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Review

Progress of Experimental Studies on Oblique Detonation Waves Induced by Hyper-Velocity Projectiles

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Abstract: Oblique detonation waves (ODWs) are hypersonic combustion phenomena induced by oblique shock waves. When applied to air-breathing engines, ODWs offer high thermal cycle efficiency, adaptability to a wide range of flight Mach numbers, and the advantage of a short combustion chamber, making them highly promising for hypersonic propulsion applications. Despite numerous numerical studies on the heat release and multi-wave flow mechanisms of ODWs, practical applications of oblique detonation engines (ODEs) remain limited due to several technical challenges. These challenges include generating the required high-velocity test environments, achieving effective fuel and oxidant mixing, and measuring the flow field structure in hyper-velocity and high-temperature flows. These limitations hinder the development of ODEs, underscoring the importance of experimental research, particularly for understanding the initiation and propagation mechanisms of ODWs. One of the primary experimental techniques involves inducing oblique detonation using high-velocity models. This method is extensively used to study the initiation process, shock structure, initiation criteria, and ODW propagation. It is advantageous because the state of the experimental mixture is controllable, and the model state can be precisely measured. This paper reviews studies on oblique detonation induced by hyper-velocity projectiles, presenting advances in experimental methods, detonation wave structures, unsteady processes, and initiation characteristics. Additionally, we discuss the deficiencies in existing studies, noting that the current measurement methods fall short of the requirements for observing the ODW initiation process, propagation process, and fine structure. The application of advanced combustion diagnostic techniques and the exploration of the relationship between initiation processes and criteria are crucial for advancing our understanding of ODW initiation and stabilization mechanisms. Finally, we summarize the current state of experimental facilities and measurement techniques, providing suggestions for future research on the measurement of shock waves and chemical reaction zones.

Keywords: oblique detonation wave; high-velocity launcher; non-intrusive measurement; initiation process; shock wave structure

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1. Introduction

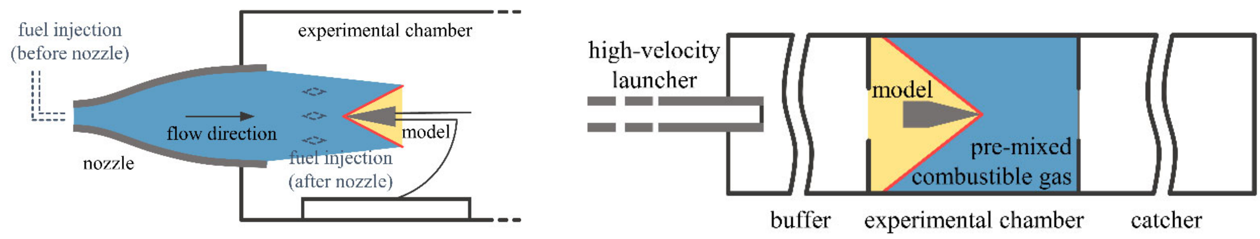
Detonation is a phenomenon of supersonic combustion induced by a shock wave. According to thermodynamic theory, detonation represents a self-pressurized mode of combustion that approximates isochoric combustion, leading to high thermal efficiency [1]. Additionally, the rapid combustion that follows shock wave compression results in a high heat release rate, supporting its application in air-breathing hypersonic propulsion systems. Over the past decades, various engines based on detonation have been proposed, such as the pulse detonation engine (PDE) [2], rotating detonation engine (RDE) [3], and oblique detonation engine (ODE) [4]. The ODE is an aspirated propulsion concept that utilizes a standing oblique detonation wave (ODW) to combust fuels. Its combustion chamber can self-ignite, generate continuous thrust, and operate at higher incoming flow Mach numbers compared to the well-known Scramjet engine. Consequently, it has several advantages, including a rapid heat release, high specific impulse, a short combustion chamber, and few moving parts, making it one of the most promising technical routes for air-breathing hypersonic propulsion.

The standing ODW is induced by a model moving through a combustible gaseous mixture. As the high-velocity flow passes the model, the mixture is compressed and heated, initiating chemical reactions behind the shock wave. As the post-shock temperature increases, these reactions accelerate, forming a combustion wave that eventually couples with the shock wave, resulting in a detonation wave. The concept of oblique detonation propulsion was proposed in the 1950s and 1960s, and significant progress has been made in understanding the ODW mechanism. However, research on ODWs remains in its early stages. More in-depth studies on the initiation process, self-sustained propagation, and control of ODWs are necessary to advance the engineering applications of the ODE. In addition, most studies on ODWs have been based on numerical simulations, focusing on the effects of incoming flow conditions, wedge angle, chemical reaction models, and fuel characteristics on the ODW structure and critical conditions. These studies often use overall reaction or reduced chemical reaction kinetic models to describe the combustion process. The numerical findings on the ODW's initiation characteristics, wave structure, and stability require experimental validation [5–10]. Therefore, developing and improving the experimental methods for ODWs is crucial for advancing the ODE toward practical engineering applications.

Experimental studies on oblique detonation are challenging due to the high-velocity and unsteady nature of the process. Over the past three decades, several investigations have employed high-velocity launchers to explore the structure and criteria of ODWs. This paper reviews these studies and discusses future directions for experimental research. Notably, due to limitations in the launching capabilities and measurement technology, there has been relatively little literature on this topic in the past decade. The focus is on the following aspects: the experimental method of inducing ODWs using high-velocity models, the structure of ODWs, the unsteady processes and criteria of ODWs, and the challenges and opportunities for further advancement in this field. In this paper, Section 2 outlines the experimental methodology for generating oblique detonation waves (ODWs) using hyper-velocity projectiles. Section 3.1 provides an overview of conventional oblique detonation experiments, while Section 3.2 delves into the shock structure generated by the projectile-induced ODWs. Section 3.3 focuses on the wavefront characteristics of the ODWs, and Section 3.4 conducts an in-depth study on the initiation attributes of ODWs induced by high-velocity projectiles.

2. Experimental Method for Inducing ODWs Using Hyper-Velocity Projectiles

Experimental studies on oblique detonation face numerous technical challenges, including the simulation of high-velocity environments, the mixing process of fuel and oxidizer, and the measurement of high-temperature combustion flow fields. Consequently, research in this area remains limited. Existing experimental methods for studying oblique detonation can be categorized into two primary approaches. The first approach involves using a static experimental model to compress a high-velocity flow of combustible mixture, thereby generating a detonation wave, as illustrated in Figure 1a. The second approach employs a moving model to ignite an oblique detonation wave (ODW) in a premixed combustible mixture, as illustrated in Figure 1b.



(**a**) (**b**)

Figure 1. Schematic diagram of the experimental methods for studying ODWs: (**a**) motionless model; (**b**) hyper-velocity model.

The first method primarily relies on direct-connected supersonic combustion facilities [11–13], pulse wind tunnels [14,15], or expansion tunnels [16]. This approach can simulate the entire process of fuel mixing, ODW initiation, stabilization, and quenching, providing a longer experimental time for measurements. However, it also faces significant challenges, such as preventing premature fuel combustion and accurately measuring the equivalence ratio of fuel and oxidizer in the high-velocity incoming flow. These factors can affect the analysis of the oblique detonation experiment results. The expansion tunnel method can address some of these challenges by adjusting the initial conditions of the driving and driven tubes. By controlling the static temperature of the combustible mixture after the incident shock wave in the driven tube, combustion is inhibited in the driven tube, allowing for the creation of a premixed high-velocity incoming flow. However, this method also imposes restrictions on the experimental conditions for generating the high-velocity incoming flow.

The second method utilizes a high-velocity model that flies through a static premixed combustible mixture, compressing and heating the mixture to initiate an ODW. This approach allows for the independent control of the flight velocity and the experimental mixture conditions. The experimental conditions are primarily dependent on the performance of the high-velocity launchers and the design of the experimental chamber. The duration of the experiment is determined by the model's flight velocity, with the measurement window for a single optical window typically lasting tens of microseconds. This necessitates a measurement system with a high time resolution and response frequency. This method offers several advantages, such as premixing the combustible mixture, eliminating incoming disturbances, and accurately measuring the model velocity. These features facilitate the analysis of the criteria, structures, and unsteady processes of the ODW and aid in exploring the initiation and propagation mechanisms. With continuous improvements, this method has evolved into a more mature experimental and measurement system comprising four main subsystems, as shown in Figure 2 and explained in the following:

(1) High-velocity launcher: This component accelerates the model to a predetermined velocity. Existing studies have employed either light gas guns or smoothbore powder guns. Powder guns feature mature technology and larger calibers; however, their maximum firing speed is limited by the sound speed of the gunpowder gas. In contrast, light gas guns can achieve higher firing speeds to meet their experimental requirements, making them more widely used in recent research.

(2) Experimental section: This section includes a buffer chamber, an experimental chamber, and a catcher. After the model is launched, the high-temperature and high-pressure driving gas is also expelled from the muzzle. The buffer chamber mitigates its impact on the oblique detonation experiments. It is typically filled with low-pressure gases (e.g., N_2 or CO_2) that do not react with the driving gas. The experimental chamber is pre-filled with the experimental gases, and the model breaks through a diaphragm to initiate the ODW. The catcher stops the model after it exits the experimental chamber.

(3) A timing control system regulates signal generation for the measurement apparatus to precisely gather and record experimental data. Trigger timing typically hinges on methods like pressure sensor signals, laser–photodiode signals, changes in magnetic field strength from model-mounted magnets, and the impact line method, used to measure the model's position or velocity.
(4) A measurement system typically incorporates optical, pressure, and optical signal measurements. Optical techniques such as schlieren and shadowgraph are predominantly used, while pressure and optical signals effectively discern the occurrence of chemical reactions following a shock wave.

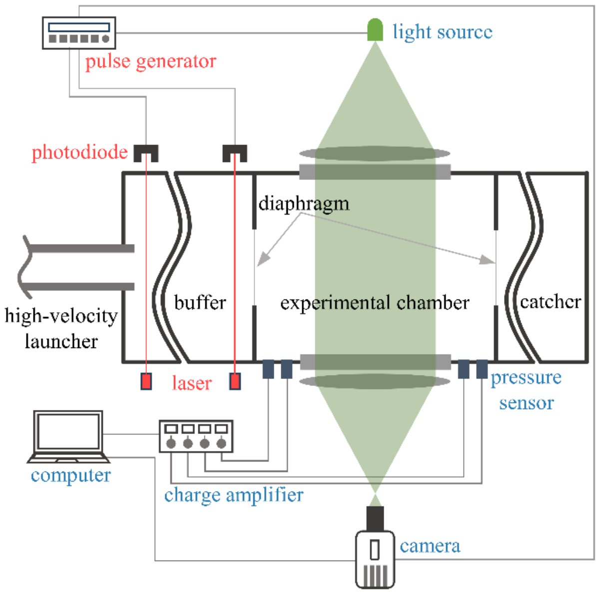


Figure 2. Schematic diagram illustrating the experimental setup for ODWs induced by hypervelocity projectiles.

Numerous experiments have explored the influence of design parameters in the experimental setup, such as the buffer chamber conditions, diaphragm thickness, and model attack angle, on observed phenomena. For instance, Higgins [17] conducted experiments with varying buffer gases and diaphragm thicknesses to separate the buffer and experimental chambers. His findings indicated that filling the buffer chamber with 25 kPa CO_2 effectively mitigates the influence of driving gas and sabot-generated shock waves on experimental phenomena. Higgins also demonstrated that diaphragm thicknesses of 13/400 μm did not significantly affect the results, although thicker diaphragms produced debris that hindered the optical measurements. Maeda et al. [18] investigated the diaphragm's influence on detonation by using a flat plate with a hole to pass projectiles, observing a consistent ODW initiation regardless of the plate position relative to the projectile trajectory. They also analyzed how the model attack angle affects detonation. Chernyavskii et al. [19] employed a buffer chamber to minimize the driving gas effects yet introduced randomness into a cylindrical model's attack angle upon chamber entry, complicating the shock wave structure and model state observations. In summary, extensive research has made the current experimental system for model-induced ODWs comprehensive. Key challenges remain in enhancing high-velocity launch systems and refining measurement technologies.

3. Progress in Experimental Studies on ODW

3.1. Overview of Typical Oblique Detonation Experiments

Since the 1960s, numerous studies have utilized high-velocity launchers to investigate shock-induced combustion (SIC) at high speeds, focusing on phenomena and mechanisms such as the combustion wave structure [20], SIC ignition delay [21], and unsteady combustion mechanisms [22,23]. Researchers have applied oblique detonation in propulsion fields [24,25], noting several advantages. Utilizing high-velocity launchers with varying performances and principles, various studies have conducted experiments on model-induced oblique detonation waves (ODWs), analyzing the experimental phenomena and detonation mechanisms. A summary of these experiments is presented in Table 1. Typically, studies employ gunpowder or light gas guns as high-velocity launchers, with the experimental mixtures often including hydrogen/oxygen, acetylene/oxygen, and ethylene/oxygen in stoichiometric ratios. Inert gases are sometimes used to dilute the experimental mixtures to adjust their physical and chemical characteristics. Experimental models commonly feature spherical or conical shapes.

Table 1. Typical experiments of ODWs induced by hyper-velocity projectiles.

No	Institute	Launching Device	Projectile/Diameter	Velocity (km/s)	Experimental Gases	Measurement Technique	Reference
1	Moscow State University, Moscow, Russian	light gas gun	blunt cylinder, 12.7 mm	2.57~3.06	$2H_2 + O_2$	schlieren	[19]
2	Siberian Division of the Russian Academy of Sciences, Siberian, Russian	smoothbore powder gun	cylinder, 7.63 mm	0.8~1.4	$C_2H_2 + 2.5O_2$	schlieren	[26,27]
3	University of Washington, Washington, USA	light gas gun	sphere, 4.76~25.4 mm	0.6~2.3	$2H_2 + O_2 + 7Ar$	-	[17,28]
4	California Institute of Technology, California, USA	gas gun	sphere, 25 mm	2.6~3.0	$2H_2 + O_2 + N_2/2H_2 + O_2 + 3.76N_2$	shadowgraph/differential interferograms	[29]
5	Nagoya University, Nagoya, Japan	two-stage light gas gun	cone, 10 mm	2.8~3.0	$2H_2 + O_2$	schlieren	[30–34]
6	University of Tsukuba, Tsukuba, Japan	two-stage light gas gun	sphere, 3.18/4.76 mm	1.3~2.5	$C_2H_2 + 2.5O_2 + 10.5Kr/C_2H_2 + 2.5O_2 + 3.5Ar/C_2H_4 + 3O_2 + 4Ar/2H_2 + O_2 + 3Ar$	schlieren/shadowgraph	[18,35–42]
7	McGill University, Montreal, Canada	one-stage light gas gun	cone, 12.7 mm	1.7~2.2	$2H_2 + O_2 + 7Ar$	schlieren	[43]
8	Nanjing University of Science and Technology, Nanjing, China	smoothbore powder gun	cone, 25 mm	1.7~2.1	$1.4/1.0H_2 + O_2$	shadowgraph	[44,45]
9	Kyoto University, Kyoto, Japan	two-stage light gas gun	sphere, 9.52 mm	1.8~2.2	$nH_2 + O_2 + 3Ar$	shadowgraph	[46]
10	Institute of Mechanics, CAS, Beijing, China	two-stage light gas gun	blunt cylinder, 30 mm	2.2~4.1	$2H_2 + O_2$	shadowgraph	[47]

The experimental studies on model-induced ODWs require high-performance, high-velocity launchers. The Chapman–Jouguet (C–J) detonation propagation velocity typically ranges from 1.9 to 2.9 km/s for fuel/oxygen (or air)/dilute mixtures at stoichiometric ratios. To establish an ODW, the model velocity must exceed the C–J detonation velocity, necessitating launch velocities higher than this range. Table 1 summarizes studies typically employing gunpowder or light gas guns with large muzzle energy. However, the velocity of the model is constrained by the sound speed of the gunpowder gas, limiting launch speeds to below 2 km/s [48]. Earlier studies utilized gas guns or light gas guns adapted from shock wave tunnels to achieve higher launch velocities yet faced limitations in the muzzle energy and model diameter [49]. A recent study [47] introduced a detonation-driven two-stage light gas gun for spherical model-induced ODW experiments, achieving superior launching performance by accelerating a 30 mm diameter model to 3.7 km/s [47].

Experimental studies on ODWs typically employ spherical, cylindrical, and blunt cylindrical models. The spherical model is preferred for its shock wave structure, which remains consistent regardless of the attack angle [18,28,29], as depicted in Figure 3. On the other hand, conical models are often used in theoretical studies due to their aerodynamic properties, which can be adjusted by varying the cone angle to induce detached or oblique shock waves [30,43], as illustrated in Figure 4. Researchers have also examined how the ballistic trajectory and attack angle affect experimental outcomes. However, varying the attack angle alters the shock structures significantly, emphasizing the need to minimize its impact in experiments. Verreault and Higgins [43] explored the effects of different model barycenter positions on firing attack angles using conical models for ODW and shock experiments. They concluded that adding a metal balance weight at the model's base enhances the projectile's stability in the bore while reducing aerodynamic instability by minimizing the distance from the muzzle to the experimental chamber.

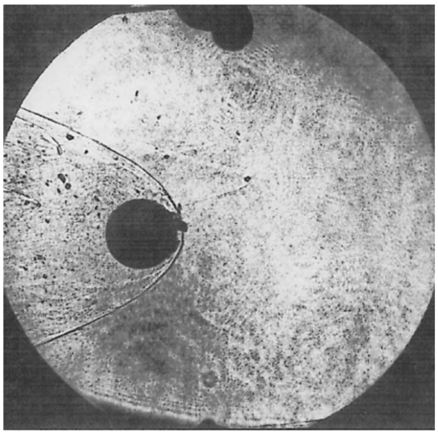


Figure 3. Shadowgraph of bow shock induced by spherical projectile.

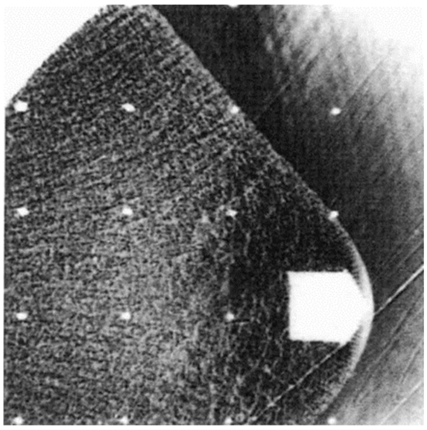


Figure 4. Shadowgraph of ODW induced by cone projectile.

Most existing experiments on model-induced ODWs are conducted under conditions of a low launching velocity and small model diameter. Typically, these experiments utilize gunpowder or light gas guns for the model's launch. Gunpowder guns provide a high muzzle energy, yet their maximum model velocity is restricted by the sound speed of gunpowder gas. Light gas guns, particularly two-stage systems, offer higher theoretical maximum launch velocities but suffer from low energy conversion efficiency and difficulty in accelerating larger models to high speeds. While some experiments have achieved high velocities or used larger model diameters, they are constrained by equipment performance and often fail to meet both requirements simultaneously, as illustrated in Figure 5. Thus, the current studies lack experimental data on ODW initiation and propagation using large-diameter models at high speeds. Additionally, experimental conditions such as the high-velocity flight of the model and intense chemiluminescence of detonation pose challenges for measurement techniques. Schlieren, shadowgraph, and differential interferometer [50] are commonly used optical measurement systems in these experiments, employing parallel light to visualize the density changes in the flow field and to observe the ODW structures. However, these methods produce two-dimensional projections of three-dimensional flow fields, which are susceptible to interference from three-dimensional effects. The stability of the detonation wave closely correlates with the fine structure of its surface, a phenomenon that is challenging to measure due to interference. Therefore, employing non-intrusive combustion diagnostic techniques advances the study of ODW wave structures and unsteady flows, significantly facilitating an understanding of phenomena such as wave fine structures, composition distributions, and chemical reaction processes. In conclusion, advancing the understanding of model-induced ODWs necessitates more experimental data to investigate their mechanisms, while existing measurement techniques continue to face significant limitations.

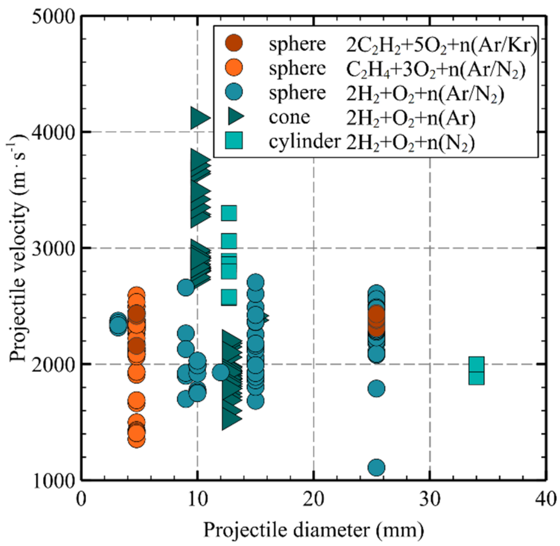


Figure 5. Operation conditions for hyper-velocity projectiles.

3.2. Shock Structures of the ODW Induced by Projectile

The model induces a shock wave as it travels through the combustible mixture, compressing and heating it. Once the post-shock temperature reaches a critical level, chemical reactions within the combustible mixture are initiated. The experimental phenomenon is influenced by factors, including the model's configuration, the properties of the combustible mixture, and the design of the experimental facility.

Kaneshige and Shepherd [29] demonstrated that at a constant model speed, the intensity of post-shock reactions increases with higher pressures in the experimental chamber. Maeda et al. [18,36,38,39] inferred that enhancing the model's speed and initial pressure across various experimental conditions intensifies model-induced chemical reactions in different experimental mixtures. Depending on the occurrence and interaction of chemical reactions with shock waves, high-velocity model-induced shock wave structures can generally be classified into four types: inert shock waves, shock-induced combustion, straw-hat-type ODWs, and stabilized ODWs [30,43], as depicted in Figure 6. The shock wave structure in a non-uniform mixture is notably more complex. Iwata et al. [46] studied the initiation and quenching processes of model-induced detonation waves under varying equivalence ratios. They introduced a side slit injector at the top of the experimental chamber to establish an equivalence ratio gradient from top to bottom. In addition to the model-induced detonation waves, confined spaces within the experimental chamber can host detonation waves triggered by shock wave reflections from the chamber walls and ends. These waves do not adhere closely to the Chapman–Jouguet (C-J) condition due to the wall effects [51]. Furthermore, shock wave reflections can initiate detonation waves after the model exits the experimental chamber [28].

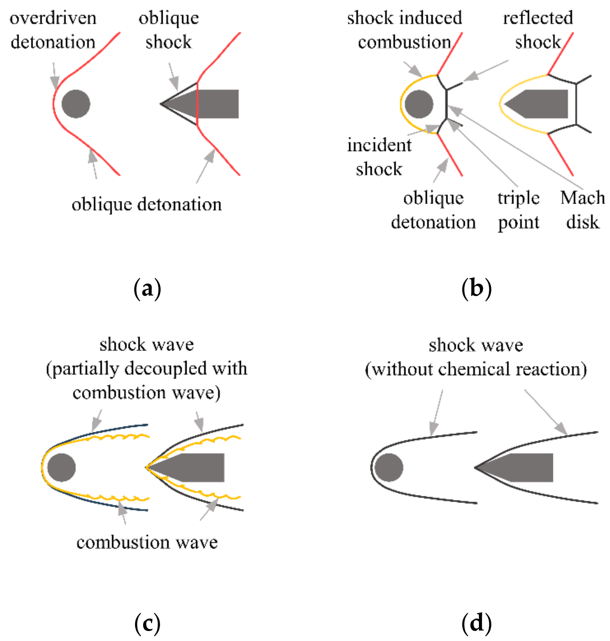
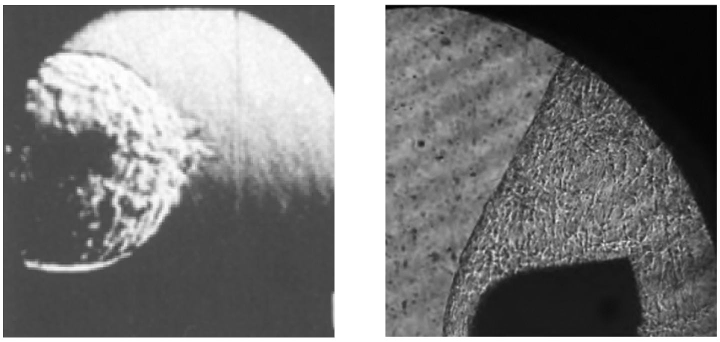


Figure 6. Shock structures induced by hyper-velocity models in combustible mixture: (**a**) stabilized ODW; (**b**) straw-hat-type ODW; (**c**) shock-induced combustion; (**d**) invert shock.

The stabilized ODW can be initiated directly by the shock wave compressing and heating near the model's nose, attenuating the overdriven detonation wave produced by the detached shock, or by the detonation induced by high-temperature and high-pressure gases following the oblique shock wave. The shock wave structure near the model is influenced by its shape, while the detonation wave away from it is determined by physical and chemical characteristics, as well as the effect of expansion waves. The straw-hat-type ODW represents a transition from shock-induced combustion to a detonation wave. Interaction between the model-induced combustion wave and shock wave generates hot spots, which then trigger a new detonation wave surface at a distance from the model. The positions of the three wave points in this structure oscillate near the model [37]. If continuous hot-spot generation is not sustained, the ODW will gradually move away from the model until it extinguishes, and the straw-hat-type ODW will transform into shock-induced combustion. In addition, if the size of the projectile continues to decrease in the same inflow condition, the wave structure will experience these four conditions in turn. Additionally, numerical simulations [52–61] have been employed to study and analyze the ODW shock structures and their dynamic processes, corroborated by experimental validation [58,60].

Various experimental studies on the model-induced unsteady process of ODW initiation yield similar results, as depicted in Figure 7. Vasiljev [26] and Shang et al. [47] launched models of different shapes (examples include a cylinder projectile of finite height in Figure 7a and a spherical projectile in Figure 7b) into combustible mixtures and observed that the initial ODWs are spherical shapes. Subsequently, as the model continues to induce new ODWs, the spherical shape transforms into a conical shape. The detonation wave propagates away from the ballistic trajectory, shaping the ODW into a cone. Furthermore, larger diameter models can initiate detonations at speeds below the C–J detonation velocity. The self-propagating detonation wave moves forward and away from the model. Kaneshige and Shepherd [29] found that behind the projectile induces a nearly planar detonation wavefront, which will induce a shock wave. At this point, the model can no longer influence the detonation wavefront, and the detonation wavefront becomes completely decoupled from the flow induced by the model, as depicted in Figure 8.



(**a**) (**b**)

Figure 7. The initiation process of ODW is induced by projectiles of various shapes [2,26]: (**a**) cylinder projectile [26]; (**b**) spherical projectile [47].

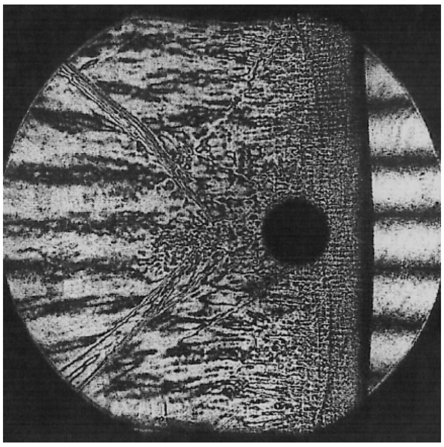


Figure 8. Shadowgraph of the detonation wave and bow shock induced by sphere projectile [29].

Higgins and Brucknet [28] utilized an experimental chamber slightly larger in diameter than the model, observing that pressure sensors and photoelectric sensors detect a combustion wave propagating from the outlet to the inlet after the model exits the chamber. Sumiya et al. [51] investigated the reflection process of ODWs on chamber walls, showing that when the chamber diameter significantly exceeds that of the model, the reflected ODW minimally affects the incident ODW. Therefore, studies focusing on the physical and chemical characteristics of combustible mixtures and model conditions typically employ chambers with diameters that are an order of magnitude larger than the models to eliminate the confined space effects on ODW initiation and propagation. In such cases, models can be categorized as large models capable of initiating detonation waves and small models that cannot, based on the type of shock wave induced at flight velocities below the C–J detonation velocity of the experimental mixture. At higher speeds, the experimental phenomena for large models include inert shock waves, shock-induced combustion, detonation waves, and ODWs. For small models, phenomena include inert shock waves, shock-induced combustion, and ODWs with increasing speed. The interaction between shock wave surfaces and combustion waves in high-velocity model-induced combustion/detonation processes is highly complex. Transitional states between these phenomena occur, influenced by the physical and chemical characteristics of the experimental mixture, such as the decoupling of combustion waves from shock waves due to the expansion wave effects or the transition of combustion waves to detonation waves forming straw-hat-type ODWs. Understanding these intricate processes requires detailed insight into the flow dynamics of detonation waves, making it a priority in high-velocity model-induced oblique detonation research.

3.3. Wave Surface of the ODW

3.3.1. Propagation Velocity of the ODW

The propagation velocity of the ODW represents the normal component of the projectile velocity relative to the wave. It is influenced by the model velocity and the physical and chemical properties of the experimental mixture. This velocity serves as a direct indicator of the flow conditions and the state of chemical reactions at the wavefront, playing a crucial role in studies of the detonation wave structure. The propagation velocity of the detonation wave can be determined by measuring the shock angle at different positions of the ODW in experimental images. This angle is defined as the angle between the tangent line of the detonation wave shape and the ballistic trajectory in the image:

$$\overline{V_{\mathrm{p}}} = V_{\mathrm{p}} / D_{\mathrm{C\text{–}J}} \tag{1}$$

$$\theta_{\mathrm{C\text{–}J}} = \arcsin\left(\overline{V_{\mathrm{p}}}^{-1}\right) \tag{2}$$

$$V_{\mathrm{n}} = V_{\mathrm{p}} \sin\theta \tag{3}$$

where $D_{\mathrm{C\text{–}J}}$ is the C–J detonation velocity of the experimental mixture, $\overline{V_{\mathrm{p}}}$ is the non-dimensional model velocity, θ is the shock angle, subscript C–J denotes the C–J detonation state, and V_n is the normal propagation velocity of the detonation wave. The ratio of the normal propagation velocity of the ODW to the C–J detonation velocity can be determined by comparing the experimentally measured ODW shock angle with the C–J detonation shock angle ($\theta_{\mathrm{C\text{–}J}}$). In most of the existing experiments, the normal propagation velocity of the ODW away from the model closely approximates the C–J detonation velocity. The ODW shock angle and normal propagation velocity are critical parameters that influence the chemical reaction process. Kasahara [30] analyzed the polar curve of the shock wave angle and concluded that, for various pressures, the difference in heat release between the detonation wave surface and the C–J state is typically within 10%, with a maximum deviation reaching 20% under certain conditions.

Verreault and Higgins [43] conducted experiments using a conical model to initiate an ODW and measured the shock angle. They observed instances where the shock angle of the ODW was smaller than that of the C–J detonation, as illustrated in Figure 9. This phenomenon was attributed to the unsteady effects or the curvature of the ODW. Maeda [40] demonstrated that the shock angles of stable straw-hat and stationary ODWs closely approximate those of the C–J detonation wave. In contrast, the shock angle of the decaying straw-hat structure exceeds that of the C–J wave, rendering it unable to sustain a stationary detonation wave. Consequently, ODWs gradually move away from the model and extinguish it. The research of Maeda et al. [18] on the shock angle of the ODW in different states also shows that the shock angle of a stabilized ODW close to the critical state of initiation is different from that of C–J detonation (blue zone) and in conditions higher than the critical state of initiation, the propagation velocity of the ODW front is close to the C–J detonation (red zone), as shown in Figure 10.

Aside from the propagation velocity of the ODW away from the model, the velocity near the model reflects the influence of model compression and expansion waves on the combustion process of the wave, making it a widely studied phenomenon. Maeda et al. [41] determined the normal propagation velocity of the detonation wave from the stagnation point to the edge of the observation window through fitting and differentiation of experimental ODW-shape measurements. They concluded that in the region near the model, the detonation wave propagation velocity is typically 0.8–0.9 times that of the C–J detonation velocity, as depicted in Figure 11. This region marks the transition from a bow-shaped overdriven detonation wave to a conical ODW, influenced by the expansion waves originating from the model. The re-acceleration of the detonation wave in this area determines whether the model can initiate an ODW or not. Maeda et al. [38] also demonstrated that at lower speeds approaching the critical state, expansion waves have a greater effect, resulting in a lower minimum wave propagation velocity. At higher speeds, the ODW shape becomes more planar, and the minimum propagation velocity increases.

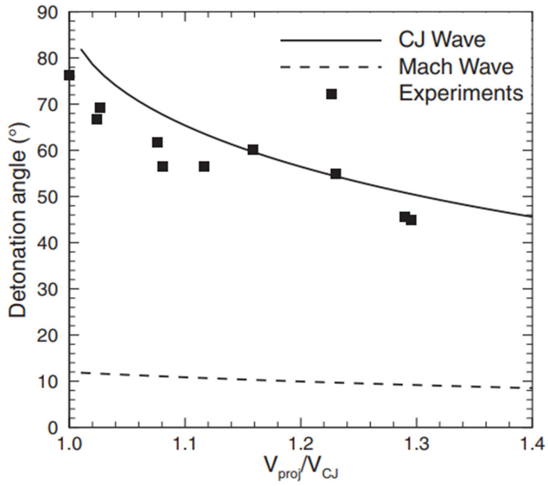


Figure 9. Non-dimensional projectile velocity and detonation wave angle [43].

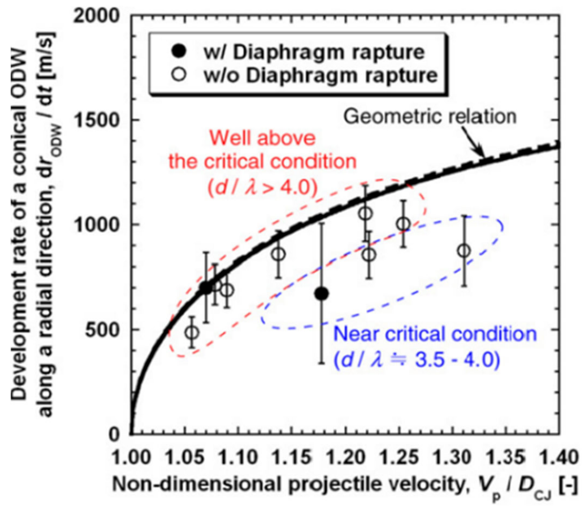


Figure 10. The development rate of the ODW and non-dimensional projectile velocity [18].

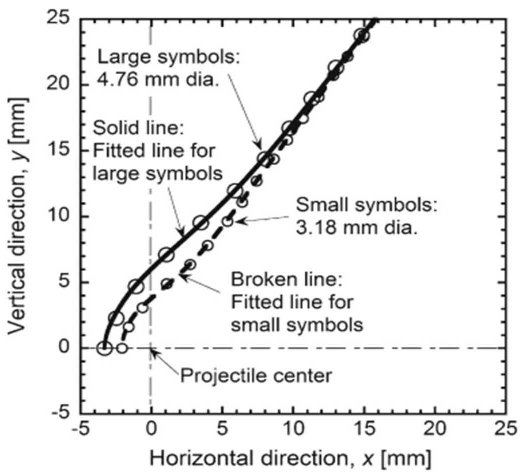


Figure 11. Fitted shape of the ODWs [41].

3.3.2. Wave Surface Structure of Self-Sustaining Propagation in ODW

The structure of the ODW is closely tied to its propagation dynamics and critical state. Observing the ODW structure aids in analyzing the mechanisms of detonation initiation and propagation through the lens of combustion instability. With its strong coupling between combustion and shock waves, the ODW exhibits nonlinear characteristics and unsteady flow processes. In experimental images, the conical shape of the ODW often appears flattened, yet it serves as an indicator of instability where fine flow structures sustain the propagation of the detonation wave. Near the model, the detonation wave is influenced by compression and expansion waves, whereas these effects diminish further away. The flow process approaches self-sustained propagation, where the wave system and ignition's delay effects become pronounced. However, due to the continuous ignition by the model, the ODW flow differs from that of a conventional detonation wave. These characteristics highlight how the propagation process and critical state of ODWs hinge on the structure of the detonation wave. Therefore, observing the ODW structure contributes to our understanding of the stabilization mechanisms of detonation waves from the perspective of combustion dynamics.

Kasahara et al. [31] conducted an analysis of reaction intensity on the wave based on chemiluminescence measurements. They demonstrated that the reaction strength in the head region of the model-induced stabilized ODW is significantly higher than that in the shock wave region further away from the model. Utilizing parameters such as the shock angle, post-shock Mach number, and normal propagation velocity of the ODW derived from OH chemiluminescence images, they categorized the detonation wave into four distinct regions: strong overdriven, weak overdriven, quasi-C–J, and C–J detonation waves. Their experimental findings revealed that the quasi-C–J detonation region is minimal in low-speed scenarios, with the detonation wave swiftly transitioning from overdriven to C–J detonation states. This transition process in the stabilized detonation wave structure sustains the propagation of the ODW. Furthermore, analyzing this process is essential for advancing the criteria theories related to detonation wave propagation mechanisms.

The straw-hat structure is a phenomenon observed when shock-induced combustion transitions into an ODW. During this process, the chemical reaction surface near the model interacts with the shock wave's surface, creating a hot spot that initiates and sustains the detonation wave. Maeda et al. [36,37,39] extensively studied the unsteady process of the straw-hat structure, identifying the formation of hot spots after the shock wave as critical for maintaining ODW propagation. They concluded that in the straw-hat-type ODW, these hot spots continuously generate new detonation waves, anchoring the ODW in place relative to the model. However, if the combustion waves become detached from the shock wave and fail to produce hot spots, the detonation waves will gradually retreat until they extinguish, the same phenomenon was observed in our recent experiments, as depicted in Figures 12 and 13. They further deduced that a stabilized ODW can evolve from a straw-hat-shaped structure, where the positions of the three wave points may shift backward or disappear depending on the model's velocity and ODW shock angle. During this transition, hot spots generated by the combustion wave are replaced by those generated within the wave system on the detonation wave, thereby sustaining ODW propagation. Despite these insights, experiments specifically focused on the hot-spot generation process in the straw-hat-type ODW remain limited. There is still a lack of experimental data to thoroughly investigate the hot-spot generation mechanism and establish the flow dynamics of the new detonation wave.

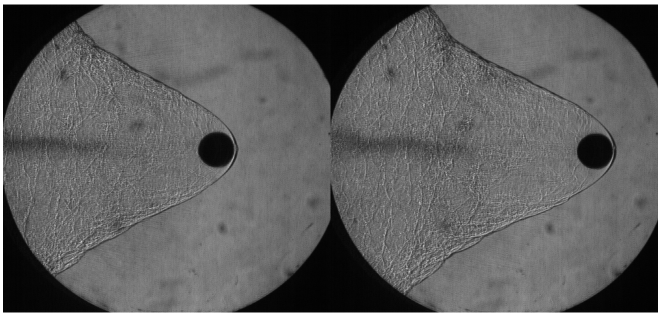


Figure 12. The straw-hat-type ODW initiated by a hot spot induced by a 30 mm-sphere projectile: $V_p = 4258$ m/s, $p_0 = 12.0$ kPa, H_2: O_2 = 2:1 (The experiment was conducted by the authors in November 2023, and the results of the experiment were not officially published. The experimental setup can be found in Reference [47]).

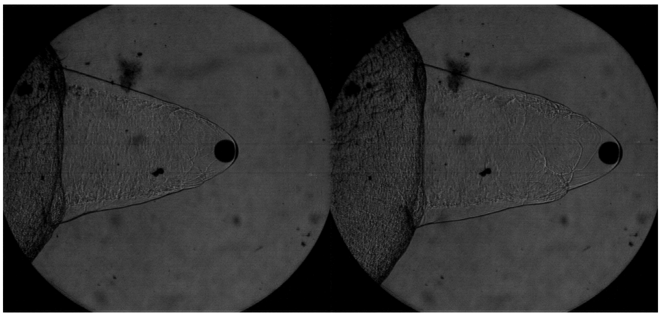


Figure 13. Propagation of ODW away from the model induced by a 20-mm sphere projectile: $V_p = 4837$ m/s, $p_0 = 21.0$ kPa, H_2: O_2 = 2:1 (The experiment was conducted by the authors in November 2023, and the results of the experiment were not officially published. The experimental setup can be found in Reference [47]).

The primary distinction between the shapes of stabilized ODW waves and normal detonation waves lies in the presence of curvature, which induces mass diffusion affecting wave propagation in various locations. Kasahara et al. [30] demonstrated that with an increased initial pressure or decreased Mach number of the model, the minimum curvature of the detonation wave diminishes. This suggests a smoother transition from an overdriven detonation wave at the model's head to a C–J detonation, altering the shock wave structure from a straw-hat-type to an ODW. Maeda et al. [18] further illustrated that the curvature of the detonation wave near the model influences ODW stability, with mass diffusion contributing to wave attenuation. They analyzed the impact of the detonation wave curvature on ODW stability using the $D_n - \kappa$ relation, concluding that when the curvature decreases below a critical threshold, the detonation wave is quenched by expansion waves.

The fine structure of the wave plays a pivotal role in influencing the stability of ODWs across different configurations. However, due to the limitations in measurement techniques, there is a scarcity of data on the fine structure of detonation waves, particularly regarding the typical phenomenon of detonation cell patterns, which remains largely unexplored. Maeda et al. [39] conducted a comparison between the width of regular stripes observed behind ODWs in experiments and the cell pattern of normal detonation waves under corresponding experimental mixture conditions. They concluded that these widths are identical. Nonetheless, they noted challenges in measuring post-shock structures due to the three-dimensional effects inherent in the schlieren techniques. Furthermore, the effect of diluting inert gases on ODWs follows a similar principle to their impact on normal detonation waves: gas dilution suppresses the transverse waves of detonation, alters the chemical reaction characteristics, and elevates the critical detonation state.

The various ODW structures observed experimentally correspond to distinct modes of detonation initiation. The straw-hat structure relies on the sustained detonation of hot spots behind the bow-shaped shock wave induced by the combustion wave. In contrast, the stabilized ODW depends on the process where the detonation wave's normal propagation velocity undergoes attenuation and subsequent re-acceleration. These processes are intricately linked to the interaction between the shock wave and the combustion wave. However, there remains a paucity of experimental studies in these areas. Further investigation into the unsteady flow processes at the detonation wave, along with an analysis of the relationship between the state of the detonation wave and its characteristics, will enhance our understanding of how to control oblique detonations. This understanding could potentially advance the application of ODWs across various engineering fields.

3.4. Investigation of the Initiation Characteristics of ODW Induced by High-Velocity Projectiles

The study of the initiation characteristics of ODWs is fundamental for achieving stable and controllable ODWs in engineering applications. This has also been a focal point of research in the field. Lee [61,62] proposed the energy limit theory, which states that when the aerodynamic resistance work of the model exceeds the minimum energy required for the experimental mixture to initiate a cylindrical detonation wave, the model can initiate an ODW. Vasiljev [26,27] proposed a similar theory and demonstrated through experiments that the critical initiation energy correction factor for the model is comparable to the critical factor for initiating cylindrical detonation waves using cylindrical explosives. Building on this foundation, several studies have conducted experiments and numerical validations of the energy limit theory for detonation [27,60,63–65]. Higgins [28] illustrated the constraints of this theory through an analysis of experimental outcomes, as depicted in Figure 14. He concluded that the theory reliably predicts experimental outcomes when the model velocity closely matches the C–J detonation velocity. However, it shows limitations under sub-detonation conditions, particularly when lower Mach numbers and higher chamber pressures lead to significant deviations from the predicted outcomes. For instance, instances where the chamber pressure exceeds 7.5 bar and the model's flight Mach number is much higher than predicted but fails to initiate detonation exemplify these deviations. Higgins [28] further demonstrated that the model velocities predicted by the energy limit theory sufficiently meet the criterion that the energy deposition rate must exceed the detonation propagation speed, thereby explaining its effectiveness under conditions of higher model velocities.

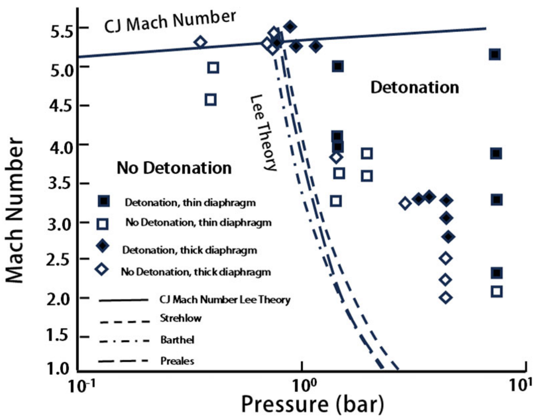


Figure 14. Difference between the experiments and the energy limit theory [28].

The energy limit theory of detonation primarily considers the aerodynamic work of the projectile, overlooking chemical processes. Experimental observations reveal that a detonation wave only forms if the model initiates detonation before exiting the experimental chamber. Verreault and Higgins [43] investigated how different pressures and cone angles of conical models influence the critical detonation state. They found that the theory holds true at low pressures and cone angles greater than 28°, but it underestimates detonation velocities under high-pressure conditions. To address this discrepancy, they introduced a kinetic limit theory, which accounts for the ratio of flow times on the conical surface to those in the reaction-induced zone, as depicted in Figure 15. Ju et al. [66] proposed a kinetic limit theory based on ignition delay, asserting that a detonation wave only occurs if the ignition delay is shorter than the characteristic time of the model's flight. Given the finite length of the experimental chamber, failure of the model to initiate detonation within this timeframe results in a deviation from the energy limit theory for critical detonation states and is especially pronounced under high-pressure conditions with extended induction times. Ju et al. [66] addressed this by proposing a combined theory integrating energy and kinetic limits, validated through experimental verification, as depicted in Figure 16.

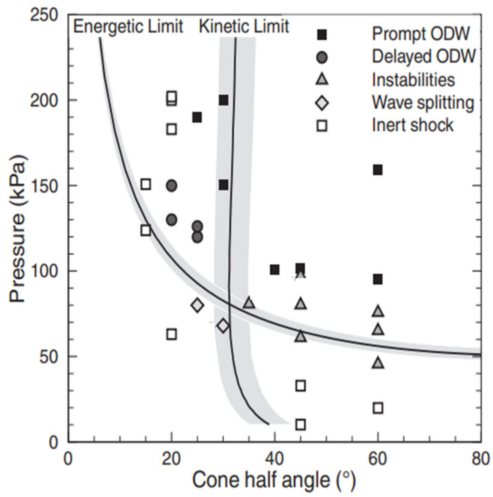


Figure 15. Difference between the experiments and the kinetic limit theory [43].

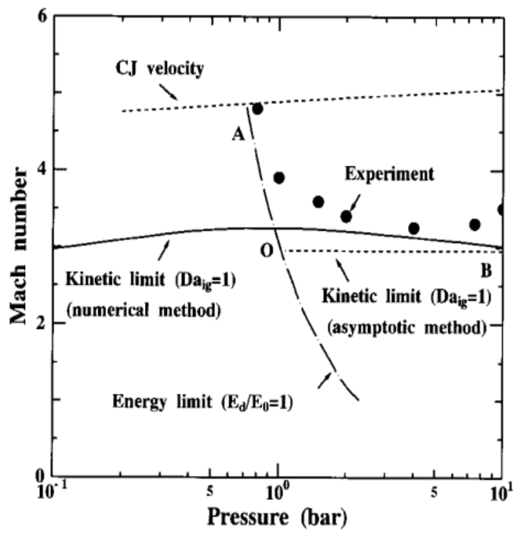
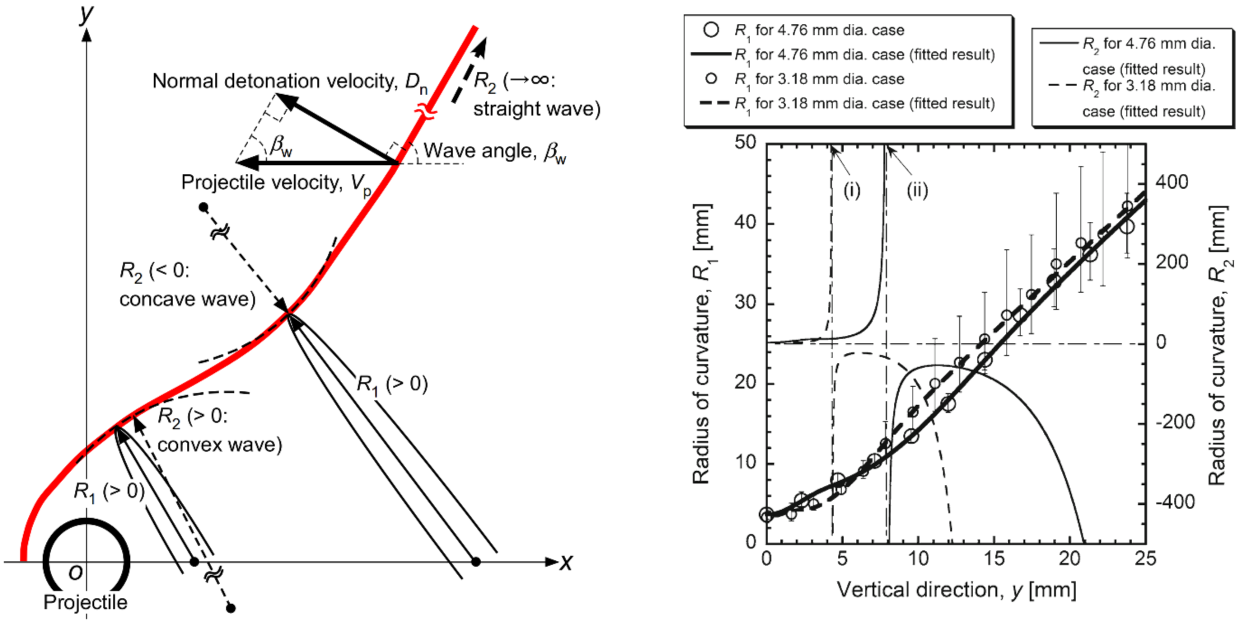


Figure 16. Experimental verification of the joint theory of energy limit and kinetic limit [66].

Research into the initiation characteristics of ODWs has extended beyond the energy limit theory, with a focus on the empirical criteria derived from the analysis of experimental images. Kasahara et al. [27] analyzed stabilized ODWs from experimental data and introduced the mean curvature coefficient as a pivotal criterion for ODW initiation. Maeda et al. [41] explored the influence of a detonation's wave surface curvature by relating it to the ratio of the ODW shape's radius to the chemical reaction length (induction zone length). They non-dimensionalized the ODW shape's curvature using the ratio of wave radius to cell width, which showed a consistent reduction in the detonation velocity. Figure 17 illustrates this concept. They further compared the non-dimensional characteristic curvature radius at minimal wave propagation velocities for varying stoichiometric mixtures under different pressures, ranging from 8–10 and 15–18. Iwata et al. [46] conducted experiments with oblique detonation in non-uniform equivalence ratio mixtures, highlighting the non-dimensional characteristic radius of the curvature as a critical determinant of ODW propagation.



(**a**) (**b**)

Figure 17. Curvature radius of the ODW [41]: (**a**) schematic diagram of the ODW curvature radius; (**b**) distribution of the radius of curvature along the vertical direction.

Maeda et al. [41] investigated the influence of the model size on critical parameters by using spherical models of two different diameters and varying experimental conditions. They normalized the model velocity and ODW shape using the C–J detonation velocity and model diameter, respectively. Comparisons were made based on the non-dimensional shock wave's shape at different non-dimensional model velocities. Their findings indicated that the non-dimensional shock wave's shape remained consistent across similar non-dimensional model velocities, suggesting insensitivity to the model radius. Therefore, they identified the non-dimensional model diameter, specifically the ratio of the model diameter to the normal detonation wave cell width of the experimental mixture, as a critical parameter. This parameter correlates with the non-dimensional characteristic radius of curvature in critical ODW initiation processes.

Maeda et al. [39,41] conducted measurements on the critical parameter of non-dimensional model diameter using various gaseous mixtures, as illustrated in Figure 18. They concluded that this critical parameter is sensitive to both mixture composition and model shape. Variations in the mixing ratio, dilution ratio, and model configuration significantly influence the critical parameter for detonation. Consequently, the accurate prediction of experimental conditions using these criteria necessitates the accumulation of comprehensive experimental data across different mixtures and model geometries.

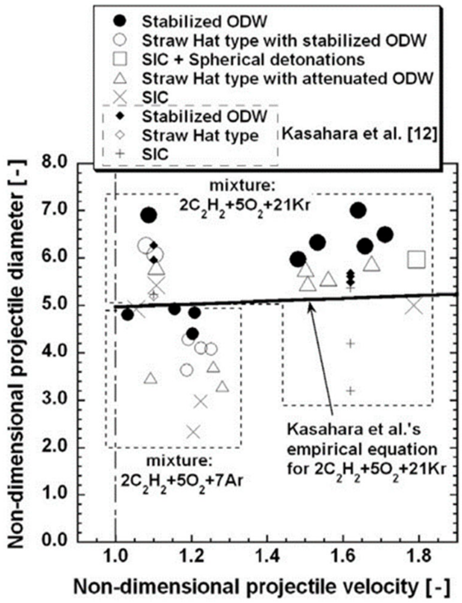


Figure 18. Oblique detonation results of various non-dimensional projectile diameters and velocities [39].

4. Conclusions

Several studies have focused on high-velocity model-induced ODWs, investigating their criteria, shock wave structures, and propagation dynamics. Significant progress has been made in understanding the propagation and critical mechanisms of oblique detonations through the analysis of existing experimental, theoretical, and numerical studies. However, there remains a notable gap in comprehensively addressing the initiation and propagation processes of ODWs to advance their engineering applications in propulsion technology. The scarcity of experimental data and the limitations of combustion diagnostic technologies impede further advancements in understanding ODW mechanisms. This paper aims to describe and analyze experimental methodologies and research advancements related to high-velocity model-induced ODWs. It also proposes several key areas that warrant further investigation in future research, as follows.

(1) To advance the understanding and control of oblique detonation, it is imperative to undertake an experimental investigation into the unsteady process of high-velocity models traversing combustible gaseous mixtures and inducing various shock wave structures. Previous experimental observations of ODWs have documented diverse shock wave phenomena, including inert shock, shock-induced combustion, straw-hat-type ODWs, and stabilized ODWs. While these studies provide insights into the flow processes of stabilized ODWs, they often lack in-depth analyses of propagation mechanisms and unsteady flow dynamics due to the limitations of optical measurement techniques. Additionally, there is a lack of experimental research on the formation processes of different shock wave structures, particularly concerning the unsteady initiation processes near the critical state. To enhance our comprehension of the oblique detonation mechanisms, future experimental studies should focus on elucidating the initiation processes and characterizing unsteady flow dynamics. Establishing a clear linkage between the flow processes and detonation wave criteria will be essential for advancing our understanding and control of oblique detonation phenomena.

(2) To comprehensively understand ODWs, it is essential to conduct experimental observations and measurements focusing on the fine flow structure and chemical reaction processes involved. ODWs exhibit complex, unsteady behaviors, even when relatively stationary, with respect to the model. This complexity encompasses the surface wave structure of ODWs and the initiation of hot spots by combustion waves following the shock wave, which are crucial for sustaining detonation wave propagation. Current experimental findings on flow processes at the wave primarily rely on high-velocity

schlieren and OH chemiluminescence images, which are limited by three-dimensional effects. As a result, these methods do not facilitate quantitative analysis of the ODW structure and post-ODW flow processes. Therefore, there is a critical need to design tailored optical measurement systems and employ advanced combustion diagnostic techniques capable of capturing three-dimensional flow fields and chemical reaction processes. Such advancements are pivotal for advancing our understanding of oblique detonation propagation mechanisms.

(3) Developing robust criteria for ODWs is crucial for advancing our understanding and control of their initiation processes. Current studies predominantly rely on the energy limit theory, which focuses on the aerodynamic work of the model relative to the critical energy required for detonation in the experimental mixture. This theory includes non-dimensional projectile diameter measurements, integrated as part of the energy limit theory, which assesses the ratio of model aerodynamic work to critical detonation energy. However, the energy limit theory has notable limitations. It often uses experimentally derived cell sizes based on semi-empirical formulas or theories, which may not fully capture all physical nuances. Additionally, kinetic limits have been proposed to address specific flow process variations, but these are not universally applicable across all initiation scenarios. To overcome these drawbacks, a generalized criteria theory for ODWs should be developed. This theory should consider a broader range of factors, including physical and chemical characteristics of the experimental mixture, chemical reaction dynamics, and detailed flow processes. By incorporating these elements, a more comprehensive understanding of ODW initiation can be achieved. Furthermore, refining and supplementing existing ODW initiation theories with experimental data is essential. Experimental validation will provide insights into the mechanisms underlying ODW initiation and aid in developing effective control strategies. This approach will ultimately contribute to advancing the field of oblique detonation wave propulsion technology.

(4) Integrating combustion diagnostic methods with new facilities. Advanced optical observation methods play a crucial role in the study of oblique detonation mechanisms. Early detonation diagnostic techniques primarily used the smoked foil method and high-speed cameras. Integrating more testing techniques could further advance the observation of detonation propagation characteristics. Possible testing techniques include OH-PLIF, CH-PLIF, chemiluminescence combustion diagnostics, 3D-CTC, et al. Furthermore, this paper focuses on experimental work conducted in high-speed launching devices, which have their own limitations. Integrating different experimental platforms, such as direct-connected supersonic combustion facilities, pulse wind tunnels, or expansion tunnels, and collaborating to enhance these facilities' capabilities continuously is one of the future directions. Additionally, rapid advancements in numerical simulation technology have empowered researchers in combustion and detonation to conduct extensive studies. This technology facilitates the creation of detailed combustion process models, enabling controlled and repeatable analyses. Thus, the integration of combustion diagnostic methods with different facilities, coupled with the rapid development of numerical simulation and computer technologies, will significantly contribute to the advancement of oblique detonation propulsion technology.

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