The Impact of a Micro-Rounded Bump on the Initiation of Oblique Detonation Waves

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1 Introduction

In recent years, extensive research studies have been conducted on the oblique detonation wave engine (ODWE) due to its potential to revolutionize high-speed propulsion [1]. The basic design of an ODWE is to use the vehicle geometry such as a wedge surface to induce, from an incoming, supersonic flow of detonable mixture, an oblique shock wave (OSW) which subsequently transits into an oblique detonation wave (ODW) after an initiation zone.

Apart from pioneering analytical works for example using detonation polar analysis providing wave angles and steady structures as the basic foundation for a standing oblique detonation wave attached to a semi-infinite wedge [2, 3], fundamental studies focus more on the complex morphology at the initiation region and the transition process from the OSW to the ODW as well as the inherently unstable nature of the oblique detonation surface, e.g., [4- 9]. Notably, depending on initial conditions such as inflow Mach number and wedge angle, as well as combustible mixture proprieties, there exists two key transition types, namely, the abrupt transition from the OSW to the ODW where a non-reactive oblique shock, a set of deflagration waves, and the oblique detonation surface, all united on a multi-wave point; and the smooth transition characterized by a smoothly curved shock [6]. More recent investigations have been performed to look at more realistic situations such as the effect of unsteadiness, multiphase composition and fuel-air mixture inhomogeneity of the incoming supersonic flow on the ODW dynamics [10-12].

Due to its strong dependence on both the incoming flow and physical condition such as the vehicle geometry as well as the chemical properties of the reactive mixture, it remains technically challenging to establish the onset of oblique detonations in high-speed combustible mixtures for practical propulsion applications given many design constraints such as the engine scale limit. From an engineering perspective, a key challenge on the development of ODWE is to come up with practical methods for controlling the trigger location of the oblique detonation wave and reducing the initiation length, which is defined as the distance from the tip to the onset of ODW.

Recent works have turned into the use of a hot jet to actively control the oblique detonation initiation and stabilize it at the desired position [13]. Putting this method into practice will require a high-pressure hot gas injection possibly extracting from the burned gas. Inspired by the use of ramp-cavity in supersonic combustion for ignition and flame stabilization, a novel wedge geometry with a step is also studied by Qin & Zhang to control the trigger location of the oblique detonation wave through variations of the step location and the rear wedge angle [14].

In this work, we focus on the topographical properties of the wedge surface on the ODW initiation. The motivation is to investigate how a simple micro-rounded bump on the wedge surface could affect the ODW dynamics, see Fig. 1. In particular, the present study aims to achieve a promoting effect of the micro-bump on the ODW initiation. The ultimate goal is to shed light on how the wedge surface topography could significantly influence the initiation dynamics of ODW. To ease the analysis and focus primarily on the gas dynamic effects induced by the micro-bump, the strategy adopted is to conduct high-resolution, numerical simulations using an ideal-gas, reactive flow model given by the inviscid Euler equations with a simplified chemistry model, e.g., the standard one-step irreversible Arrhenius kinetics. The present computations are carried out using the Graphics Processing Units (GPUs) computing technology. This first set of parametric studies reports the effects of bump locations on the different types of ODW initiation with different mixture activation energies *E*a. The relationship between the initiation location and the bump location is analyzed. Key features resulting from the presence of the micro-bump on the flow structure in the vicinity of the ODW initiation region and the fully developed ODW unstable surface are discussed in detail.

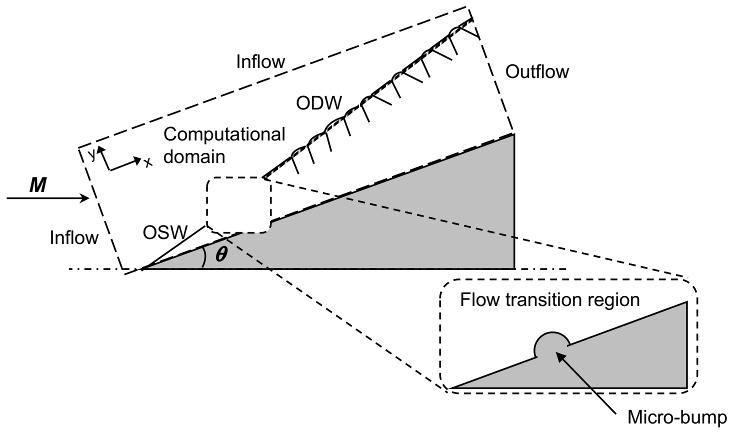

Figure 1: A schematic of the computational setup

2 Problem Formulations and Numerical Methodology

The reactive flow dynamics is based on the standard inviscid, reactive two-dimensional Euler equations coupled with a single-step, irreversible Arrhenius chemical kinetic model:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F(U)}}{\partial x} + \frac{\partial \mathbf{G(U)}}{\partial y} = \mathbf{S(U)} \tag{1}$$

where the conserved variable **U**, the convective fluxes **F** and **G**, and source term **S** are, respectively,

$$\mathbf{U} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e \\ \rho\lambda \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ u(\rho e + p) \\ \rho u\lambda \end{bmatrix}, \mathbf{G} = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + p \\ v(\rho e + p) \\ \rho v\lambda \end{bmatrix} S = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ \dot{\omega} \end{bmatrix} \tag{2}$$

with $e = \frac{p}{(\gamma-1)\rho} + \frac{1}{2}(u^2 + v^2) + \lambda Q$ and $p = \rho T$. ρ, u, v, p, T and e are density, particle velocities in x- and y- directions, pressure, temperature and total energy, respectively and the single-step Arrhenius kinetic rate law expresses:

$$\dot{\omega}_I = -k\rho\lambda \exp\left(-\frac{E_a}{T}\right) \tag{3}$$

where λ denotes the reaction progress variable varying between 1 (for the unburned reactant) and 0 (for the product). All thermodynamic variables have been made dimensionless by reference to the unburned state. The mixture is assumed to be ideal and calorically perfect (with a constant specific heat ratio γ = 1.2). The pre-exponential factor k in Eq. (3) is chosen such that the ZND half-reaction zone length of the corresponding CJ detonation is unity, i.e., $L_{1/2} = 1$. Following our earlier work [15], the dimensionless heat release is fixed with $Q = 50$, the inflow Mach number and the wedge angle are set at $M_0 = 10$ and $\theta = 26°$, respectively. The mixture activation energy E_a, is used as the bifurcation parameter to generate initially, without any micro-bump on the wedge, the two types of ODW initiation structure, i.e., with either a smooth or an abrupt transition. In all simulations, a grid resolution of 32 pts per $L_{1/2}$ is used.

The schematic shown in Fig. 1 describes as well the overall computational setup. The computational domain bounded by the dashed lines is rotated to the direction along the wedge surface. The Cartesian grid in this rectangular domain is thus aligned with the wedge surface and the inflow velocities to the computational domain are determined and projected based on the rotation angle. Inflow conditions are thus employed for the left and top boundaries; a transmissive boundary condition is implemented on the right boundary and few grid cells before the wedge tip. Slip reflective boundary condition is used on the wedge surface. To represent solid objects in the computational domain, i.e., the semi-cylindrical solid bump with radius R, we follow the ghost fluid boundary representation described in Fedkiw et al. [16]. The originally formulated method uses the level set of a signed distance function to represent the interface between the two fluids; it can also be adapted to model single-phase flow around arbitrary solid geometries.

The solutions to the above equation systems are obtained numerically using a 2nd order MUSCL-Hancock scheme with an HLLC Riemann solver [17], with a CFL number of 0.90. To reduce the simulation run-time, the entire flow solver was implemented using NVIDIA CUDA programming language (NVIDIA Corp., Santa Clara, CA, USA) and run on an NVIDIA Tesla K40 General Purpose Graphics Processing Unit GPGPU [15, 18, 19]. The application of the GPU-CPU framework improves significantly the computational performance allowing high-resolution simulations and parametric study with large computation domain to be performed efficiently.

3 Results and Discussion

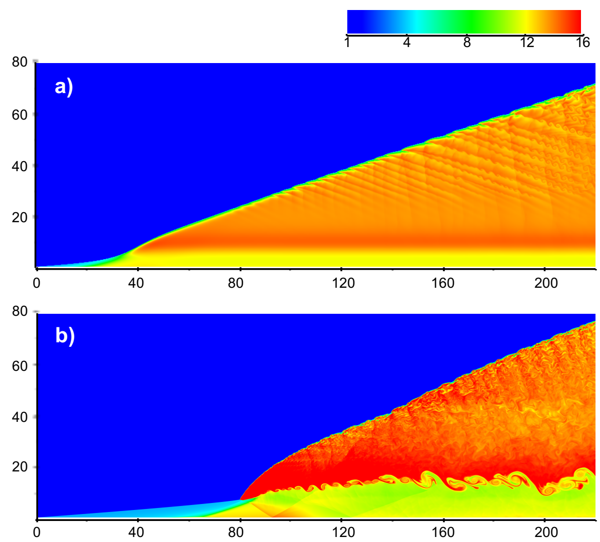

Figure 2: The two types of OSW-ODW transition with a) E_a = 20; and b) E_a = 35.

Figure 2 first shows the final ODW formation structures obtained with $\theta = 26°$, $M_0 = 10$, and $E_a = 20$ and 35 for the one-step Arrhenius kinetic model. The two activation energies E_a give rise to the two types of OSW-ODW transition, i.e., a smooth transition for $E_a = 20$ with a curved shock shown in Fig. 2a and an abrupt transition with a multi-wave point for $E_a = 35$ shown in Fig. 2b. Approximately the initiation points are $x_{ini} \sim 40$ and 80, respectively, for the smooth and abrupt transition cases. The higher E_a also leads to a more unstable ODW surface and irregular flow field downstream after the initiation.

Figure 3 present some simulation results of temperature flow fields showing the effects of the micro-rounded bump on the ODW initiation dynamics and wave structures for initially a smooth transition with $E_A = 20$. The white dashed lines indicate the bump location on the wedge. When the bump is located at the initiation region of the base case (i.e., a smooth wedge without any bump), the ODW initiation is promoted and the initiation point moves forward (Fig. 3a and b) with $x_b \leq x_{ini} \sim 40$. The bow shock induced by the bump raises further the thermodynamic state in the initiation region behind the initial oblique shock from the interaction of the incoming flow with the wedge, causing an earlier OSW-ODW transition. The effect is similar to the blunt body-induced initiation [20]. With the gas dynamic effect of the micro-rounded bump in the initiation region, the transition changes into an abrupt type (see Fig. 3a). When the micro-bump is located behind the original initiation point of the base case, $x_b > x_{ini}$, the smooth transition and the initiation structure are not affected. Closer to the x_{ini} from downstream where instability on the ODW is not yet manifested with transverse waves generation, the bump may have an effect in delaying the development of instability on the ODW surface due to the overdrive from the interaction of the bow shock and the initially smooth ODW (Fig. 3c).

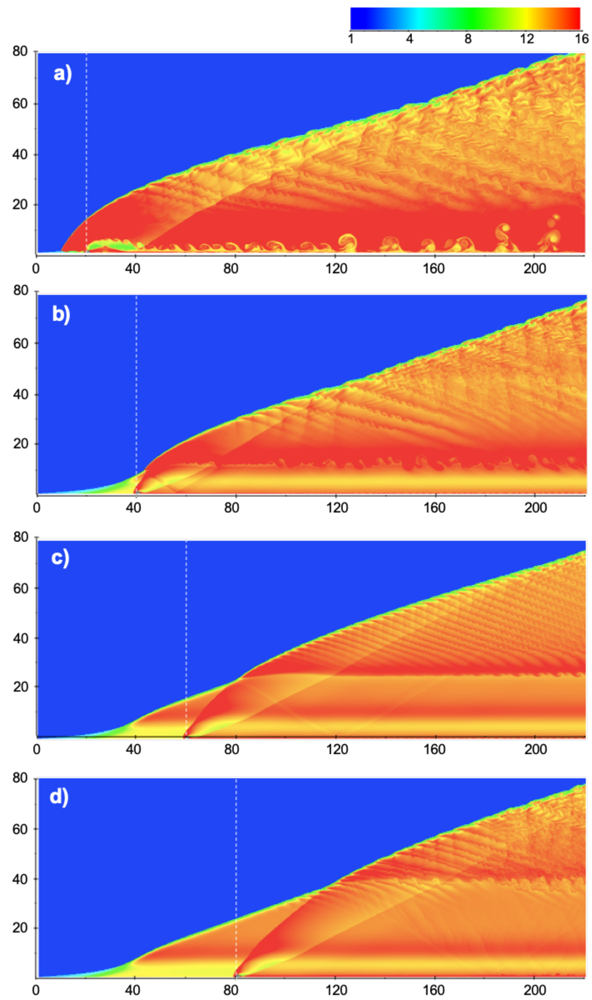

Figure 3: Temperature fields with different bump locations, a) $x_b = 20$; b) 40; c) 60; and d) 80 for $E_a = 20$.

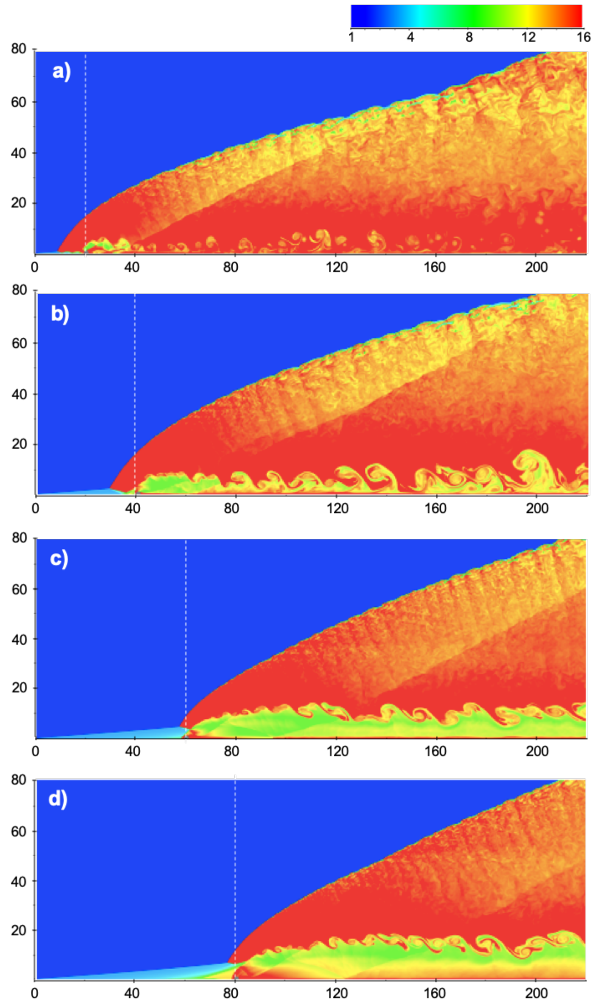

Figure 4: Temperature fields with different bump locations, a) x_b = 20; b) 40; c) 60; and d) 80 for E_a = 35.

Similarly, the effects of the micro-rounded bump and its location on the initially abrupt OSW-ODW transition for E_A = 35 are elucidated in Fig. 4. With the presence of the bump perturbation in the initiation zone $x_b \leq x_{ini} \sim 80$, the initiation structure moves forward. The wave configuration remains as an abrupt type with a multi-wave initiation point but the ODW induced is highly overdriven initially with a large oblique detonation angle. After the overdriven oblique detonation is relaxed, cellular instabilities are developed on the ODW surface. Large-scale vortex shedding has also resulted from the bump downstream close to the wedge surface.

4 Concluding Remarks

Two-dimensional numerical simulations of ODW initiation induced by a wedge with a micro-rounded bump on the surface are performed. The results show that the initiation dynamics are very sensitive to the wedge surface characteristics. The results show that within a range of bump locations, ahead of the initiation point for a smooth wedge surface, the reflected bow shock generated by the micro-bump could strengthen the initial OSW, provides a promoting effect on the transition to an ODW. The effect of the micro-bump also resulted in the change of an initially smooth transition (with E_a = 20 into an abrupt type. The bump location could also be used to delay the surface instability of the downstream established ODW. A more detailed parametric study will be carried out to look at the wedge's surface roughness given by different micro-bump locations and sizes on the different types of ODW initiation with different Mach numbers of incoming flow and wedge angles. The relationship between these parameters and the detonation dynamics will be further investigated. The present preliminary results open up an applied research direction and provide insights on how the flow perturbation by a mechanical mean to change the wedge surface topography can be considered to control the ODW initiation and its subsequent surface instability, which can influence the macroscopic dynamics of the oblique detonation.

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