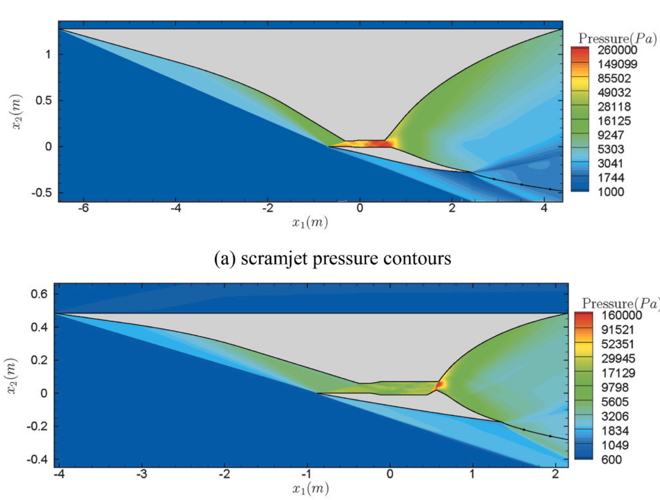
Fig. 2. Flow unsteadiness resulting in combustion oscillations in a scramjet combustor [44].

(shcramjet), and detonation wave ramjet [45–47]. One of their results is cited in Fig. 3 for reference, showing pressure distributions in the spanwise center domain with $x_3 = 0.01$ m. The configurations of the scramjet and shcramjet are also observable from this figure. Numerical performance of these hypersonic ramjet engines is obtained by solving Navier-Stokes equations implemented with the H_2-air chemical kinetics model of Jachimowski at a flight Mach number of 11. The inlet exit flow temperature is set to be 1500 K for the scramjet, 800 K for the shcramjet and above 900 K for the detonation wave ramjet. The inlet exit Mach number is 3.72 for the scramjet and 5.58 for the shcramjet. The numerical results show that the fuel specific impulse of the scramjet is higher than the shcramjet, but the shcramjet is appreciably smaller and lighter than the scramjet. As to the comparative study of the shcramjet and the detonation wave ramjet, Sislian and co-workers show that the thrust generation can be enhanced by 10 % higher than the detonation wave ramjet in the range of flight Mach numbers from 13 to 16. They commented that most of the thrust gain of the shcramjet is due to the lower compression ratio and thus less compression work in the inlet. However, it was emphasized that the combustion must be entirely shock-induced to attain the maximum thrust.

From Sislian's numerical research, come two interesting points. The first is that the oblique detonation engine is considered to belong to the family of hypersonic ramjet propulsion. Actually, detonation is a kind of supersonic combustion, but the extreme one where the leading shock wave is closely coupled with the combustion zone. The second is high inflow Mach numbers at which the ramjet flows are stable. This may indicate that the high kinetic energy of the coming flow can restrain upstream-propagating of shock waves.

2.3. Competition between upstream-propagating shock wave and inlet flow

Shock/combustion interaction is a dominating factor for operation instability of hypersonic ramjet engines. To find out the mechanism underlying competition between the inlet exit flow and the upstream-propagating shock wave, Jiang et al. showed the propagation of an upstream-propagating shock wave in supersonic flows at different Mach numbers [16]. Their test case is a two-dimensional straight flow passage with a chemical heat release source in the middle. The chemical energy is released continuously at a fixed reaction rate being equal to that occurring in a hypersonic ramjet combustor. Total chemical energy is determined from the H_2/O_2 reaction at full equivalent ratio. The computational domain is 20 mm in width and 200 mm in length.



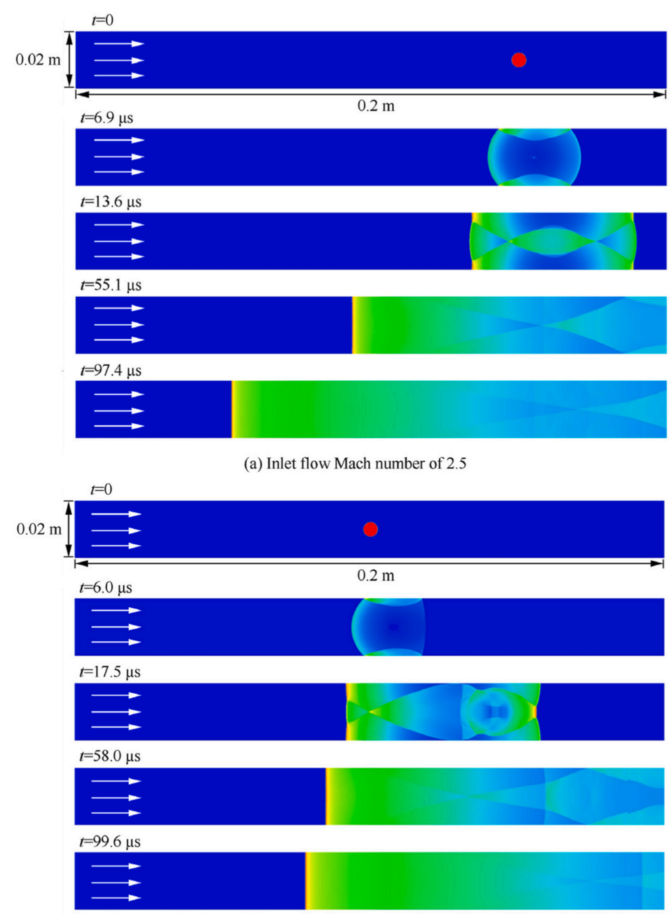
(a) scramjet pressure contours

(b) shcramjet pressure contours

Fig. 3. The pressure contours in the spanwise center domain for two modes of supersonic combustion, $x_3 = 0.01$ m.

Numerical simulations were carried out by solving the Euler equations at the inlet exit flow Mach number of 2.5 and 4.5. Pressure distributions of five time-sequential frames from each test case are presented in Fig. 4 to show the propagation of the upstream shock wave. Fig. 4(a) shows wave propagation at Mach 2.5 and Fig. 4(b) does that at Mach 4.5.

Fig. 4 shows five frames in two test cases, presented in chronological order. The first frame is the chemical heat releasing point and timing counter is set to zero at the moment. From the figure, it is observed that the upstream-propagating shock wave in the first test case at Mach number 2.5 propagates faster than the one in the second case at Mach number 4.5. Both the shock waves propagate at constant speeds. Two physical issues were identified and considered to play an important role in the shock/combustion interaction. The first physical issue, occurring at the early stage of the chemical energy release, is a circular shock wave around the region where the chemical energy is released continuously as happens in a hypersonic ramjet combustor. Two planar shock waves developed from the circular shock reflection : one is propagating upstream and the other is downstream. The inlet flow is compressed by the upstream-propagating shock wave, resulting in flow deceleration. The downstream flow expands because the downstream-propagating shock wave is leaving, resulting in flow acceleration. The flow physics is similar to Mach cone generation and the strength of the generated shock wave depends on the chemical heat release rate. It is understood that the flow temperature in the heat-release region is very high due to chemical heat addition and the reacted gas flow becomes locally subsonic. The second physical issue that the reflected shock catches up with the



(a) Inlet flow Mach number of 2.5

(b) Inlet flow Mach number of 4.5

Fig. 4. The upstream-propagating shock wave resulting from a continuous chemical heat releasing in a straight flow passage; (a) the pressure distribution at a Mach number of 2.5 and (b) the pressure distribution at a Mach number of 4.5 [16].

leading shock rapidly and the planar shock waves propagate even faster. It is because the flow expansion behind the planar shock wave is much weaker than the circular shock, indicating that the confined ramjet flow passage can enhance the upstream-propagating shock wave.

There may exist other phenomena in hypersonic ramjet flows, such as fuel injection, flame holding and boundary layer development, being important in the shock/combustion interaction, but these two issues as discussed above are always present as fundamental physical issues. Moreover, the upstream-propagating shock wave becomes slower and slower as the inflow Mach number increases, therefore, it would be reasoned that there exists an inflow Mach number at which the upstream-propagating shock wave will stand at the position where chemical reaction heat is releasing continuously. At this special Mach number, the competition between the upstream-propagating shock wave and the coming flow is in a dynamic balance point. This Mach number is dominated by the reaction heat-released ratio and must be a critical parameter for hypersonic ramjet propulsion.

3. Critical conditions for standing oblique detonation

Unlike typical jet engines, such as the turbojet or the turbofan, the hypersonic ramjet does not use any rotating or fan-like component to compress the air, but requires high kinetic energy of hypersonic flows to compress the incoming airflow to engine operating conditions. The combustion is organized in the combustor and the reacted product gas expands from the nozzle for thrust generation. Inlet unstart will occur if the back pressure increases to the point upon which the upstream-propagating shock wave moves into the inlet throat. The back pressure will increase, for example, if the chemical energy released in the combustor increases or the exhaust nozzle throat area decreases. Once the upstream-propagating shock wave reaches the inlet throat it is unstable in the sense that any infinitesimal disturbance can cause the shock wave to be disgorged by the inlet, resulting in the inlet unstart. Inlet unstart must be avoided at almost any cost because it deprives the engine of the airflow necessary for thrust and the shock upstream of the inlet face diminishes the total pressure necessary for performance. Also, the pressure and temperature of the gas in the flow path become excessively high, leading to catastrophic failure.

3.1. Maximum heat resulting in state transition

The upstream-propagating shock wave generated from combustors is still observable even if the air flow entering into the combustors is supersonic. The local state transition of the chemically-reacting flow from supersonic to subsonic is the necessary environment for the upstream-propagating shock generation. To demonstrate the physical mechanism behind the flow state transition, Jiang et al. simplified the hypersonic ramjet engine as a straight pipe with constant heat addition, but without external work [16]. This is a classical problem in gas dynamic text books, named Rayleigh heat addition. It is a well-known principle that the heat input makes the pipe flow approach the sonic state whether it is originally supersonic or subsonic. By applying one-dimensional flow theory, the maximum heat, q_{max}, required to drive the local flow into sonic state is given by the following equation:

$$\frac{q_{max}}{C_p T_{01}} = \left[\frac{1+\gamma Ma^2}{(1+\gamma)Ma}\right]^2 \left[\frac{1+\gamma}{2+(\gamma-1)Ma^2}\right] - 1 \quad (1)$$

where M_a is the inflow Mach number; γ is the specific heat ratio; C_p is the heat capacity at constant pressure; and T_{01} is the flow temperature before the heat release.

The maximum heat for different flow Mach numbers calculated with Eq. (1) is presented in Fig. 5, showing that the maximum heat needed in subsonic states is much higher than supersonic or hypersonic states. Actually, the chemical reaction energy contributes to the increase of both the kinetic and internal energies of the airflow in subsonic states,

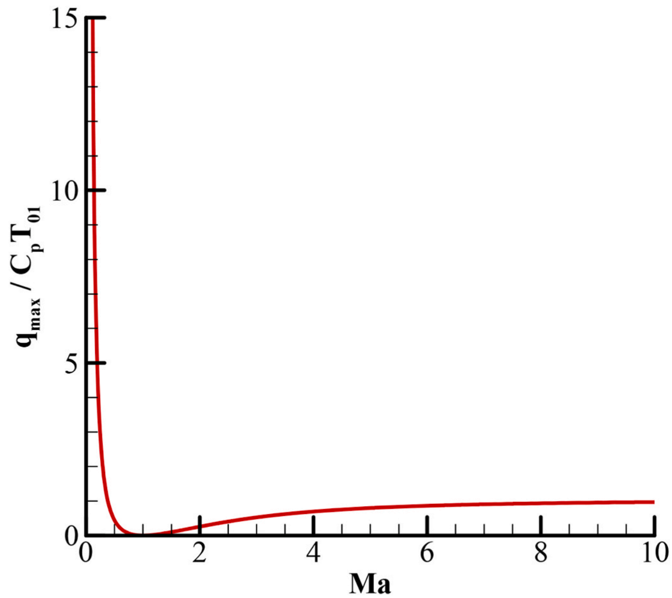


Fig. 5. The maximum heat required to drive one-dimensional flow into the sonic state [16].

but only to the increase of the internal energy in supersonic states. Hence the local Mach number decreases rapidly to the sonic value as the local sound speed of the supersonic flows increases. The maximum heat is defined as the first critical criterion that could be used to decide flow states in hypersonic ramjet propulsion, that is, supersonic or subsonic ones in the chemically-reacting flow after chemical reactions are completed. This criterion indicates a fundamental mechanism underlying the supersonic chemically-reacting flow, that is, how combustion waves are propagating.

Combustion waves can be generated and propagate upstream if the released heat from combustion is higher than the maximum heat, otherwise, the waves will travel downstream with local supersonic flow. It is understandable the flow upstream of the chemically-reacting flow region will be decelerated to subsonic since it is compressed by the waves, and the downstream flow will be accelerated to supersonic because the flow is expanding. Therefore, the subsonic flow region can exist even if the flow downstream is supersonic. Furthermore, the upstream-propagating combustion waves will transit into a shock wave as it is frequently observed from experiments in inlets. The shock wave will get stronger and stronger as the chemical heat release ratio is getting higher and higher. The debate about “supersonic” or “subsonic” combustions in scramjet engines has existed for decades, and an inspiring answer is indicated in Fig. 5. For ramjet-based engines, supersonic flow exists in the chemically-reacting flow region as long as the chemical reaction energy released is less than the maximum heat. Once the released reaction heat is higher than the maximum heat, local subsonic flow will be generated. The flow state transition is the environment for generation of an upstream-propagating shock wave that develops from unsteady combustion.

3.2. Critical Mach number for stable supersonic combustion

Inlet unstart will occur if the Mach number of the upstream-propagating shock wave becomes higher than the inlet exit-flow Mach number. The low equivalence ratio is often accepted in scramjet engine testing to weaken the upstream-propagating shock wave, which results in even lower engine thrust [15]. Therefore, it is understandable that the hypersonic ramjet operation stability is dominated by the inflow Mach number and the chemical reaction heat. The more the reaction heat addition in the combustors, the higher the inflow Mach number. There must exist a critical inlet exit-flow Mach number, at which hypersonic ramjet engines can be operated stably at full equivalence ratio. In other words, what is the critical criterion of the inlet exit-flow Mach number for a hypersonic ramjet engine? This Mach number is critical because the inlet unstart will take place once the upstream-propagating shock wave becomes stronger than the Mach number. It is important because hat no airliner can accept an engine that may work in an unstable operation mode, therefore, defining such a critical Mach number is of significant importance for developing hypersonic ramjet engines.

For a given inlet Mach number, the upstream-traveling shock wave is generated after a sonic state is reached as chemical reactions in the combustor are getting more and more intensive. The Mach number of the upstream-traveling shock wave is related to the amount of the released reaction heat, gaseous media and its thermal state. By assuming one-dimensional, steady flow with continuous heat addition at an infinitely fast rate in hypersonic ramjet engines, the critical Mach number for stable supersonic combustion can be given for a perfect gas by following after the C-J detonation theory [16].

$$\begin{cases} \mathrm{M_{Cri}} = \left[\dfrac{\gamma_0}{\gamma_1} \cdot \left(1 - \dfrac{2}{1 + \sqrt{1 + \frac{4}{\mathrm{K}} \frac{\gamma_0}{\gamma_1}}} \right) \right]^{-\frac{1}{2}} \\ \mathrm{K} = \dfrac{2\gamma_0(\gamma_1 + 1)}{\gamma_1^2} \left[\dfrac{\gamma_1 - \gamma_0}{\gamma_0 - 1} + \dfrac{\gamma_0(\gamma_1 - 1)\mathrm{q_{total}}}{\mathrm{c_0^2}} \right] \end{cases}, \tag{2}$$

where $_{\mathrm{MCri}}$ is the Mach number of the upstream-traveling shock wave, and q_{total} defines the total amount of the chemical energy that can be released from combustible gas mixtures at a given initial state. Subscript "*0*" stands for the flow state before combustion, and subscript "*1*" indicates the state after combustion. γ and c are the specific heat ratio and the sound speed, respectively.

Equation (2) shows that M_{Cri} depends mainly on the total chemical energy, q_{total}, being a key parameter for hypersonic ramjet engines. The upstream-propagating shock wave may be spit out of the inlet if the inlet Mach number is less than this critical value, which results in not only unsteady combustion but also engine surging [42]. The critical criterion defined with Eq. (2) is the maximum Mach number for inlet exit flows, above which the hypersonic ramjet engine surging will not happen. Detonation is supposed to happen in the combustor according to Eq. (2), therefore, the critical Mach number is considered as the maximum Mach number because most of hypersonic ramjet engines accommodate deflagration that is much weaker than detonation. The detonation is a unique pressure gain combustion with the fastest reaction rate in nature, and can drive out the strongest upstream-propagating shock wave than other combustion modes. For hypersonic ramjet engines operated in the deflagration mode with the same gas mixture at the same initial condition, the inflow Mach number could be smaller than the critical criterion, and also may vary with the way how to organize combustion, but is a meaningful limitation below which the engine operation stability may be a problem. This critical criterion is of significant importance not only for designing the hypersonic ramjet engines but also for understanding the shock/combustion interaction in hypersonic flows, and named as the second critical criterion of the standing oblique detonation [16]. From Eq. (2), it can be seen that the second critical criterion depends on both the total chemical reaction heat and the initial state of combustible gas mixtures. By reducing equivalence ratios at the same initial conditions, the critical Mach numbers, M_{Cri} for different fuels, are presented in Fig. 6.

It is observed that the critical Mach number is higher than 4 even though the equivalence ratio is taken to be 0.5 for all the considered fuels. Unfortunately, for most of the currently-investigated scramjet engines, the inlet Mach numbers fall between 2.5 and 3.5. This is the reason why many research papers had reported that subsonic combustion was observed frequently in experiments, and the upstream-propagating shock waves were observed frequently at inlet entrances.

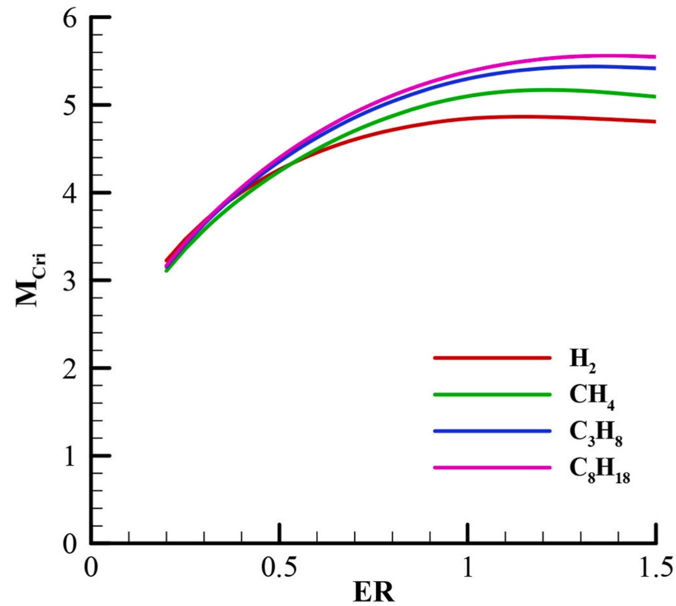


Fig. 6. Variations of the critical Mach number, M_{Cri} with equivalence ratio for different fuels [16].

It is also the reason why the equivalence ratio was usually chosen to maintain stable combustion, resulting in that the full equivalence ratio becomes far beyond the steady combustion region, as reported by Yu and Fan [15]. Furthermore, using low equivalence ratios is really an effective means to stabilize hypersonic ramjet engine operation, but the engine thrust is reduced significantly because the total chemical reaction heat is reduced. In other words, the total pressure loss has already been incurred during inlet flow compression, the low equivalence ratio means that the oxygen in the compressed flow cannot be totally consumed, resulting in less reaction heat release.

It is possible to lower this critical Mach number by distributing heat-releasing sources along the combustor, thereby reducing the chemical reaction rate. It is also a good means to expand the reacted gas flow as soon as chemical reactions are completed. In these ways, the useable equivalence ratios can become a bit bigger, but the problem is still not solved totally because the critical Mach number required is Mach 4.8 for H_2 and Mach 5.5 for C_8H_{18} under conditions of full equivalence ratio, being far beyond the designed inlet Mach numbers. In hypersonic ramjet engines, the designed inlet Mach number must match with total chemical reaction energy, $q_{total,}$ to gain stable engine operation. Equation (2) expresses their relationship that can be used as a reference point because that the upstream-propagating shock wave cannot propagate out of the engine inlet at this inlet Mach number. Of course, this critical Mach number is derived from detonation theory and can become smaller for hypersonic ramjet engines operated in deflagration modes as discussed above. Moreover, Sislian had accepted much higher inlet Mach numbers and there was no report on engine stability.

3.3. *Critical wedge angle for standing oblique detonation initiation*

The critical Mach number defined with Eq. (2) is one of the important requirements for hypersonic ramjet propulsion. This is a stable condition over which a standing oblique detonation may be generated if an adequate initiation source is provided in the combustor. It is well known that oblique detonation can be induced by oblique shock waves generated from a sharp wedge so a critical wedge angle for oblique detonation initiation must exist. To find this parameter, two polar curves at conditions of the same inflow Mach number and specific heat capacity ratio are plotted in Fig. 7, showing oblique shock wave and oblique detonation wave for comparison [17].

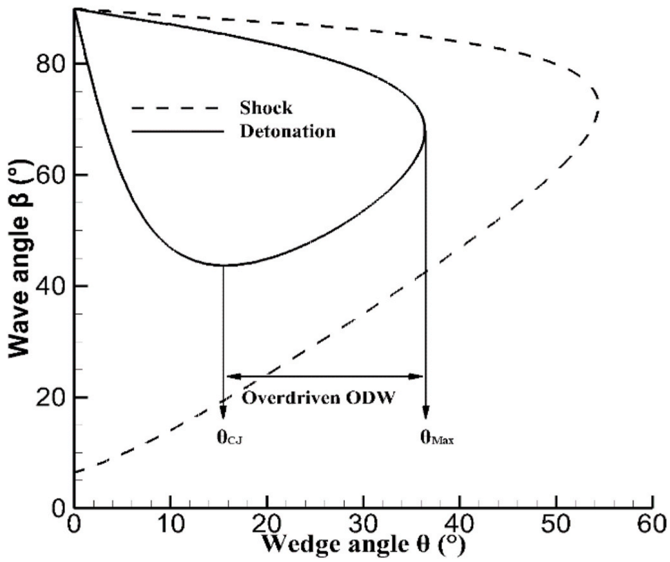


Fig. 7. Polar curves of oblique shock and oblique detonation [17].

Fig. 7 shows that the shock curve has two branches that are recognized as strong and weak solutions, respectively. The detonation curve has three branches. Its upper branch represents the strong solution that is hardly found in nature. The low branch stands for the weak solution corresponding to the oblique detonation waves observed widely. The additional branch on the left side is thought to be of no physical significance. Moreover, the oblique detonation has a larger wave angle than the oblique shock wave at the same wedge angle, and this phenomenon is considered to be induced by chemical reactions that elevate the post shock temperature and pressure, which push the leading shock wave forward. This is an obvious difference from the wave structures between the shcramjet and sodramjet.

On the weak solution branch of the oblique detonation, there is a standing window of the attached oblique detonation. At the lowest point of the detonation polar curve, the chemically-reacting gas flow becomes sonic and the local Mach number approaches to units. The solution at this point is called the C-J oblique detonation and the angle corresponding to the critical value is called the critical wedge angle, θ_{CJ}. At this detonation state, the total pressure loss due to shock compression is the lowest one and the gas dissociation becomes less so that the high thermal efficiency could be expected from the sodramjet engines. From this C-J detonation point to right along the weak solution branch, the detonation solution is named as the overdriven detonation. The larger wedge angle induces the stronger oblique shock wave that triggers more intensive chemical reaction that leads to the more powerful standing oblique detonation. From a viewpoint of engineering, engine performance in the overdriven detonation mode is evaluated to be high because of the increased post-shock pressure that plays an important role in net engine thrust generation in spite of a bit of higher total pressure loss. The critical wedge angle, θ_{CJ} as labeled in Fig. 7, is defined as the third critical criterion for the standing oblique detonation. The oblique shock wave of the critical wedge angle is just powerful enough to trigger a detonation [31].

Creating an oblique C-J detonation could be the ideal goal for organizing combustion in hypersonic flows, but the over-driven oblique detonation is also acceptable since the engine thrust loss is minor. Across the standing oblique detonation, the coming flow is compressed to auto-ignition level by the oblique shock wave, the shock-induced reactions provide with appropriate energy to maintain the oblique shock wave to be constant in return. As a result, the standing oblique detonation is not only stable, but also self-sustainable. This is a unique character of the standing oblique detonation, being remarkably different from various combustion modes in the scramjet and shramjet engines. In the sodramjet engine, the oblique shock wave acts like an efficient compressor and chemical reaction zone works like a turbine in modern turbojet engines. Coupling of the oblique shock wave and the chemical reaction zone makes the standing oblique detonation stable. The third critical criterion indicates the minimum wedge angle for a given inlet Mach number, at which an oblique shock wave can be generated due to the post-shock temperature that reaches auto-ignition level of combustible gas mixtures. Moreover, the bigger the wedge angle, the shorter the initiation process.

4. Evolution of standing oblique detonation

Producing an appropriate oblique shock wave for oblique detonation ignition is the first step for developing the sodramjet engine and gaining good performances. It has been demonstrated that the standing oblique detonation in the C-J detonation state is an ideal combustion mode for hypersonic ramjet propulsion and the over-driven oblique detonation is also acceptable [17,46]. Therefore, understanding on the evolution of the standing oblique detonation is very important for designing the sodramjet engine. There were many papers published on initiation and evolution of the standing oblique detonation [20–23,54–63], and the important progresses will be summarized in this chapter from four aspects, that is, the oblique detonation initiation, the decay of overdriven detonation, detonation front instability and other important effects on the standing oblique detonation.

4.1. Wave structures in initiation region

For standing oblique detonation from the wedge tip downstream, there exists a multi-wave structure in its initiation region, indicating an initiation process of shock-induced-detonation. This oblique detonation initiation region was simulated numerically first and visualized experimentally later [49,50]. The standing oblique detonation is difficult to carry out with wind tunnels because the required Mach number of the pre-mixed detonable gas flow is very high for detonation initiation. Viguier et al. had proposed a smart experimental method [50] and their experimental image of the multi-wave structure of the oblique detonation is shown in Fig. 8. In Viguier's experiment, two kinds of combustible mixtures were used. One gas mixture was used to generate a normal detonation acting as a gas dynamic wedge and the other mixture was used to trigger oblique detonation. Their study revealed that there is indeed a multi-wave structure in which the oblique shock wave and the

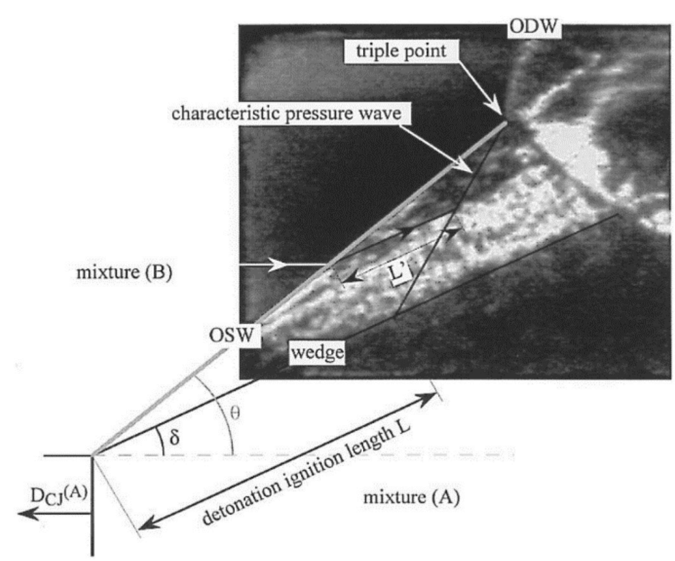


Fig. 8. Experimental image of the multi-wave structure of oblique detonation initiation [50].

oblique detonation wave intersect at a triple point from which a transverse wave is observable. The experimental image is basically consistent with numerical predictions but careful comparison shows that there are still some obvious differences, mainly manifested in the combustion reaction zone that is not simulated properly with their experimental method.

Wave structures in the oblique detonation initiation region have complex configurations which are related closely to the inflow Mach number and the wedge angle. One of a numerical simulation result is cited from Ref. [54] to show the role of the inflow Mach number. The initial condition is the stoichiometric H_2-air mixture at a pressure of 1.0 atm and a temperature of 300 K. The standing oblique detonation is initiated with a 25° sharp wedge. Pressure contours and temperature distributions are plotted together in Fig. 9, demonstrating wave structures varying with the freestream Mach number.

It is found that the transition from an oblique shock to oblique detonation appears to be from smooth to abrupt when the freestream Mach number decreases from 10 to 7. The multi-wave structure is a meaningful indicator of the oblique detonation initiation, showing how the oblique shock wave induces the standing oblique detonation. Fig. 9 shows that at the same initial condition, the higher the inflow Mach number, the stronger the oblique shock wave and the shorter the transition process. Therefore, the triple wave point is moving downstream as the inflow Mach number decreases, as shown in Fig. 9 where coordinate scales are different for each. The sharp wedge is also a key parameter for the wave structure configuration and different cases were examined by Teng et al. [56], Xiang et al. [57] and Yang et al. [58]. The effect of boundary layers was investigated by Bachman and Goodwin [59].

The initiation process of the standing oblique detonation is similar to the deflagration-to-detonation (DDT) process. Zhang et al. had demonstrated the fact by using a space-time correlation between a two-dimensional oblique detonation induced by a finite wedge and one-dimensional unsteady detonation driven by a moving piston [60]. Their numerical simulations were completed by solving multi-species Euler equations with detailed chemical kinetics of the H_2-Air mixture. Pressure and temperature distributions from two test cases are presented in Fig. 10. The two-dimensional case is in Fig. 10(a) and the one-dimensional case in Fig. 10(b). Comparison between the two cases showed that under the same overdriven degree, the multi-wave structure and state parameters calculated from the one-dimensional case fitted well with the two-dimensional test case after the space-time transformation. This study validated not only the space-time correlation method, but also the fact that the oblique detonation initiation belongs to the family of the DDTs. This work is helpful to understand the nature of the multi-wave structure of the standing oblique detonation, but the cellular structure downstream is beyond the capability of their one-dimensional simulation.

The shock-induced initiation process is the top issue for developing sodramjet engines. The inflow Mach number must be higher than the critical Mach number for given gas mixtures. The critical wedge angle is also a necessary condition at which an adequate oblique shock can be generated to induce a standing oblique detonation. The stronger the oblique shock wave, the shorter the initiation process. The sodramjet engine has a limited cross-section so that understanding on the multi-wave structure could be an important issue for designing the sodramjet combustor.

4.2. Standing oblique detonation development

The development of standing oblique detonation is a fundamental issue in gaseous detonation dynamics and related closely with detonation instability and front evolution. To our knowledge, the numerical research work was reported first in 2000 and the grid number used in the simulation was insufficient to achieve grid independence due to limited computational resources at that time, but the unstable wave front can nevertheless be observed. It has been a long time since then that the further investigation had not been reported and it would be hard to ascertain whether the oblique detonation instability derives from numeric perturbations or physical factors. Recently, as computational resources improve, more numerical research has been reported and numerical simulations have become more reliable.

Teng et al. investigated evolution of cellular structures of the standing oblique detonation in a stoichiometric hydrogen-air mixture, and observed transition patterns and unstable surfaces were reported [20–22,62]. Yang et al. examined standing oblique detonation instability with a two-step reaction kinetic model and the triple point movement along oblique detonation surfaces is reported [23,63]. The review paper by Teng and Jiang summarized more progress on the oblique detonation stability to classify the underlying mechanism [64].

Choi et al. demonstrated that the C-J oblique detonation could be destabilized and evolve into multi-wave structures similar to cellular detonations [61]. Their numerical results were calculated with a simple one-step irreversible heat release model, classic shock-capturing schemes and a much finer grid. The unstable detonation front surfaces were demonstrated to be physical and are independent from chemical models. Some results are shown in Fig. 11 with different activation energies at the same grid scale. Fig. 11(a) shows the dimensionless temperature distribution of the oblique detonation simulated with an activation energy of 20 and the oblique detonation front appears stable without visible disturbances. When the grid number is increased from 250 to 2000 per unit in the wave propagating direction, the detonation front still looks smooth, indicating that the oblique detonation at this activation energy level is essentially stable. At the same condition, numerical results show that the oblique detonation remains stable if

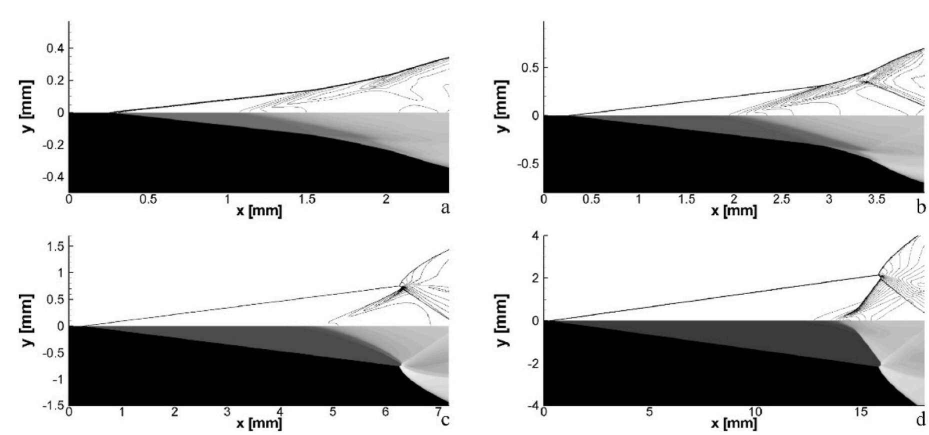
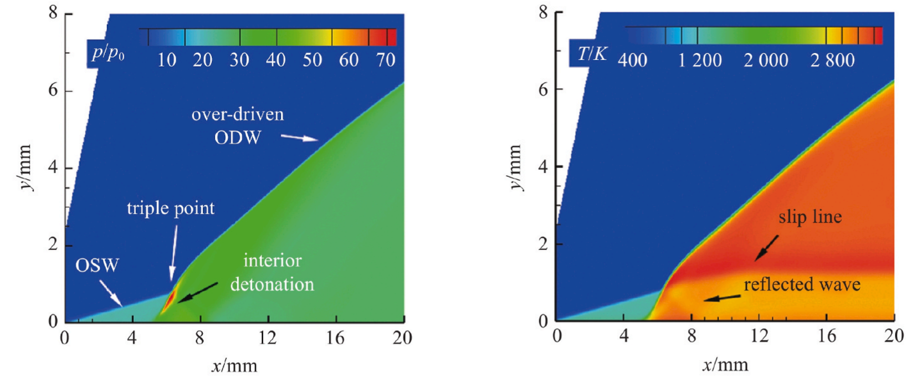
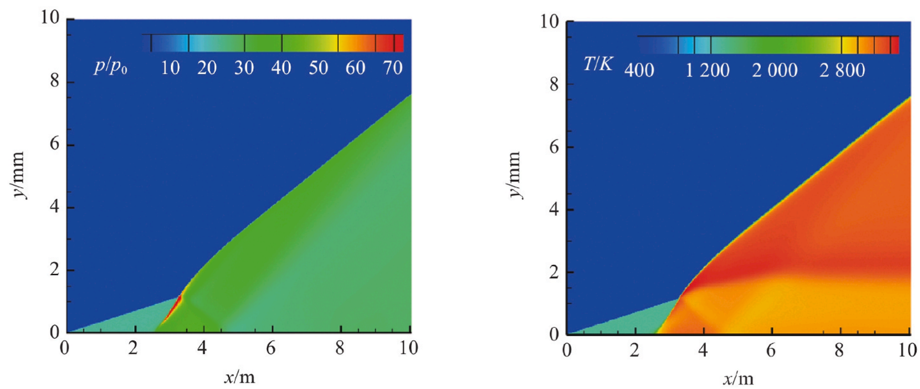


Fig. 9. Pressure contours (upper) and temperature (low) distributions in each figure, showing SOD initiation structures of stoichiometric H_2-air mixture over a 25° sharp wedge at room pressure and temperature: (a) *Ma = 10*; (b) *Ma = 9*; (c) Ma = 8; (d) *Ma = 7* [54].



(a) Two-dimensional case: pressure (left) and temperature (right) distributions



(b) One-dimensional case: pressure (left) and temperature (right) distributions

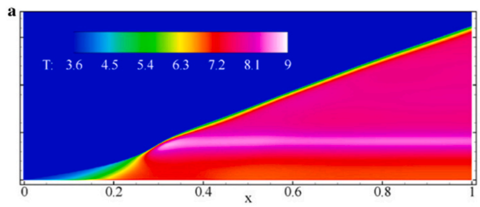
Fig. 10. A space-time correlation between the two-dimensional standing oblique detonation induced by a finite wedge and the one-dimensional detonation driven by a moving piston [60].

computed with a set of coarse grids, but becomes unstable if the fine grid is applied. Then, the same grid number of the previous vase is accepted with activation energy of 25, and the disturbed detonation front appears downstream near the right boundary of the computational domain and several triple points are observable, as shown in Fig. 11(b). The observed triple waves face left and are recognized as the upstream-moving transverse waves, but are transported downstream due to local supersonic flow. The oblique detonation simulated with activation energy of 30 is presented in Fig. 11(c). The disturbed detonation front appears earlier than in the second case and the intensive instability is triggered, leading to complex wave structures in which some triple points move upstream and others move downstream. Obviously, it is a classical feature of the freely-propagating detonation and the standing oblique detonation is demonstrated to evolve from an over-driven detonation into a cellular one. These numerical results indicated that the activation energy plays an important role in development of standing oblique detonation instability. The grid resolution is also an important parameter in computation, but it is still unclear how the grid scale behaves in destabilizing oblique detonation waves.

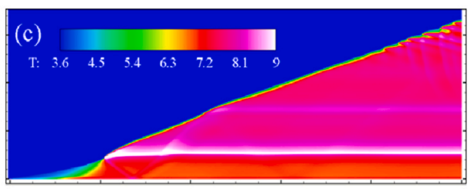
It is well known that overdriven oblique detonation can be induced by a sharp wedge of a larger angle than the critical wedge angle , θ_{CJ}, therefore, the overdriven oblique detonation decaying to the C-J state as the wedge angle decreases is also an interesting topic to investigate. Teng et al. reported their numerical simulations at an inflow Mach number of 15 with activation energy of 50 and their numerical results are presented in Fig. 12 [62]. In their test cases, the wedge angle is set to be 30°, 27° and 24°, respectively to produce the standing oblique detonations at different overdriven levels. Fig. 12 indicates that the oblique detonation is getting more and more unstable as the wedge angle becomes smaller and smaller, resulting in shorter and shorter smooth front surfaces. For the smaller wedge angle, the overdriven detonation could keep the smooth front surface near the triple point but becomes easier to get into cellular ones, as shown in Fig. 12(c). Moreover, even at the higher wedge angle corresponding to the stronger overdriven detonation, the oblique detonation destabilization occurs in its final stage, as shown far right in Fig. 12(a) and developed wave patterns look similar to those obtained by varying the activity energy.

The cellular structure evolution in a long computational domain was also carried out by Teng et al. to get the whole evolution process [22]. Fig. 13 presents temperature distribution from one of their test cases in which the combustible gas is a hydrogen/air mixture, the inflow Mach number is set to 12 and the wedge angle θ is taken to be 26°. Four noteworthy regions can be observed from Fig. 13. The first one is the transition region from the wedge tip to the triple point on the oblique detonation wave front. The second one is the decaying region from the overdriven to free-propagating states. The third is the full-developed cellar detonation. The last one is the developed boundary layer in which combustion waves from chemically-reacting gas flows could propagate upstream due to local subsonic state. Bachman and Goodwin had carried out the viscous wedge surface simulations by using a double-angle wedge [59]. Their results demonstrated that the presence of the boundary layer augments the oblique shock angle and provides sufficient shock compression to ignite and form the standing oblique detonation, and thus, boundary layers have a significant effect on the SOD initiation. Similar results had also been reported by Fang et al. [27].

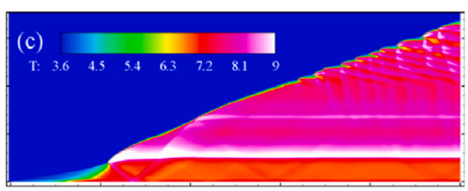
In summary, standing oblique detonation evolves via three stages.



(a) Oblique detonation instability simulated with activation energy of 20



(b) Oblique detonation instability simulated with activation energy of 25



(c) Oblique detonation instability simulated with activation energy of 30

Fig. 11. Effects of the activation energy on instability of standing oblique detonation [61].

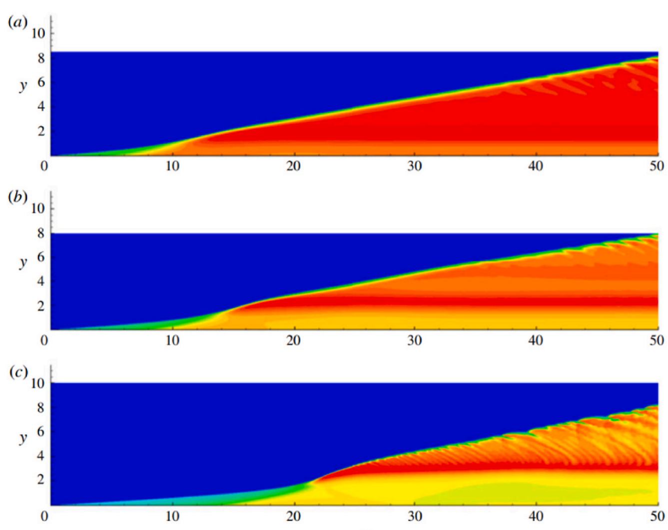


Fig. 12. Temperature distributions of standing oblique detonations with activation energy of 50 for an inflow Mach number of 15 at wedge angles of (a) 30°, (b) 27° and (c) 24°, respectively [62].

The first is the oblique shock-induced initiation and combustion mode transition, being similar to a conversional DDT process. The second is decaying of the overdriven detonation to the C-J state. It is well known that both the direct detonation initiation and the DDT can result in the overdriven detonation that develops later into steady states. It seems that the standing oblique detonation obeys the same physical mechanism. The last is the fully-developed cellular detonation of self-sustaining and self-organizing characteristics. During this evolving process, expansion waves play an important role and the mechanism underlying the phenomenon still needs to be classified clearly.

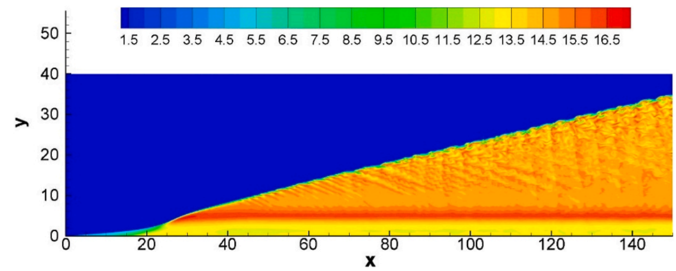


Fig. 13. Numerical result showing evolution of shock-induced standing oblique detonation [22].

4.3. Role of expansion waves

In the previous subsections, numerical simulations were calculated in computational domains having infinite wedges. However, sodramjet engines can accommodate only a wedge of finite length, therefore, flow expansion will be generated at the end of the finite wedge surface and imposes important effects on standing oblique detonation. Flow phenomena are schematically drawn in Fig. 14, showing the interaction between the standing oblique detonation and expansion waves. Three phenomena and two parameters are labeled in Fig. 14 for the further explanation, that is, the oblique shock wave (OSW), the oblique detonation wave (ODW), expansion waves, the inflow Mach number (M_0) and the wedge angle (θ). Generally speaking, the post-shock flow behind the OSW and ODW moves parallel with the wedge surface, and the flow expansion will take place once the flow moves over the turning point of the wedge surface. The ODW will be affected by the thus-generated expansion waves and the turning point of the wedge surface is a dominated parameter.

Xiang et al. examined the standing oblique detonation over one or two finite wedges, respectively and expansion wave effects on the ODW appeared obviously [57,58]. Wang et al. investigated the ODW reflection before an expansion corner and found that the corner expansion plays an important role in movement of the reflected detonation [65,66]. To explain the role of expansion waves, some results from systemic work by Fang et al. were cited for reference [21].

Fang's numerical simulations were carried out first by using an infinite wedge as baseline cases at inflow Mach numbers of 7 and 10, respectively. The detailed chemical reaction model of stoichiometric hydrogen-air mixtures was accepted and computed at the static pressure of 1 atm and the temperature of 300 K. Temperature distributions of their numerical results are presented in Fig. 15, showing wave structures in the two cases corresponding to the baseline cases. The oblique shock had induced successfully a standing oblique detonation, but the transition processes in the two cases appeared different with each other. The higher Mach number leads to the faster initiation, resulting in a smooth

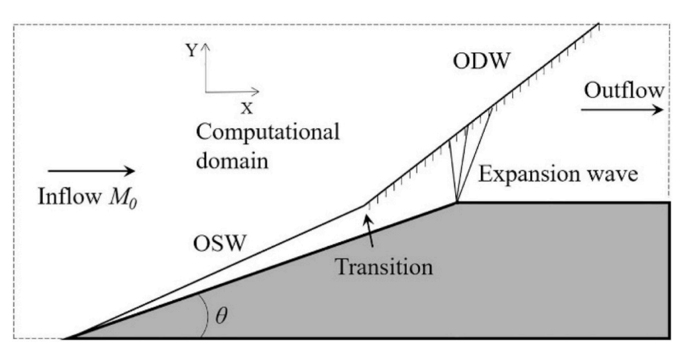


Fig. 14. Schematic of the OSW, the ODW and expansion waves over a finite wedge [21].

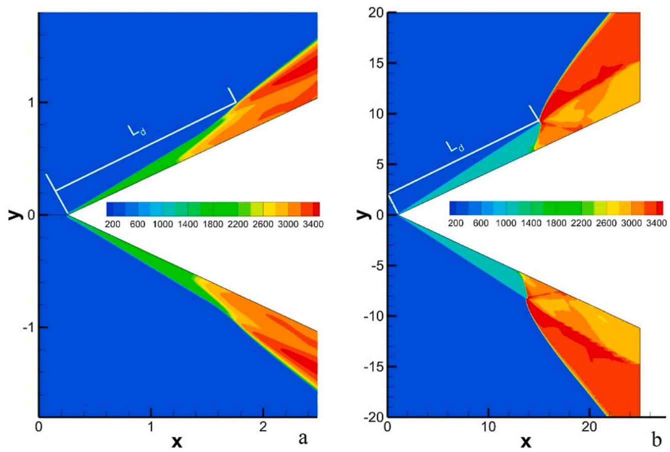


Fig. 15. Temperature distributions of the ODW over an infinite wedge of 25° angle; (a) the case of Mach 10 and (b) the case of Mach 7, the upper and low half of each figure calculated with different grids [21].

transition, as shown in Fig. 15(a). The initiation region in length is approximately one tenth of the low Mach number case. To adapt to different physical lengths, the computational domain is 2.5 mm × 2.0 mm for the Mach 10 case, and 25 mm × 20 mm for the Mach 7 one. By doubling the grid number per unit length, the results are plotted in the low half of Fig. 15(a) and (b), respectively. Checking carefully two images at different grids indicates that discrepancy is minor for the Mach 10 case and slightly obvious for the Mach 7 case, but their wave structures look almost the same.

The interaction of the ODW with the expansion waves was simulated over a finite wedge of 25° at the same initial conditions of the previous cases. Numerical temperature distributions are shown in Figs. 16 and 17, respectively. To facilitate the following discussion, two lengths L_e and L_d are defined to quantify the turning point position at which expansion waves are generated. L_e corresponds to the length from the wedge tip to the turning point, and L_d stands for the length from the wedge tip to the multi-wave point. So, the length ratio L_e/L_d represents the normalized position of expansion waves. The L_e/L_d is 1.0 for Figs. 16(a) and 0.8 for Fig. 16(b). By comparing Fig. 16(a) with Fig. 15(a), it is found that wave structures in initiation regions are similar to each other, but the temperature distributions behind the standing oblique detonation appear obviously different. The expansion waves result in the lower temperature behind the standing oblique detonation in Fig. 16(b) than in Fig. 16(a). By checking Fig. 16(b) carefully, it is observable that the standing oblique detonation looks weaker and uncoupling between the oblique shock and the reaction zone is going to occur.

Effect of the expansion waves on the standing oblique detonation is more obvious in the Mach number 7 case, as shown in Fig. 17. The post-shock temperature in Fig. 17(b) becomes much lower than that in Fig. 17(a). Actually, the oblique detonation disappeared from Fig. 17(b) where $L_e/L_d = 0.8$. The detonation initiation is not successfully completed in the last case. In conclusion, the interaction between the standing oblique detonation and expansion waves is unavoidable in sodramjet engines because the finite wedge must be accepted. The expansion waves act to weaken the standing oblique detonation and the L_e/L_d is a dominated parameter in the interaction. There must exist a critical L_e/L_d for a given inflow Mach number so that the oblique detonation might get uncoupled if the L_e/L_d is lower than the critical value. The detonation initiation process cannot be completed properly for low L_e/L_d even if the wedge angle is set to be the critical wedge angle.

5. Experiments of standing oblique detonation

A large number of the numerical research papers on standing oblique detonation has been published, which reveal the detonation phenomenon from different aspects and provide vast information. However, experimental research on the standing oblique detonation is hard to find. There are at least three problems that must be solved before carrying out successful experiments in the laboratory. The first one is the experimental facility that should be capable of producing the test flow at realistic flight conditions which are required for testing hypersonic engines where the chemically-reacting flow is dominated, especially for the test flow of Mach numbers higher than 8. The second one is the test gas that must be pure air to ensure that the detonation chemistry is correct. The third one is the scale of the test flow that is required to be large enough to accommodate the full-scale oblique detonation engine. Some uncertainties of the SOD stability have been left so far because of the lack of experimental validations, and development of the sodramjet engines was also far behind the scramjet engine. In this chapter, experimental research works are summarized in detail with emphasis not only on experimental data but also experimental methods and test facilities.

5.1. Visualization of oblique detonation initiation

A series of experimental works was reported by Viguier et al. from 1994 to 1998, and a stabilized structure of oblique detonation initiation were visualized with the Schlieren method [50–52]. Comparison between experimental and numerical results were also carried out, demonstrating good agreement. Their experimental photographs had showed clearly the structure of the oblique detonation initiation for the first time and has been widely accepted for verification of numerical simulations since then. The contribution of their experimental work to detonation research is of significant importance and their experimental method is also remarkable to remember.

The schematic representation of Viguier's experimental setup is shown in Fig. 18 and they called their test facility an oblique shock tube [51]. In the test facility, the driver section is filled with a detonative gas mixture that is chosen to be the driver mixture (A) according to its CJ velocity, and D_{CJ} is the one required for obtaining the desired Mach number M in the test section. The driven section contains the test gas that is a hydrogen-air stoichiometric mixture (B). The two gas mixtures are separated with a very thin Mylar film of 10 μm. Once the test starts,

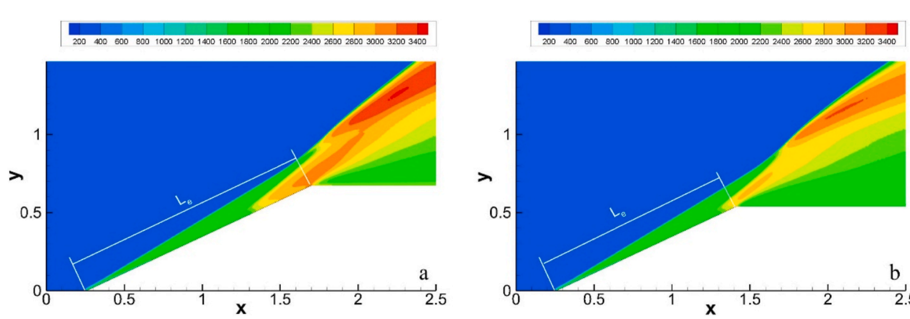


Fig. 16. Temperature distribution of the SOD over a finite wedge of 25° angle for the test case of Mach 10: (a) $L_e/L_d = 1.0$ and (b) $L_e/L_d = 0.8$ [21].

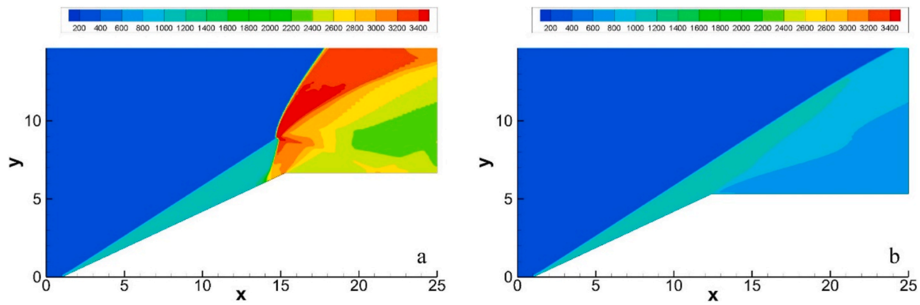


Fig. 17. Temperature distribution of the numerical simulations over an infinite wedge of 25° angle for the case of Mach 7; (a) $L_e/L_d = 1.0$ and (b) $L_e/L_d = 0.8$ [21].

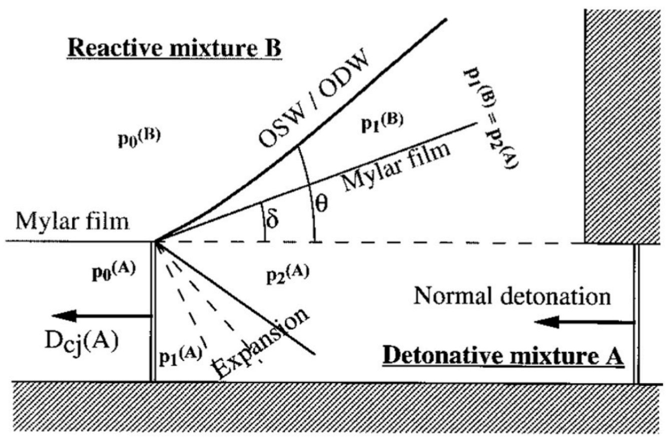


Fig. 18. Schematic representation of the experimental setup of the oblique shock tube [51].

the lateral expansion of the detonation product of the driver mixture (A) results in a birth of a gas dynamic wedge that has a constant angle (δ) and propagates through the reactive mixture (B). This propagation drives an oblique detonation wave in the reactive mixture (B), which has an angle (θ). Both the gas dynamic wedge and the oblique detonation wave move with the C-J velocity of the detonable mixture (A). As a result, the Mach number of the gas dynamic wedge with respect to the test gas is $M = D_{CJ}/c_{B0}$, where c_{B0} is the sound speed of the reactive mixture (B). In the oblique shock tube, the stable oblique detonation sustained by a gas dynamic wedge is generated in the driven gas of the hydrogen-air mixture at an initial temperature of 293 K, the pressures ranging from 0.2 to 0.8 bar and the Mach numbers of 6 and 7.5.

The wave structure obtained with the experimental method is presented in Fig. 8 and three physical issues are interesting to point out. The first is that the leading shock angle (θ) is a constant of about 30° with a good agreement with theoretical value, indicating success of the experimental method. The second is the existing flow region between the leading oblique shock wave and the flame front, in which the gas mixture initiation and chain-branching reactions take place; hereafter, this region is referred to as the initiation region. The last issue appearing at the end of the initiation region is an abrupt transition from the oblique shock wave to the oblique detonation.

This experimental method is very smart and their papers contain more detailed information. The above-mentioned experimental data validated the numerical simulations with a good agreement on stabilized wave structures, but the position of the triple point is not as directly related to chemical induction time of the shocked gas in the experiment as in computations. Moreover, the boundary layer is not reproduced as the rigid wall does so is the wave reflection. Actually, the stabilized oblique detonation structure is driven out by the detonation product of the driver mixture, which acts like a free piston. It is also understandable from the space-time correlation, proposed by Zhang et al. [60], that the wave structure in the initiation region is able to be reproduced with a piston, but some effects of viscosity and boundary layer cannot be covered.

5.2. Standing oblique detonation in a combustion-based facility

Rosato et al. published more practical experiments for standing oblique detonation, and progress was achieved on both the experimental method and test facility development [53]. Pre-mixed high-enthalpy flow is generated and the achievement of their experimental research is valuable. The experimental domain is taken from a hypersonic vehicle powered by the sodramjet engine, Fig. 19 highlights along with the experimental location in the ramjet engine flow path and illustrates the relation of their experimental domain with the computational one. The experimental domain looks much similar to the combustor of the sodramjet engine but the flow region around the wedge tip is actually a compressed corner, being different from the flow over a pure sharp wedge.

The test facility developed by Rosatos et al. consists of five major components, as shown in Fig. 20. The inflow preheater for achieving a stagnation temperature range from 800 to 1200 K consists of a coaxial hydrogen-air jet flame surrounded by evenly spaced co-flow air jets. A static temperature of 180–320 K is reached in the test section with the preheater. The mixing chamber is a square channel with an internal height of 45 mm and a length of 350 mm. The CD nozzle has an axisymmetric square cross-section along the entire length of the nozzle and is designed to provide a Mach number of $M = 5.0$ for dry air at 300 K. The effective Mach number depends on the temperature and the heat capacity ratio of the mixture entering the nozzle for the test, which results in a Mach number range of 4.3–4.6. The fuel is a mixture of hydrogen and air, and provided from a pressure source tank at 34.45 MPa. More parameters of the HyperReact facility are indicated in Fig. 20.

Experimental shadowgraph showing a stabilized standing oblique detonation over a ramp in hypersonic flow is presented in Fig. 21, in which the flow density gradient with the chemiluminescence from chemical reactions is overlaid. In the experiment, the test flow is

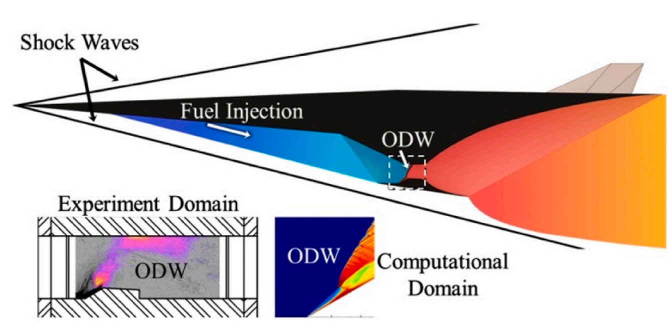


Fig. 19. Schematic of the experimental and computational ODW domains in engine flow path [53].

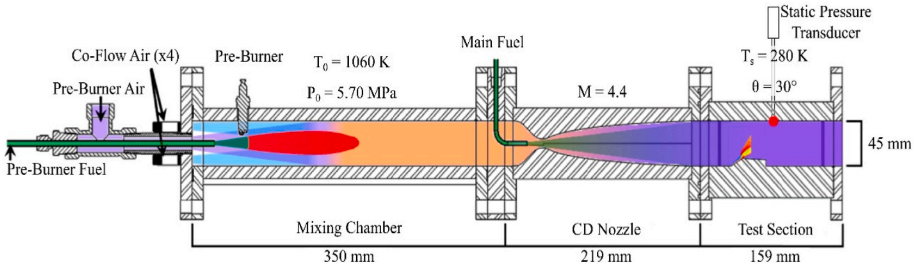


Fig. 20. Schematic of the HyperReact facility [53].

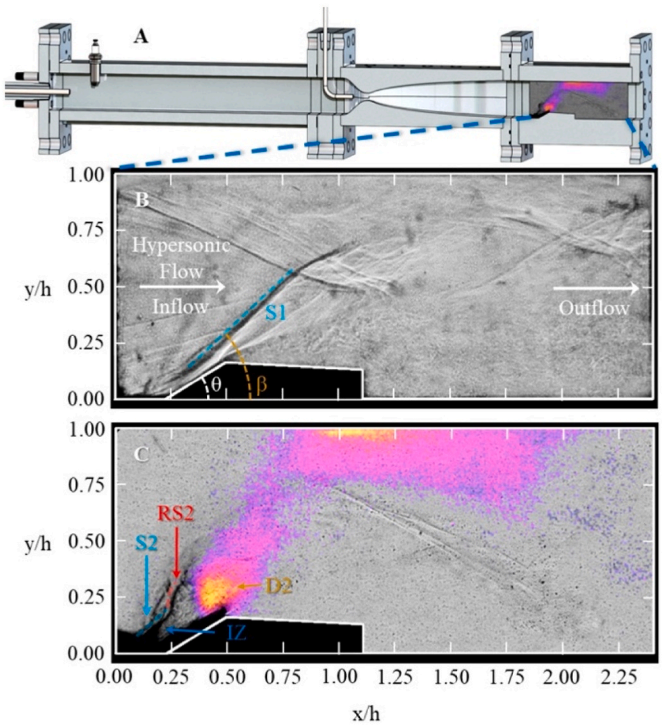


Fig. 21. Experimental results: (A) HyperReact facility; (B) nonreacting flow field; and (C) stabilized ODW [53].

generated with the Mach 5 nozzle as shown in Fig. 21(A), resulting in an effective exit Mach number of 4.4. The stagnation pressure *(P_0)* is 5.63 MPa and the stagnation temperature *(T_0)* is 1060 K. The nonreacting hypersonic flow, as shown in Fig. 21(B), was obtained when the pre-burner was operating and the main fuel injection was not activated, the corresponding oblique shock wave was observed clearly. The same hypersonic flow with the fuel turned on is presented in Fig. 21(C), resulting in the generation of a stabilized ODW. The nonreacting flow field was analyzed first to have the oblique shock wave that matches the theoretical adiabatic oblique shock solution for a 30° ramp. The predicted oblique shock angle is 42° for an inflow Mach number of 4.4 with a specific heat ratio of 1.3. An ODW sustained during the experimental test for approximately 3 s, shown by the reacting shock structure (RS2) in Fig. 21(C). The highest chemiluminescence signal intensity was observed immediately above the ramp due to the presence of the sustained detonation.

The whole physical process goes as follows. As the incoming flow passes through S2, it enters the induction region and is heated by the temperature rise across the oblique shock wave. The chemical reaction process occurs through autoignition and the detonation is initiated with a steeper angle of 73°. The flow velocity is calculated as being 99.7 % of U_{CJ} in this mixture. The static pressure measured downstream of the ramp shows a pressure rise that is generated due to chemical reactions when compared to the nonreacting pressure. The peak pressure is about 2.7 times higher than the nonreacting pressure and 10.5 times higher than the nozzle exit pressure, which is strong conformation of the detonation formation.

A standing oblique detonation was generated in this facility and the experimental data obtained in a pre-mixed detonable gas mixture is invaluable. Design concept of the facility works well to generate hypersonic flow with required enthalpy and the test flow becomes pre-mixed detonable gas without noticeable combustion before the standing oblique detonation is initiated. However, the test flow Mach number falls into a range of 4.3–4.6, and is obviously lower than the critical Mach number, $M_{Cri,}$ from Fig. 6. Therefore, it is recommended to increase the test flow Mach number above 5 to generate a stabilized standing oblique detonation. As to the experimental data, the effect of the boundary layer separation on the oblique shock wave has to be considered. As a result, the oblique shock wave is not originated from the wedge tip, but from a separation bubble existing in a compressed corner ahead of the compression ramp, as shown in Fig. 22(B). Moreover, the stabilized ODW does have a triple point, indicating the shock-induced detonation transition, but the oblique detonation disappears very soon, as shown in Fig. 22(C) where the chemical reactions downstream of the ODW are getting weaker and weaker while the chemiluminescence becomes less bright. The phenomenon indicates the significant effect of expansion waves from finite wedges, as discussed before. The standing oblique detonation may become more stable if the L_e/L_d of the 30° ramp can be made bigger than the present experimental domain.

5.3. Experimental validation of the sodramjet engine

An experimental research article on the sodramjet engine validation was published by Jiang et al. [16]. The corresponding progress was reported in detail [30,31]. Around this time, a series of numerical papers was published and dedicated to stabilization of the standing oblique detonation in hypersonic ramjet flow passage. Zhang et al. investigated fuel pre-injection in a Mach 9 oblique detonation engine and the standing oblique detonation was stabilized in the combustor [28,29]. Wang et al. explored the reflection of the standing oblique detonation from an outward turning wall and before an expansion corner, respectively, and mechanisms underlying the observed complex waves were discussed in detail [65,66]. Han et al. had stabilized the reflected detonation that behaves stranger than the original standing oblique detonation by adjusting the flow expansion induced with an expansion corner [67]. Jiang's designed concept of the sodramjet engine was proposed according to the critical condition and the above-mentioned flow control methods, and then validated successfully with a hypersonic wind tunnel.

The wind tunnel used for Jiang's experiments is the JF-12 hypersonic flight-duplicated shock tunnel (JF-12 shock tunnel). The JF-12 shock tunnel is about 268 m in length with a converging–diverging nozzle of 2.5 m in diameter, as shown in Fig. 22. Its performance calibration has demonstrated that the JF-12 shock tunnel is capable of producing hypersonic airflows with Mach numbers from 5 to 9 at altitudes of 25–50

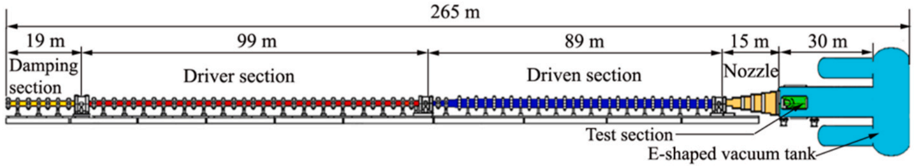


Fig. 22. Schematic of the JF-12 shock tunnel and the dimension of its main parts [32].

km with more than 100 ms test duration [32,33]. As shown in Fig. 22 from right to left, the first part is the E-shaped vacuum tank for damping the precursor shock reflection from the nozzle-starting process. The vacuum tank with a volume of 600 cubic meters is 34 m in length and 3.5 m in diameter. Owing to the vacuum tank, the test will be completed before the reflected shock wave arrives at the test section. The second part is the test section that is 15 m in length and 3.5 m in diameter. The contoured nozzle is 15 m in length and 2.5 m in diameter. The test flow field is large enough to accommodate the full-scale sodramjet engine. Next to the contoured nozzle is the driven section, being 89 m in length and 720 mm in diameter. The detonation section is 99 m in length and 400 mm in diameter. The damping section is 19 m in length and 400 mm in diameter. The 100 ms test time was achieved with the three main parts.

The JF-12 shock tunnel was operated in the backward-running detonation mode, that is, the detonation is ignited at the right end of the driver section and propagates toward the damping section. The JF-12 shock tunnel is equipped with a 640-channel digital data acquisition system and several 6-component force and moment balances designed according to its 100 ms test duration. The large test flow field, the long test time and hypersonic flight-duplicated capability make the JF-12 shock tunnel a unique facility for testing hypersonic ramjet propulsion, especially for the sodramjet engine.

The sodramjet engine test model is composed of four main parts: that is, three strut-injectors evenly spaced for hypersonic fuel pre-mixing, the single-stage compression inlet of a 15° angle, the combustor with a sharp wedge of a 15° angle, and the short nozzle being 400 mm in length. The sodramjet engine test model is 2.2 m in length, 550 mm in height and 450 mm in width. The engine combustor is 410 mm in length and 76.5 mm in height. The sodramjet engine is rather shorter than scramjet engines even though it is to operate at much higher Mach numbers. Boundary layer suction technique is also used to control boundary separation bubbles and stabilize the standing oblique detonation. The sodramjet engine test model and its installation in the JF-12 shock tunnel test section are shown in Fig. 23. The uniform test flow was measured to be 2.0 m in diameter so that the sodramjet engine test model could be fully placed within the core of the test flow. The sidewall of the combustor is replaceable with glass windows to ensure that the standing oblique detonation can be visualized with a high-speed camera during testing. Pressure transducers are also installed along the test model to show pressure variations during engine operation. Experiments are carried out at a nominal Mach number of 9 and the total temperature of the test flow is 3377 K. From experimental data, the oblique detonation standing in the combustor was observed to maintain a stable state for as long as 50 ms, all the engine control techniques worked well and the sodramjet engine was running stably. So, the sodramjet engine test was very successful.

One of the video frames is presented in Fig. 24 and the corresponding hydrogen concentration from numerical simulations is shown in Fig. 25, presenting the hydrogen fraction distribution and pressure isolines together. From Fig. 24, it is clearly observed that the standing oblique detonation existed in the combustor and developed from an oblique shock wave to an oblique detonation. The hydrogen was consumed out behind the oblique shock in a very short distance, as shown in Fig. 25. The region behind the oblique shock wave is the so-called reaction zone and its width indicates the chemical reaction intensity. Very tight coupling of the oblique shock wave with the reaction zone indicated generation of the standing oblique detonation. This standing oblique detonation is observed to compose of two different regions, the detonation initiation region and the fully-developed oblique detonation. The initiation region is from the wedge tip to the inflexion point where the reaction zone catches up with the oblique shock wave and the reaction zone in this region becomes significantly narrower, as shown in Fig. 25.

The concept of oblique detonation engine has been proposed for several decades and many numerical simulations have been carried out for investigation since then, but it is the first time that the concept was demonstrated successfully with a high-enthalpy and hypersonic wind tunnel. The success benefits mainly from the three criteria proposed for the standing oblique detonation and the JF-12 shock tunnel that provides excellent high-enthalpy test flows. Flow control techniques are also very important, such as hypersonic fuel pre-mixing, boundary layer absorbing and detonated gas flow expansion. From Jiang's experimental results, two issues deserve future attention. The first one is the hypersonic pre-mixing device from which two parallel fuel jets still need time to diffuse into each other, as shown in Fig. 25. The other is that the nozzle is too short for engine thrust generation. It is understandable that their concern in this experimental research is on stabilization of the

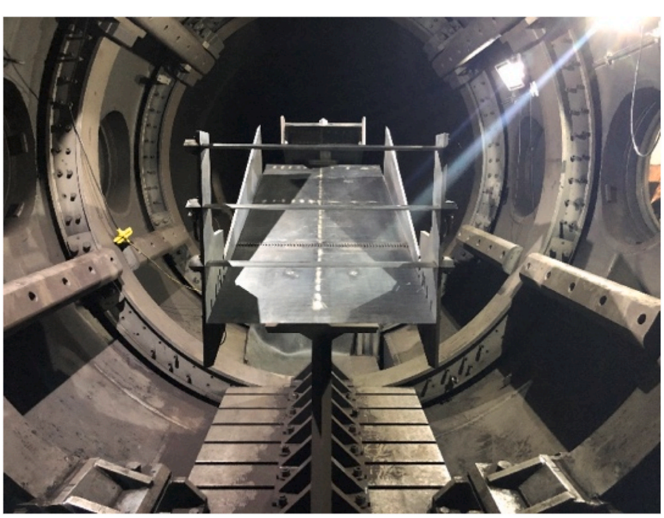


Fig. 23. The sodramjet engine test model and its installation in the JF-12 shock tunnel [16].

Fig. 24. Experimental photo of the oblique detonation standing in the combustor of the sodramjet engine test model for Mach number 9 [16].

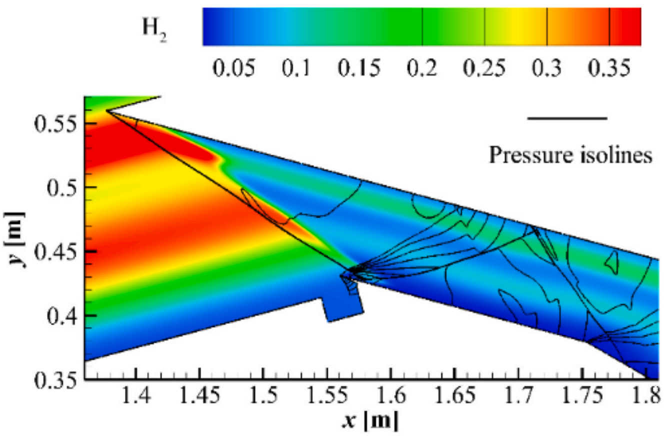


Fig. 25. Numerical simulation of the corresponding hydrogen concentration of the sodramjet engine test model [16].

standing oblique detonation and the stable operation of the sodramjet engine, but the engine thrust should be measured to confirm the thermal efficiency of oblique detonation engines.

Finally, it is important to point out that the exhaust gas flow behind the standing oblique detonation is supersonic and the detonable gas mixture is consumed at supersonic speeds, resulting in a real supersonic combustion. Although the sodramjet engine belongs to the family of the hypersonic ramjet propulsion, its combustion mode is unique because the standing oblique detonation is a self-sustainable and pressure-gain combustion phenomenon. The word “standing” is a critical requirement for designing the oblique detonation engine because the requirement is a primary base for stable operation of the oblique detonation engine. The “oblique” is a unique feature that can extend the sodramjet engine operation range widely. Gas dissociations are controllable as the inflow Mach number increases because the detonation is oblique.

6. Concluding remarks

Significant research progress on standing oblique detonation has been achieved during the recent decades, indicating that the practical oblique detonation engine for hypersonic propulsion is approaching. Conclusions and perspectives are presented from five aspects for reference as follows.

1) The instability of chemically-reacting flows is an intrinsic characteristic of supersonic combustion and the shock/combustion interaction plays an important role in it. The upstream-propagating shock wave driven by continuous heat release in hypersonic ramjet engines is a key phenomenon, enhanced by flow passage walls and accelerated during its upstream-propagating through the inlet where the negative temperature-gradient exists. The more the chemical reaction heat releases, the higher the shock Mach number becomes. The dominant factors for the shock wave are the total chemical reaction energy of combustible gas mixtures and the reaction heat release rate. The hypersonic ramjet engine can operate continuously even if the unsteady combustion takes place in its combustor, but will fall into the engine surging mode if the Mach number of the upstream-propagating shock wave is higher than the critical inflow Mach number. The engine surging had been observed widely in various scramjet engine experiments at high equivalent ratios and its underlying mechanism is the motion of the upstream-propagating shock wave that is closely related to the shock/combustion interaction. The combustion instability is a fundamental research issue for the chemically-reacting gas flow, and the shock/combustion interaction and high-temperature boundary-layer development, dominated by multi-parameters and affected by high-dynamic environment, are two interesting topics for future research.
2) The standing oblique detonation has very complex wave structures and its evolution is the key physical phenomenon that should be understood for developing hypersonic ramjet propulsion. It had been demonstrated that the standing oblique detonation develops via three stages according to the previous research information. The first stage is the shock-induced initiation where the wedge angle and the inflow Mach number are two key parameters. The second one is the detonation-decaying stage from the overdriven to the C-J states, during which expansion waves originating from finite wedges play an important role. The last is the fully-developed stage where transverse waves are observable and act like freely-propagating detonations. Moreover, the standing oblique detonation may not stand at the required position in a confined flow passage because of the boundary-layer/shock interaction that may result in boundary layer separation.
3) Critical conditions for the standing oblique detonation are essential for hypersonic ramjet propulsion and had been confirmed with the information available from the previous detonation and scramjet engine research. The first criterion, named as the maximum heat, can be used to determine local flow states of combustion products in chemically-reacting supersonic flows, indicating the mechanism underlying the generation environment of the upstream-propagating shock wave when organizing combustion in supersonic flows. The second criterion defines the critical inflow Mach number required for a hypersonic ramjet combustor to operate stably at the full equivalent ratio. Its theoretical base is the detonation, the strongest combustion even observed in hypersonic propulsion research, therefore, the critical Mach number would be a necessary condition for the hypersonic ramjet engine that will never fall into the engine surging mode if it operates above the Mach number. The last one stands for a critical value for a wedge angle at which an oblique shock thus-induced is just strong enough to trigger an oblique detonation. The bigger the wedge angle for a given inflow Mach number, the shorter the shock-induced transition process. Actually, the critical wedge angle is the smallest one for the sodramjet engine at the given inflow Mach number, and the length ratio also has important effect on it. The first two criteria are effective not only for the sodramjet engine but also for other types of hypersonic ramjet propulsions in which the balance between the total chemical reaction heat and the inflow dynamic energy must be achieved to maintain a stable engine operation. The critical conditions are the basic criteria for the sodramjet engine development and more parameters are required to classify in future
4) A great progress on experimental research has been achieved so far for both the high-enthalpy test facilities and experimental methods. Experimental data play an important role in investigating the standing oblique detonation. CFD validation had been realized from the data and the feasibility of sodramjet engines had been demonstrated with many numerical simulations. However, from the experimental research works available in this paper, four key issues are identified to be fundamental for future experimental study. The first one is the reliable hypersonic test facility that is expected to be capable of duplicating real hypersonic flight conditions, including the flight speed, the static pressure and temperature at a given altitude. The second one is the large uniform test flow region that is required to be big enough to accommodate the full-scale test model of the sodramjet engine because of chemically-reacting flows in it. The third one is the effective test time that must be long enough for the standing oblique detonation to be stabilized. The last one is how to make an oblique detonation stand at the required position in the sodramjet engine when the inlet exit flow Mach number is higher than the second criterion. This means that the flow control techniques are absolutely necessary because that the standing oblique

detonation may not stand in the combustor if it is put into a confined flow passage.

5) During development of modern aviation industries, the piston engine works well for low subsonic airplanes and the turbojet engine has been invented for high subsonic and supersonic flights. What kind of engine is suitable for hypersonic vehicles that can be powered into space at speeds from Mach 5–15? The 70 years' exploration on hypersonic ramjet propulsion has demonstrated that the revolutionary concept is real in need for air-breathing hypersonic propulsion. Reconsideration on various propulsion concepts that have been investigated for decades is absolutely necessary from an engineering viewpoint. From discussions in this review paper, it could be concluded that the sodramjet engine is a very promising candidate for hypersonic ramjet propulsion. It is because that the sodramjet engine is capable of operating not only at a wide flight range, but also at a pressure-gain combustion mode. The standing oblique detonation being self-sustaining with an own-compressor is unique for hypersonic ramjet propulsion. There is no doubt that this feature deserves to be emphasized repeatedly.

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.

Data availability

No data was used for the research described in the article.

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