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Hysteresis phenomenon of the oblique detonation wave

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Hysteresis phenomenon of the oblique detonation wave (ODW) is numerically studied. Two-dimensional unsteady reactive Euler equations are numerically solved as governing equations with a two-step reduced reaction mechanism. Wedge angle variation is realized by modifying inflow direction. It is found that hysteresis phenomenon does exist in ODW problem, i.e., the final state of the ODW is closely relevant to initial condition. Two types of hysteresis are discovered in this study: the hysteresis of upstream-downstream triple point and the hysteresis of smooth-abrupt transition pattern. Detonation/Shock polar analysis on primary triple point structure of abrupt ODW demonstrates that the precursor shock of the ODW near primary triple point is actually a strong shock solution and therefore characterized by local detachment behavior which is responsible for primary triple point's upstream moving. Similar to hysteresis of shock reflection, irreversibility is the mechanism for ODW's hysteresis. It is found that hysteresis will disappear when the wedge angle is smaller than a certain value, which means that it may be impossible to obtain a standing Chapman–Jouguet (CJ) ODW without ignition delay or with short ignition delay at a CJ wedge angle via hysteresis.

1. Introduction

The oblique detonation engine (ODE) [1,2] is one for high-Mach-number flight, using oblique detonation wave (ODW) at the combustor to produce thrusts and having advantages of high cycle efficiency and fast heat release and therefore short combustor length. In past decades, basic issues about the ODW involving initiation [3–7], standing stabilization [8–10] and cellular instability [11–13] have been concerned by many researchers. From practical perspective, initiation and standing stabilization of an ODW are of special importance because both of them are the key factors for an ODE to realize its performance advantages.

Initiation of an ODW was often observed by researchers in experiments in which a high-velocity projectile passes through combustible gases. However, until 1990s, people paid more attention to shock-induced combustion (SIC) phenomenon than to ODW in high-velocity projectile experiments, like Lehr [14], McVey and Toong [15], Alpert and Toong [16], Matsuo and Fujiwara [17], and Matsuo and Fujii [18]. The oscillatory instability in SIC was comprehensively investigated in particular by these researchers. ODW's initiation by a high-velocity projectile was first theoretically modeled by Vasiljev [3] and Lee [4], individually. Their ideas are to analogize this problem to cylindrical detonation initiation by a linear energy source and they pointed out that the energy deposited per unit length by the projectile, which equals its drag force, should be no less than the critical energy per unit length required for initiation of a cylindrical detonation. After then, Ju et al. [19] argued that as an additional criterion to that proposed by Vasiljev [3] and Lee [4], the Damköhler number indicating the ratio of ignition delay time to flow characteristic time should be less than unity. Experiments by Verreault and Higgins [5] demonstrated that the energy criterion proposed by Vasiljev [3] and Lee [4] and the chemical kinetic criterion proposed by Ju et al. [19] do mutually control the ODW's initiation by a high-velocity projectile. Besides, in experiments of Verreault and Higgins [5], four combustion regimes are found: prompt ODW regime (without leading shock or ignition delay), delayed ODW regime (with leading shock or ignition delay), instabilities regime and wave splitting regime.

As for standing stabilization of an ODW, it is not as easy as that of an inert shock. Pratt et al. [20,21] made a detailed detonation polar analysis on standing ODW, pointing out that the ODW cannot be stabilized at the wedge that supports it unless the wedge angle lies between the minimum value called Chapman–Jouguet (CJ) wedge angle and the maximum value called detachment wedge angle. According to the detonation polar, they classified the ODW into three types: weak underdriven ODW, weak overdriven ODW and strong ODW, as shown in Fig. 1. Among these three types of ODW, the weak underdriven is unphysical since it violates the second law of thermodynamics.

Ghorbanian and Sterling [22] supposed a double-wedge supersonic reacting flow and analyzed possible flow structures. They

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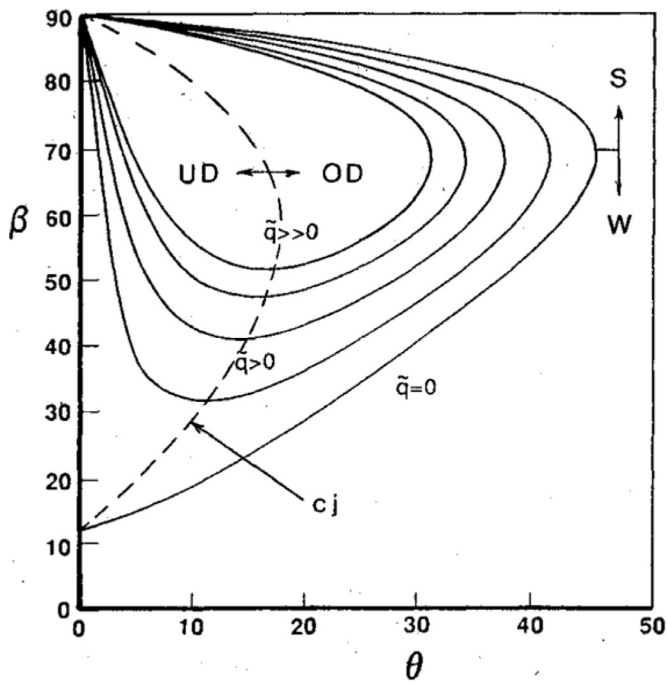

Fig. 1. Detonation polar drawn by Pratt et al. [21].

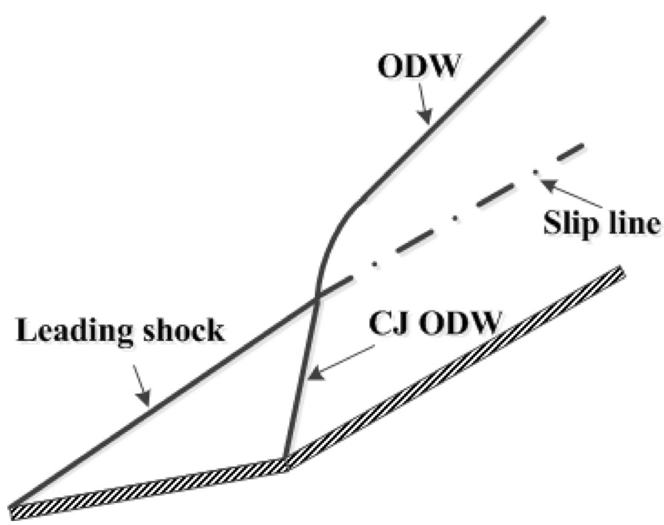

Fig. 2. ODW at a double wedge assumed by Ghorbanian and Sterling [22].

predicted a CJ ODW following the shock wave generated by the first wedge of a smaller angle and an overdriven ODW generated by the second wedge of a larger angle, as shown in Fig. 2 (Such a structure has been comfirmed by Liu et al. [23,24] in their numerical simulations with a reduced two-step reaction mechanism). Based on such a structure, they were the first to conduct detailed detonation/shock polar analysis on ODW structure. Kasahara et al. [25,26] and Maeda et al. [27,28] made a series of hypervelocity projectile experiments. They paid attention to the curvature effect and proposed the critical diameter criterion for a spherical projectile to stabilize an ODW. Liu et al. [23] paid particular attention to the triple point and the transverse shock of the ODW. They found the triple point structure can maintain stationary after initiation or propagate upstream to get closer to the wedge tip. They attributed the upstream propagation of the triple point to pressure variation due to inflow Mach number decrease or wedge angle increase. In this study, we will give another explanation for upstream moving of the triple point structure, via detonation/shock polar analysis.

For ODW's application in propulsion, a CJ ODW is always desirable because it has the minimum entropy increase. However, initiating and stabilizing a CJ ODW is not easy because of the small CJ wedge angle. One thought is that once the ODW is initiated, it is independent of downstream condition if post-detonation state is supersonic or sonic, as described in [29]. Thus, a CJ ODW with short ignition delay or even without ignition delay (prompt) is supposed to be possible if a highly overdriven ODW is first initiated by a large-angle wedge and then is decayed to a CJ ODW by decreasing the wedge angle. If this is true, or if hysteresis phenomenon exists and behaves as wished, it will be very helpful for ODW's application in propulsion. Thus, to confirm hysteresis phenomenon of the ODW is the aim of this paper. As a matter of fact, hysteresis has already been discovered in shock reflection phenomenon (see [30] and [31]). In this study, the mechanism analysis of ODW's hysteresis will also be conducted, by analogizing it to that of shock reflection.

Since detonation simulation requires high grid resolution, adaptive mesh refinement technique is necessary to reduce total grid number. In this paper, such an open-source computational fluid dynamics (CFD) program called AMROC [32] is used to conduct numerical study. In next section, a brief introduction to the numerical method and model will be given.

2. Numerical treatment

2.1. Governing equations

The governing equations are two-dimensional unsteady reactive Euler equations given as:

Continuity equation

$$\partial\rho/\partial t + \partial(\rho u)/\partial x + \partial(\rho v)/\partial y = 0 \quad (1)$$

where ρ, u, v, t, x and y denote the density, the x-direction velocity, the y-direction velocity, the time, the x coordinate and the y coordinate, respectively.

Conservation equation of x-direction Momentum

$$\partial(\rho u)/\partial t + \partial(\rho u^2 + p)/\partial x + \partial(\rho uv)/\partial y = 0 \quad (2)$$

where p is the static pressure.

Conservation equation of y-direction Momentum

$$\partial(\rho v)/\partial t + \partial(\rho uv)/\partial x + \partial(\rho v^2 + p)/\partial y = 0 \quad (3)$$

Conservation equation of energy

$$\partial(\rho e)/\partial t + \partial[u(\rho e + p)]/\partial x + \partial[v(\rho e + p)]/\partial y = 0 \quad (4)$$

where e is the specific total energy.

For perfect gas, the equation of state is

$$p = \rho RT \quad (5)$$

where R is the gas constant and T is the static temperature. Thus, the specific total energy can be expressed as

$$e = p/\rho(\gamma - 1) + (u^2 + v^2)/2 - RT_0\tilde{q} \quad (6)$$

where γ, T_0 and $\tilde{q}$ are the specific heat ratio, the static temperature of the inflow and the dimensionless local heat release using RT_0 for normalization ($\tilde{q} = q/RT_0$, where q is the dimensional local heat release), respectively.

A two-step reduced reaction mechanism (see [33]) is employed, which helps mimic the feature of a chain-branching reaction and avoid huge computational expense of detailed reaction mechanism. The two-step reduced reaction mechanism consists of a thermally neutral induction step and a rapid heat release step that follows. The reaction rates equation for both steps are given as: