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Criteria for hypersonic airbreathing propulsion and its experimental verification

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Abstract Hypersonic airbreathing propulsion is one of the top techniques for future aerospace flight, but there are still no practical engines after seventy years' development. Two critical issues are identified to be the barriers for the ramjet-based engine that has been taken as the most potential concept of the hypersonic propulsion for decades. One issue is the upstream-traveling shock wave that develops from spontaneous waves resulting from continuous heat releases in combustors and can induce unsteady combustion that may lead to engine surging during scramjet engine operation. The other is the scramjet combustion mode that cannot satisfy thrust needs of hypersonic vehicles since its thermos-efficiency decreases as the flight Mach number increases. The two criteria are proposed for the ramjet-based hypersonic propulsion to identify combustion modes and avoid thermal choking. A standing oblique detonation ramjet (Sodramjet) engine concept is proposed based on the criteria by replacing diffusive combustion with an oblique detonation that is a unique pressure-gain phenomenon in nature. The Sodramjet engine model is developed with several flow control techniques, and tested successfully with the hypersonic flight-duplicated shock tunnel. The experimental data show that the Sodramjet engine model works steadily, and an oblique detonation can be made stationary in the engine combustor and is controllable. This research demonstrates the Sodramjet engine is a promising concept and can be operated stably with high thermal efficiency at hypersonic flow conditions.

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1. Introduction

Many 21st century challenges exist in aviation science and technology, and one of these is the hypersonic vehicle from the dream for human beings to fly faster, higher and further than ever. With hypersonic airliners, we can arrive anywhere in the world within two hours. With reusable trans-atmospheric planes, we can take off horizontally from an airport runway, accelerate into orbit around the Earth, then reenter into the atmosphere, and finally land at an airport. In this way, space access will become reliable, routine and affordable. However, those exciting projects turn out to be very difficult to achieve.[1,2] It took about sixty years from Wright Brothers' first try in 1903 to the Concorde supersonic airliner taking off in 1969. During the period, we started from the very beginning of aviation, and entered successfully into the supersonic era. Now, seventy years have passed since the first object of human origin achieved a flight speed being five times faster than the speed of sound in 1949, and the practical hypersonic flight is still far ahead.[3]

There are several critical techniques for developing hypersonic vehicles, and the most challenging one must be the hypersonic airbreathing engine. The turbofan engine works well for a supersonic flight of the Mach numbers less than 3, but cannot be operated efficiently for hypersonic flights. In 1935, René Leduc of France was issued a patent on a piloted aircraft propelled by a ramjet concept. Later, the supersonic combustion ramjet (scramjet) engine concept was proposed for hypersonic propulsion. The research on the scramjet engine has spread rapidly over the world, and the word 'supersonic combustion' is accepted to describe the flow physics in the scramjet combustor. The continuous exploration on the scramjet engine has been lasting for about 70 years since then, so far it still remains as one of the hottest research topics in gas dynamic realm. Many scientific research papers reported progresses on supersonic combustion and scramjet engines, including combustion physics, thermal-efficiency and engine design principals that were investigated with numerical simulations, experiments, and even flight tests.[4–9] However, there is still no practical scramjet engine in use for aerospace engineering.

By recalling the research progress achieved in recent decades, several physical issues are considered to play an important role in scramjet development. Two of those issues are fundamental and critical. The first one is the wave propagation in scramjet flow passages due to spontaneous combustion waves arising from sudden heat release, which may develop into upstream traveling shock waves. This phenomenon can excite unstable combustion and results in inlet unstart and engine thermal choking.[10–12] The other is the low engine thrust that was demonstrated with flight tests, especially at high flight Mach numbers. It is possible to get positive thrusts for a small flight-testing vehicle, but the thrust is too small to power any practical hypersonic airliner for commercial applications.[8,9].

Another candidate for hypersonic propulsion is so-called the Standing Oblique Detonation (SOD) engine. For the SOD engine, an oblique detonation is applied to replace the diffusion-dominated combustion in scramjet combustors. The SOD engine had been theoretically demonstrated to be of the high-power density, the short combustor length and the simple engine structure.[13,14]. Ostrander et al. further calculated the specific impulse at the similar flow condition and found that it is higher than the scramjet engine.[15] Yuan and Huang did a parameter comparison of the total pressure, entropy and exergy at combustor outlets, and their theoretical results showed that the performance of the SOD mode under condition of the C-J detonation is the best among supersonic combustion modes and its entropy increase at the nozzle outlet is also the lowest one.[16] Other research results showed that the SOD mode can be operated in a wide flight Mach numbers ranging from 6-16.[13] In order to make an oblique detonation stationary, more papers dedicated to detailed detonation front structures and its evolution, and show the oblique detonation develops via three stages: initiation, transition and the full-developed one where transverse shock waves exist like normal detonation waves.[17,18]. However, there is no extensive research carried out like scramjet engines in the world, especially, there is a lack of the experimental works on the SOD engine, even it is well known that the detonation-driven engine has potential advantages over the scramjet.

Two problems may be responsible for such a situation. One is that the standing oblique detonation in combustors will take a complex structure developing from shock reflections, shock/boundary interaction and combustion instability due to the confined flow passage, therefore, it becomes a very difficult task to make an oblique detonation stationary at the required position in the SOD combustor.[19] The other is the lack of the proper wind tunnel being capable of reproducing true hypersonic flight conditions that are necessary for testing the SOD engine in its full scale. Therefore, the ground facility for hypersonic propulsion testing has been a challenge for Mach numbers higher than 8 for decades.[20–22]

When the inlet flow Mach number is getting higher and higher, the engine combustion mode may transit from subsonic, supersonic combustion to detonations at a ramjet-based engine with proper flow control techniques. So, both the scramjet and the SOD engines belong to the same class of the thermal engines. Only difference between the two engines is the operation manner with which how the combustion is organized. Therefore, this paper is dedicated to the investigation into the following four issues. The first issue is the generation of the upstream-traveling shock waves developing during scramjet combustion and its shock-enhanced mechanism. The phenomenon is important because it is the key issue related to scramjet operation instability. The second one is on the criteria for hypersonic propulsion engineers to identify combustion modes and avoid unsteady combustion. The third is the feasibility of the Sodramjet engine that is operated by maintaining a standing oblique detonation wave in its combustor. The last is on experimental verifications to confirm the concept and criteria proposed in this paper. These may not be all the key physical issues that have puzzle us a lot for decades during the practical hypersonic propulsion development, but are real the significant and fundamental ones being of worthy of much attention.

2. Generation of upstream-traveling shock waves

In the 1950s and 1960s, a variety of experimental scramjet engines had been built, and tested with hypersonic propulsion test facilities in the USA.[7,22] The significant accomplishment on the Hypersonic Research Engine had been achieved under the support of the National Aerospace Plane program (NASP) since the X-30 was to use scramjet engine as its propulsion. The engine model with flight weight is re-generatively cooled and of the aero-thermodynamic integrated engine configuration. Unfortunately, the X-30 concept demonstrator was flown only in wind tunnels and the program was canceled in 1994. Low maturity of its propulsion technology is one of the many problems.

A milestone was reached on the day of 27 March 2004 when a scramjet engine fueled with hydrogen was tested with the X-43A, a small hypersonic flight-testing vehicle, and the flight test was successfully completed. "The X-43A was a turning point," says Jim Pittman, the principal investigator for hypersonic at NASA. "We learned two things: Scramjets really do work. You really can get positive thrust out of a scramjet and you really can integrate a scramjet with a vehicle that you can fly and control. And both of those things are huge". There are also other two important issues that were revealed with the flight test data. The first issue is that the acceleration of the X-43A is small during the Mach number 7 flight and reduces to zero for Mach number 10.[9] The second one is the identification of the strong shock wave that exists in the scramjet inlet because a sharp jump was observed from the pressure distribution along the axial station through the scramjet engine. This is the upstream-traveling shock wave that had been observed frequently in scramjet ground testing and may result in inlet unstart and unstable engine operation. Pittman's two things are the brief summary for the past hypersonic research, and these two issues are also huge for future hypersonic engine development.[23]

When a diffusion-dominated combustion takes place in open air or in subsonic flows, spontaneous waves generated from sudden heat releases will propagate radially at the local sound speed, decay and disappear quickly without drawing anyone's attention. However, when the combustion occurs in supersonic flows, shock waves are generated from the nonlinear propagation of compression waves and enhanced by the confined wall reflection. These acoustic waves were widely recognized in both numerical and experimental works.[10,11] Actually, only an exceedingly small fraction of the chemical energy released in the combustion process is required to generate large excursions of acoustic oscillations, and the relevant combustion instabilities plagued the development of air-breathing propulsion systems.[12] In scramjet engines, an upstream-traveling shock wave generated from these waves may result in severe disruption in engine operation.

In order to identify the so-called upstream-traveling shock wave, a scramjet test was completed with the Performance Test Engine (PTE) model in the hypersonic-flight-duplicated wind tunnel (JF-12 shock tunnel). Fig. 1 presents the PTE model and its installation in test section. The JF-12 shock tunnel operated with the backward detonation driver is 268 m in total length with a 2.5 m nozzle, and can be used for reproducing the hypersonic flight condition from Mach number 5–9 at altitudes of 25–50 km.[20,21] The PTE model is 2.2 m long and consists of an inlet, a combustor, and an expansion nozzle. The inlet is three-dimensional one with two compression ramp surfaces. The combustor is made of with two backward steps, two fuel injections are distributed within the steps and the fuel-injected mass is adjustable for reaction heat release control. The engine nozzle is two-dimensional and 1.5 m in length. The test flow Mach number is 7 with a total flow temperature of 2200 K and the maximum dynamic pressure of 50 kPa. Forty pressure transducers are distributed from the inlet to the engine nozzle to monitor pressure variations during combustion. Two high-speed cameras are mounted toward test windows to observe both combustion products from the nozzle and the shock wave structure around the inlet.

Two typical pressure (p) variations recorded along scramjet engine model are plotted in Fig. 2, from which two operation modes are found for the PTE model. From the upper half of the figure, it is observable that the pressure profile is flat with slight pressure perturbations. The experimental data indicate that the PTE model is working continuously and a stable combustion is maintained. From the lower half of Fig. 2, the periodical pressure oscillations are identified. To investigate further the pressure oscillations, the time-sequential photos are presented in Fig. 3 and these frames were taken with

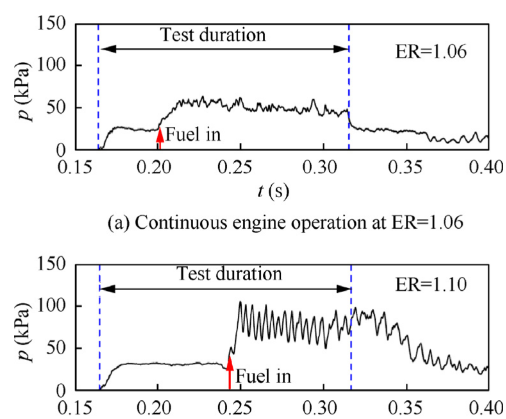


Fig. 2 Pressure variations recorded along scramjet engine model.

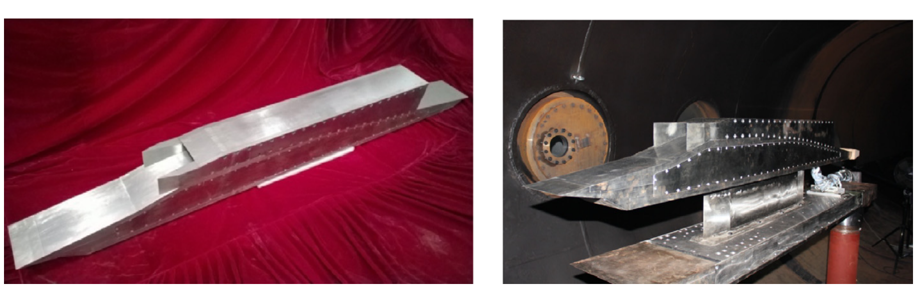
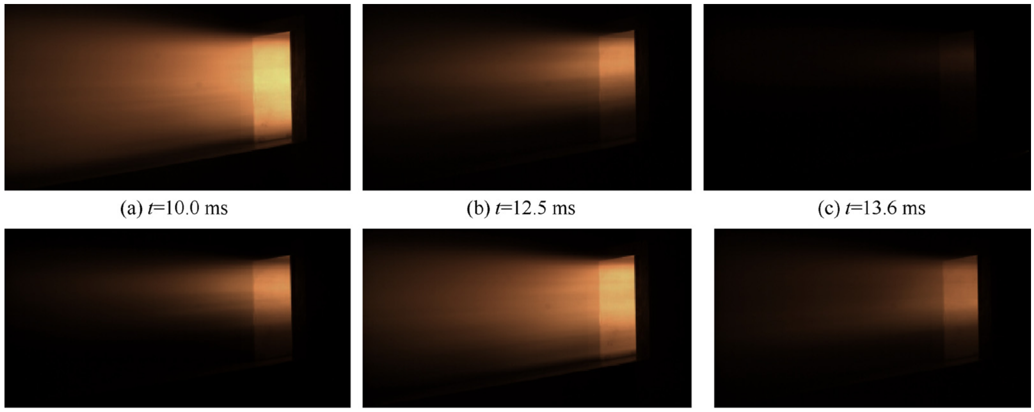


Fig. 1 Photo of performance test engine model and its installation in JF-12 shock tunnel.



(a) t=10.0 ms (b) t=12.5 ms (c) t=13.6 ms

(d) t=13.9 ms (e) t=14.5 ms (f) t=16.1 ms

Fig. 3 Time-sequential photos taken with high-speed cameras during engine surging and six frames showing about one cycle.

high-speed cameras during the PTE model operation. From this figure, it can be observed that the combustion dies out and is re-ignited periodically. The average frequency is about 220 Hz by counting the peaks of the oscillatory pressure. It seems that the combustion is dying out slower than its reignition by checking the frame time. The Equivalence Ratio (ER) is only the difference between these two tests. This important phenomenon could be defined as the engine surging that is a critical issue for scramjet operation control because there would be no practical engine that is allowed to operate in such an unstable mode.

Generally speaking, there exists a critical operation point for any scramjet engine at certain inflow conditions. Once heat release is over the critical operation point, upstream-traveling compression waves will get stronger and stronger, and then a shock wave is generated and accelerated due to the temperature gradient distribution ahead. Therefore, a thermal choking in engines takes place once the upstream-traveling shock wave reaches to the inlet entrance, the inlet goes into unstarts and the combustion flame dies out. Once the flame dies out, the upstream-traveling shock wave will decay rapidly so that the inlet would restart and the PTE model operates again. This phenomenon is taken as the hypersonic engine surging that is very interesting to understand combustion physics, but a quite tough problem for practical engine development. There must be a balance point at which the inflow Mach number matches with the reaction heat release, and then the shock wave becomes stationary in combustors.

3. Shock-enhanced mechanisms

Acoustic waves generated in nature due to sudden heat releases will decay quickly in open space. However, the physical phenomenon will behave quite differently due to wave reflection when combustion reactions occur in a scramjet engine flow passage that is a finite-confined space. Three physical issues play important roles in the shock/reaction interaction and will be discussed by assuming a supersonically-moving gas flow in a straight flow passage with a constant heat-releasing source. The first physical issue is a spherical shock wave around the area where the chemical heat is released continuously like what happens in the scramjet combustor. The flow in upstream is compressed because it is entering, and expands in downstream because it is leaving. The flow physics is the same to the Mach cone generation and the strength of the spherical shock wave depends on the amount of the released reaction heat, but the flow temperature in the heat-releasing region is very high due to the reaction. The second issue is the effect of the flow passage wall. The spherical shock wave is reflected soon from the passage wall after it is generated, and then develops rapidly into a planar one. The flow expansion behind the planar shock wave is much weaker than the spherical one so that the planar shock wave would not decay so easily. The third one is the temperature gradient in front of the upstream-traveling shock wave. The coming flow is compressed by a series of the oblique shock waves originating from the confined wall and its temperature is increased gradually from the inlet entrance to the combustor. Therefore, the temperature gradient is generated in the inlet, resulting local sound speed variations. From the above discussion, it is understandable that the upstream-traveling shock wave is generated from a series of combustion waves, enhanced by shock reflections from the confined wall and accelerated nonlinearly in the inlet due to the negative temperature gradient ahead. As a result, the shock wave is easier to generate and less to decay in the scramjet flow passage than in open space.

To demonstrate the shock-enhanced mechanism discussed above, numerical results are presented to show the generation and propagation of upstream-traveling shock waves. The test case is a two-dimensional straight flow passage with a chemically-reacting source in its middle where the heat is released continuously at the rate being equal to one occurring in a scramjet combustor, as shown in Figs. 4(a) and (b), respectively. The computational domain is 20 mm in width and 200 mm in length. The flow field is computed by solving the Euler equations and its pressure distributions are presented in Fig. 4. Fig. 4(a) is the result for the inlet flow Mach number of 2.5 and Fig. 4(b) is for the inlet flow Mach number of 4.5. For most of the experimental scramjet engines, their designed inflow Mach numbers are between 2.5 and 3.5. From this figure, it is observable that the shock wave is generated originally in a spherical form, and evolving into a planar one after wall reflections, and then propagates upstream. From those time sequential frames, the shock wave motion is much slower in

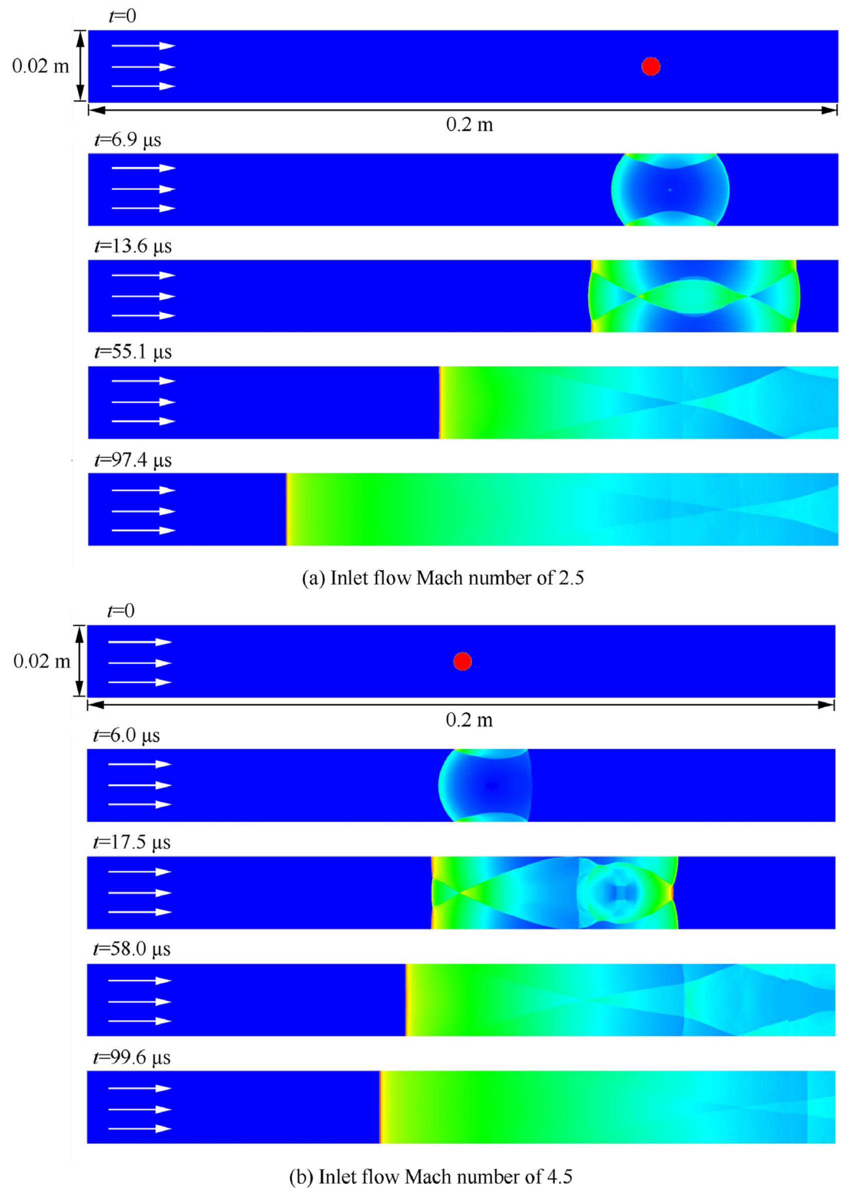


Fig. 4 Upstream-traveling shock propagation within engine flow passage.

Fig. 4(b) than in Fig. 4(a), but it still propagates upstream even though the inlet flow Mach number is as high as 4.5. This is why the low equivalence ratio is used frequently for most of scramjet experiments to maintain a stable combustion because the low heat release could reduce effectively the Mach number of the upstream-traveling shock wave. Therefore, for a ramjet-based propulsion engine, the inlet flow Mach number should match with the upstream-traveling shock wave to avoid inlet unstart and engine surging.

4. Criteria for ramjet-based hypersonic propulsions

The inlet flow Mach number is a key parameter for the scramjet engine to maintain stable combustion, and the widely-accepted values range from 2.5 to 3.5 for the current scramjet engine models. At such the inlet flow Mach numbers, the static temperature at combustor entrances could arise to the auto-ignition level under hypersonic flight conditions. However, to develop practical hypersonic engines, the engine operation instability becomes a severe problem that has to be considered according to the discussion in the above chapter.

To demonstrate the physical mechanism behind the engine operation instability in ramjet-based hypersonic propulsion systems, the one-dimensional steady flow with a constant heat addition is taken as an example. It is well known that the heat addition makes a flow approach the sonic state whether it is originally supersonic or subsonic. The maximum heat, $q_{\max}$, required to drive the flow into the sonic state is given by the following equation:

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

where Ma is the flow Mach number, γ is the specific heat ratio, C_p is the constant pressure ratio and T_{01} is the initial flow tem-

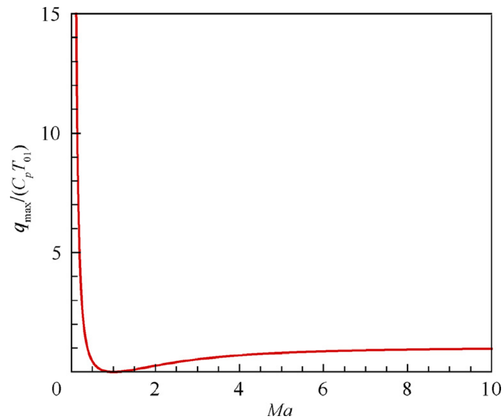


Fig. 5 The maximum heat required to drive one-dimensional flow to sonic state.

perature. The maximum heat calculated with Eq. (1) is presented in Fig. 5. From this figure, it is observable that the maximum heat needed in subsonic cases is much higher than in supersonic or hypersonic cases. For the subsonic cases, the chemical reaction heat contributes to both the flow dynamic energy and the gas temperature increases. For the supersonic cases, the heat is dedicated mainly to increase the flow temperature, therefore, the local sound speed increases quickly and the local Mach number decreases rapidly. This is the fundamental mechanism behind the unsteady combustion in scramjet engines and the maximum heat is the first critical criterion that could be used to distinguish the combustion modes in the ramjet-based hypersonic propulsion, that is, supersonic or subsonic in the heat release area after combustion reactions. It is necessary to point out that the upstream flow of the heat release area will become subsonic since the flow is coming and the downstream one will become supersonic because the flow is expanding.

The maximum heat addition imposes a big barrier on the scramjet thrust because thermal engines are not allowed to operate near the thermal choking state, so that a low equivalence ratio is often used in scramjet engine testing to avoid subsonic combustion. Using the low equivalence ratio is an effective means to stabilize the engine operation, but results in even low scramjet thrust. It is understandable that the scramjet engine operation stability is closely related to the inlet flow Mach number and the released reaction heat. The higher is the inlet flow Mach number, the more the heat addition could be. The physical mechanism is also correct for all the ramjet-based hypersonic propulsion, unfortunately, this problem has not been well recognized so far. There has been the arguing about "supersonic" or "subsonic" combustion in hypersonic propulsion realm for decades, and Fig. 5 indicates the answer inspiringly. In the ramjet-based propulsion engine, the supersonic combustion may exist as long as the chemical reaction heat released is less than the maximum heat required to drive the flow into the sonic state.

Once the chemical reaction heat released in ramjet-based engines is higher than the maximum heat, the subsonic combustion takes place. This combustion mode transition results in a shock wave that is generated from combustion waves and can propagate upstream. There must be another criterion at which the upstream-traveling shock wave can compete with the inlet flow. In other words, what is the critical inlet flow Mach number for a ramjet-based hypersonic propulsion engine? At such the Mach number, the engine can be operated stably at a full equivalence ratio without the shock-induced engine surging. This criterion is critical because there is no airliner that can accept an engine that may work in unstable combustion mode. To obtain this critical Mach number, the flow process in the ramjet-based hypersonic engine is simplified as a steady one-dimensional flow with continuous heat addition at a given reaction rate. During the heat-releasing process, the upstream-traveling shock wave will be generated after a sonic state is reached, and its Mach number depends on the amount of the reaction heat, gaseous media and its thermal state. Assuming a perfect gas, the critical Mach number for stable engine operation can be given by following after the C-J detonation theory.

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

where Ma_{Cri} is the Mach number of the upstream-traveling shock wave, and $q_{\max}$ defines the maximum amount of the chemical heat that can be released for a given combustible gas mixture. Subscript "0″ stands for the flow state before the heat addition and subscript "1" is for that after the addition. γ is the specific heat ratio and c is the sound speed. Ma_{Cri} and $q_{\max}$ can be taken as two key parameters for the ramjet-based engine design and its operation. If the inlet flow Mach number is less than this critical value, the upstream-traveling shock wave will propagate into the inlet, and may result in not only unsteady combustion but also engine surging as experimentally demonstrated above.

The critical inlet flow Mach number is the second criterion proposed for hypersonic airbreathing propulsion, as defined by Eq. (2), and the criterion depends on both the reaction heat and the detonable gas mixture. Fig. 6 presents results of the critical Mach number, Ma_{Cri} varying with the equivalence ratio for different fuels. It can be seen that the Mach number is higher than 3 even the equivalence ratio is around 0.3.

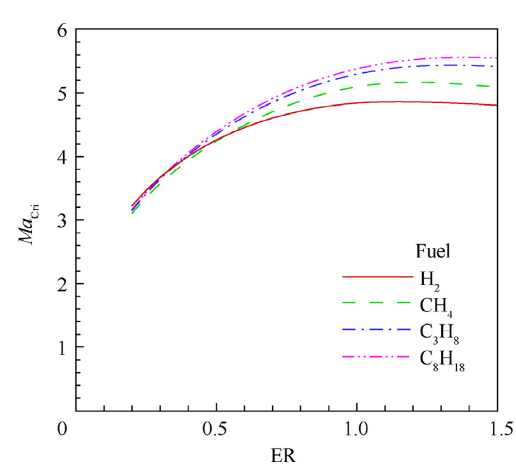


Fig. 6 Mach number, Ma_{Cri}, variations with equivalence ratio for different fuels.

Unfortunately, for most scramjet engines, their designed inlet flow Mach numbers are between 2.5 and 3.5. This is the reason why many research papers reported that subsonic combustions are observed in their combustors, the relevant combustions are unstable and the upstream-traveling shock wave is observed at inlet entrances. So, the low equivalence ratio was chosen frequently to maintain stable combustions. Actually, the low equivalence ratio for stable engine operation is not acceptable because the engine thrust is reduced significantly since the total pressure loss has already been incurred during inlet flow compression. It is also possible to lower this critical Mach number by distributing the heat release sources along the combustor and expanding the flow while the gas mixture is reacting, however, the problem still exists when trying the full equivalence ratio to increase the engine thrust.

The word, 'supersonic combustion' may not be an appropriate word that can be used to describe the flow physics in the ramjet-based hypersonic engines, and the phrase, 'combustion in supersonic flow' seems more suitable to identify the chemically-reacting flows. In supersonic flows, the diffusive combustion results in successive acoustic waves propagating radially once it takes place if the first criterion is established, and the upstream travelling shock wave will be generated when the heat addition is higher than the maximum heat required to drive the flow into the sonic state. The more the heat releases, the stronger the shock wave develops. The shock wave is enhanced by the confined flow passage wall and further accelerated due to temperature gradients within engine inlets. There exists a competing mechanism between the supersonic coming flow and chemical reactions and the mechanism can be measured with the second criterion. In a ramjet-based engine, the inlet flow Mach number must match with q_{max} for stable combustion without engine surging. Eq. (2) presents the relationship that can be used to define the second criterion for the ramjet-based hypersonic propulsion without the upstream-traveling shock wave that can propagate into the engine inlet and results in thermal choking.

5. Verification of Sodramjet engine concept

The second criterion defined with Eq. (2) presents the minimum inlet flow Mach number for the ramjet-based hypersonic propulsion. Over this Mach number, there is no shock wave that could propagate upstream into inlets, but a standing oblique detonation may be generated if an initiation source is provided in combustors. The higher the Mach number is, the small the angle of the standing oblique detonation becomes. The detonation is a shock-induced chemically-reacting wave that is a unique pressure-gain combustion in nature. With the standing oblique detonation, a nearly constant volume thermal-cycle can be organized for air-breathing hypersonic engines. Therefore, keeping the inlet flow Mach number higher than the criterion is absolutely necessary to make a detonation stationary. From this viewpoint, the criterion is actually a design parameter for the Sodramjet engine. In the engine, the coming gas flow is compressed to an auto-ignition level by the leading shock wave, the shock-induced reaction provides enough energy to support the leading shock wave in return. Therefore, the standing oblique detonation is not only stable, but also self-sustainable. The leading shock wave works like an efficient compressor and the chemical reaction coupling closely with it works like a turbine in modern turbojet engines. The Sodramjet engine belongs to the class of the ramjet-based hypersonic propulsion, but behaves quite different from the scramjet engine due to its high thermo-efficiency, simple combustor structure, low inflow compression loss, and stable engine operation.

For the Sodramjet engine, the criterion indicates a minimum flow Mach number for inlet flows because it is necessary to generate an oblique shock wave with the post-shock temperature, T_{ig} reaching to the auto-ignition level of combustible gas mixtures. According to the oblique shock wave formula, the relation between the required oblique shock angle, θ, and the inlet flow Mach number can be determined. The results calculated with the relation are presented in Fig. 7 where the ignition temperature, T_{ig} is set to be three different values, respectively. From Fig. 7, it is observable that for a given inlet flow Mach number, the higher the ignition temperature, the bigger the oblique shock angle becomes. It is also known that the overdriven detonation will cause more entropy increase than the C-J detonation so that choosing well-matched θ for detonation ignition could maximize thermal efficiency of the Sodramjet engine.

Producing a proper oblique shock wave for ignition is the first step to make an oblique detonation stand in ramjet engines, and some physical issues need to pay attention for realizing this goal.[23–25] Fig. 8 presents a temperature (T) distribution of an oblique detonation wave from the computational test case where the combustible gas is a hydrogen/air mixture, the inflow Mach number is 9, θ is taken to be 25° and the Navier-Stokes equations are solved to get solutions. From this

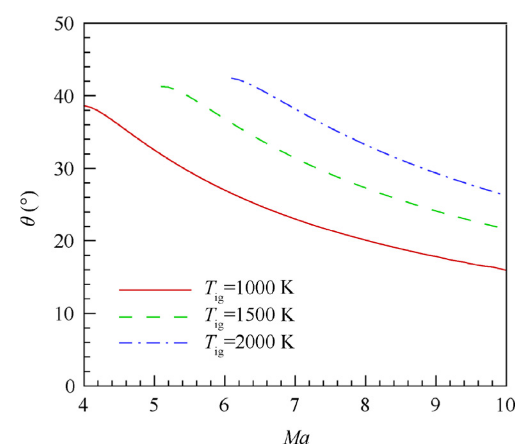


Fig. 7 Oblique shock angle variations with inflow Mach number.

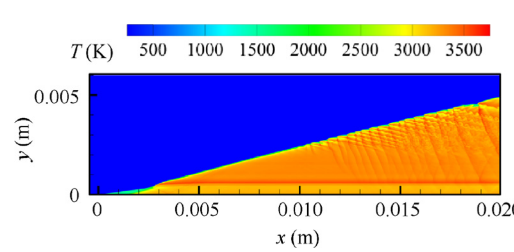


Fig. 8 Numerical result showing development of oblique shock-induced oblique detonation.

figure, four physical phenomena could be identified. The first one is the flow region from the wedge tip to the triple point on the wave-front structure, which is called the transition region where the reaction from shock ignition transits to detonation. The second one is also a transition region where the detonation transiting from an overdriven state to a free-propagating state. This feature can be observed more clearly for an oblique detonation wave over a finite-length wedge. The third part is the cellar detonation and its macroscopic characters in the normal direction of the detonation wave front could be predicted with the C-J theory. The last one is the boundary layer where the chemically-reacting gas flow in the subsonic state is dominated.

In order to design a wind tunnel test model for demonstrating the Sodramjet engine concept, a series of numerical simulations were carried out to investigate three issues that are important to make an oblique detonation stationary.[17,26–28]. The first issue is hypersonic pre-mixing since the inlet flow Mach number is usually much higher than 5. The fuel injection device must be moved into the inlet to enhance the diffusion-dominated mixing process. The injection device, as shown in Fig. 9, utilizes struts with sharp edges to avoid the bow shock generation that may result in chemical reactions earlier than required. Injection holes are arranged to be normal to streamlines so that stream-wise vortices generated behind the injection device can be used to enhance the mixing. A long distance is necessary because the mixing process is dominated mainly by the diffusion mechanism. The second issue is the chemical reaction occurring in the boundary layer behind the first transition region. Although the chemical reaction is weak in the boundary layer, acoustic waves generated from the combustion will propagate upstream due to the local subsonic state and interfere with the standing oblique detonation. Therefore, a lean mixture in the boundary layer is a better choice when arranging injection holes. The third one is the boundary layer separation near the position where the oblique detonation stands. The separation bubble can induce a bow shock wave that may excite chemical reactions which can disturb the designed oblique detonation. The boundary layer bleeding is one way to solve the problem, and computational results show the idea works well. There may be other physical issues that are effective more or less in the Sodramjet engine design, but these issues are significantly important.

According to the proposed criteria and three key issues discussed in the above chapters, the schematic of the Sodramjet engine model designed at Mach number 9 is shown in Fig. 9, where the OSW stands for oblique shock wave and the ODW for oblique detonation wave. The Sodramjet engine model is composed of three strut-injectors, a single-stage compression inlet, a combustor, and a nozzle. The dimension of the Sodramjet engine model is 2.2 m in length and 0.55 m in height. The inlet is composed of a 15°-inclined ramp that is 1.6 m in length. The combustor is 0.41 m in length and 0.0765 m in height. Obviously, the Sodramjet combustor is rather short by comparing with scramjets even it is to operate at the high Mach number. This feature is helpful for reducing both frictional force and thermal loads. Following the combustor is a short nozzle with a 15° expansion angle at one side, and 0.4 m in length. A bleed device is also equipped for boundary layer control to make oblique detonation stationary.

The configuration of the concept demonstration model of the Sodramjet engine is shown in Fig. 10(a) and its installation in the JF-12 shock tunnel test section is shown in Fig. 10(b). The JF-12 shock tunnel can provide the engine test with 100 ms test duration and its 2.5-meter nozzle can accommodate fully the test model in its uniform core flow region.[20–22,29,30] The front half of the Sodramjet combustor sidewall is replaceable with glass windows to ensure that the standing oblique detonation wave can be recorded with a high-speed camera. 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 oblique detonation standing in the combustor is observed to maintain a stable state for as long as 50 ms. One of the video frames is presented in Fig. 11 with the corresponding hydrogen concentration from numerical simulations that show the hydrogen fraction distribution and pressure isolines together. From Fig. 11(a), it is clearly observed that the standing oblique detonation wave exists in the combustor and the hydrogen burns out behind the leading shock in a very short distance, as shown in Fig. 11(b). This short distance from the leading shock wave to the line where the hydrogen is mostly consumed is the so-called chemically-reacting zone that appears to be coupled together with the oblique shock wave. The standing oblique detonation front is composed of two parts, the transition region and the fully-developed detonation. The transition region is from the originating point of the oblique shock wave to the position where the reacting front catches up with the oblique shock wave. This wind tunnel test confirms that the Sodramjet engine can be realized and is also controllable with three key techniques as discussed above. The concept of the oblique detonation engine had been proposed for many decades, but is demonstrated successfully with wind tunnels for the first time. The success benefits from the criteria proposed for the Sodramjet engine design and the flow control techniques also play a very important role in maintaining a standing oblique detonation at the required position.

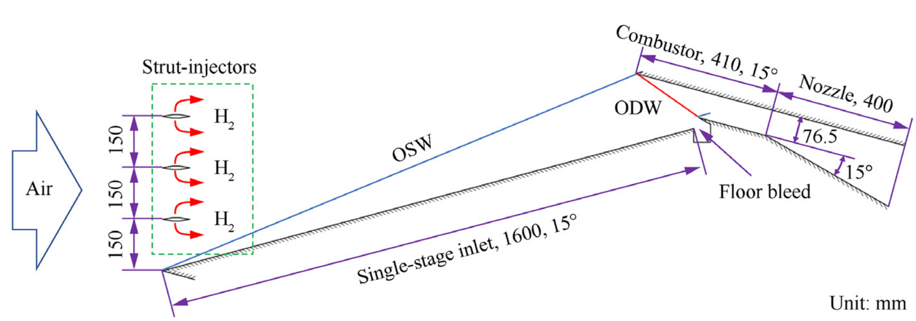
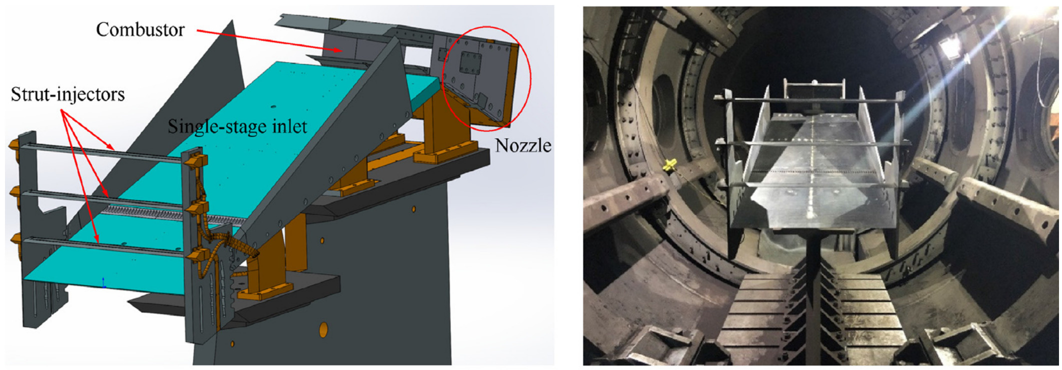


Fig. 9 Schematic of designed Sodramjet engine concept.



(a) Sodramjet engine model (b) Wind tunnel installation

Fig. 10 Concept demonstration model of Sodramjet engine and its installation in JF-12 shock tunnel.

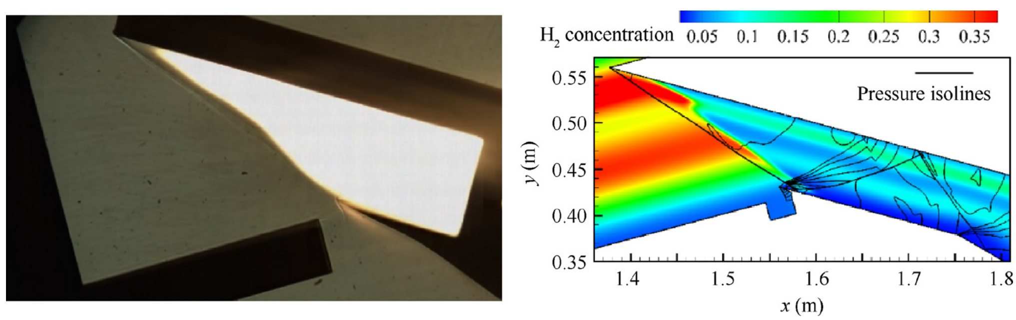


Fig. 11 Experimental photo of standing oblique detonation in combustor of Sodramjet engine model (left) and corresponding hydrogen concentration from numerical simulations (right).

The Sodramjet engine has several advantages over the ramjet-based propulsion engines. The first advantage is thermal efficiency. The thermodynamic process taking place in the Sodramjet engine can be taken as a nearly constant volume cycle, and the process in the ramjet-based engine is often considered to be a constant pressure one. Theoretical analysis shows that the thermal efficiency of the constant volume cycle is about 50% higher than the constant pressure cycle.[11,14] The second one is the combustor size. The combustor length is 410 mm for the current Sodramjet engine model but about 2000 mm or more for scramjet engines. This length reduction will cut down significantly the drag force acting on the combustor wall. The third one is the inflow compression loss. The designed inlet flow Mach number is between 2.5 and 3.5 for most of the scramjet engines, but the Sodramjet engine requires Mach numbers to be higher than 5 according to the proposed criterion. Therefore, the inlet flow compression loss of the Sodramjet engine is reduced greatly and the low total pressure loss contributes a lot to the engine efficiency. The fourth one is the thermal load reduction on the combustor. It is obvious that the short combustor will not only reduce the thermal load, but also prevent the heat loss from the combustor so that the engine efficiency would benefit. The last one is about combustion stability. The Sodramjet engine can work with the full equivalence ratio if the inlet flow Mach number meets the criterion. The oblique shock angle, θ will be smaller if the inflow Mach number increases, therefore, the standing oblique detonation could be automatically self-adjusted to be sustainable. Moreover, it is possible for us to control the wedge angle to make an oblique shock wave just strong enough to initiate an oblique detonation. The higher is the inlet flow Mach number, the smaller the θ becomes. The Sodramjet engine operating at near C-J detonation mode has the lowest entropy increase and the highest exergy at combustor outlets, which has never been reached by other kind engines before.[14]

It is interesting to point out that the exhaust gas flow after the standing oblique detonation front is supersonic and the fuel is consumed at supersonic speeds. The combustion in the Sodramjet engine is really the supersonic combustion. Eq. (1) indicates the critical criterion at which the detonation takes place because the upstream-travelling shock is getting strong enough to excite chemical reactions. Therefore, a new type of hypersonic propulsion could be defined as "standing oblique detonation ramjet engine", short for the Sodramjet engine. The engine belongs to the ramjet-based hypersonic propulsion, but its combustion mode is totally different from the scramjet engines. Theoretical analysis indicates that the Soramjet engine working as an air-breathing engine can offer a great potential to extend the flight Mach numbers from 6 to 16.[11]

By recalling the development of the modern aviation industry, the reciprocating piston internal combustion engine is used for subsonic airplanes, and the turbojet engine is developed for supersonic flights. What kind of the engine is capable of powering hypersonic vehicles? 70 years' exploration on hypersonic propulsion indicates that the revolutionary concept is really in need for hypersonic air-breathing engine development. The Sodramjet engine concept can be a very promising choice and the work presented here supports strongly this idea.

6. Conclusions

In this paper, the upstream-traveling shock wave and its enhanced mechanism are discussed, and two criteria proposed for developing hypersonic airbreathing propulsion and the Sodramjet engine concept are verified with wind tunnel tests. Progresses achieved are summarized as follows:

(1) The upstream-traveling shock wave is identified to be the intrinsic shock wave of ramjet-based hypersonic propulsion engines. The shock wave occurs naturally due to continuous heat release in supersonic flows, and is enhanced by the engine flow passage walls and accelerated when propagating upstream through the inlet where the temperature gradient exists. The more the reaction heat releases, the higher the shock Mach number becomes. The engine surging induced by this shock wave is disclosed with a scramjet model experiment in the JF-12 shock tunnel. The problem is not well recognized before, but must be solved when designing any practical hypersonic engine that is required to operate stably at a full equivalence ratio.

(2) By considering upstream-travelling shock waves, two criteria are proposed for developing hypersonic airbreathing propulsion under the assumption of the perfect gas, instantaneous heat release and one-dimensional steady flow. The first criterion can be used to identify the combustion mode, that is, subsonic or supersonic combustion in traditional saying. The second criterion is critical not only for scramjet engines to maintain stable combustion, but also indicates a minimum inlet flow Mach number for developing Sodramjet engines.

(3) A concept demonstration model of the Sodramjet engine is designed based on the second criterion with the help of several flow control techniques and the experiment is carried out in the JF-12 shock tunnel. The experimental data show that the standing oblique detonation could be made stable and it is automatically self-adjusted to be sustainable. It is the first time to verify the oblique detonation engine concept successfully with wind tunnel tests and the standing oblique detonation undergoes the initiation, transition and fully-developed stages. The experiments also demonstrated well the criteria proposed in this paper. According to research progresses on oblique detonation engines, the Sodramjet engine is very promising for hypersonic airbreathing propulsion because that the engine system is simple in its structure, efficient in the thermo-cycle, broad in its operation Mach number range and low in aerothermodynamic heating load.

Declaration of Competing Interest

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

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