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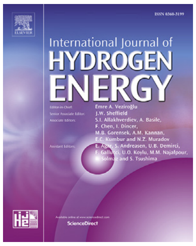

The initiation and propagation of detonation in supersonic combustible flow with boundary layer

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ABSTRACT

Adaptive simulations solving the Navier-Stokes equations have been conducted in order to get a better understanding on the detonation initiation and propagation in a stoichiometric $H_2/O_2/Ar$ supersonic mixture with boundary layer. The detonation is initiated by a continuous hot jet. When reflecting on the wall, the jet induced bow shock interacts with the boundary layer and forms the shock boundary layer interaction phenomena, while in Euler result the bow shock forms Mach reflection. The investigation shows that the Navier-Stokes simulation result is structurally in better agreement with the experiment compared with that of the inviscid Euler simulation result. The bow shock interacts with the separation shock, forming the shock induced combustion behind the interaction zone. Then the combustion front couples with shock and forms Mach stem induced detonation. The Mach stem induced detonation continues to getting higher and propagating upstream, initiating the main flow. The initiated partial detonation exists with the separation shock induced combustion front, forming an “oblique shock induced combustion-partial detonation” structure in the main flow. The investigation on the influence of free stream Mach number further confirms that the boundary layer has an important influence on detonation initiation. The parametric studies also show that there exists a free stream Mach number range to initiate the partial detonation in supersonic combustible flow successfully.

Introduction

A detonation is a coupled shock and combustion wave propagating through a reactive mixture with supersonic speed [1]. The detonative combustion process is Fickett-Jacobs cycle, while the deflagrative combustion process is isobaric Brayton-Joule cycle. The thermodynamic efficiency of the Fickett-Jacobs cycle is more than 22% higher than that of the Brayton-Joule cycle [2]. The inherent theoretical advantage of detonative combustion over deflagrative combustion greatly motivates detonation investigations for advanced propulsion systems such as pulse detonation engines [3–9], rotating detonation engines [10–17] and detonation based supersonic combustors [18–21].

Detonation initiation is one of the most important issues in detonation applications [22]. While direct initiation [23,24] can realize initiation quickly but is not generally applicable, an alternative approach for the detonation initiation is to use a hot jet [25]. Numerous studies have been conducted using a

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hot jet in quiescent combustible mixtures [26–33], but only a few investigations have been conducted in supersonic combustible mixtures. Detonation initiation and propagation using a hot jet were studied experimentally by Ishii et al. [34] in high speed combustible mixtures whose Mach numbers were 0.9 and 1.2. Han et al. [35,36] conducted experiments on detonation initiation and deflagration-to-detonation transition (DDT) process using a hot jet in supersonic combustible mixtures with Mach numbers 3.0 and 4.0. Their results confirm that detonations can be initiated through shocks or shock reflections [37–39] on the walls induced by the hot jet in a supersonic flow. Liang and Cai et al. [18,40–42] have conducted a series of numerical simulations to investigate detonation initiation using a hot jet in supersonic combustible mixtures with the adaptive mesh refinement open source program AMROC (Adaptive Mesh Refinement in Object-oriented C++) [43–47]. These numerical simulations solved the two-dimensional and three dimensional reactive Euler equations and applied a classical second-order accurate MUSCL-TVD (Monotone Upstream centered Schemes for Conservation Laws-Total Variation Diminishing) scheme with both a simplified reaction model [46] and a detailed reaction model [48].

It should be noted that most of the numerical investigations [40–42] studied detonation initiation in supersonic mixtures by solving the Euler equations and ignored the physical viscosity. Solving the reactive Navier-Stokes equations in detonation simulations has become an interesting topic [49–52]. Most of the studies focused on quiescent gases or low-speed gases. In shock tube experiments with combustible mixtures, the boundary layer back of the shock interacts with the reflected shock and forms the bifurcated shock which may have some influences to the DDT process. Oran et al. [53] found the formation of a bifurcated shock with an attached flame explaining the strange wave that is observed in shock tube DDT experiments. Gamezo et al. [54] found the shock-flame interactions occur in the presence of boundary layers. The presence of boundary layers cause the reflected shock to bifurcate and form a reactive shock bifurcation (RSB) in the 3D simulation which is different from 2D results. Gamezo et al. [55] examined the effects of bifurcated shock structures on shock-flame interactions and deflagration-to-detonation transition (DDT) in shock-tube experiments. They found that the presence of a bifurcated structure leads to an increase in the energy-release rate, the formation of Mach stems in the middle of the shock tube, and creation of multiple hot spots behind the Mach stem, thus facilitating DDT. If the coming flow is supersonic combustible mixtures, there will form boundary layer, which should be taken into account. Therefore, understanding the detonation initiation and propagation with the influence of boundary layer is important for detonation physics in supersonic flow. Besides, previous experimental observations [34–36] found that, because of the influence of boundary layer, the upstream detonation velocity is much greater than the Chapman–Jouguet (CJ) detonation velocity. Thus solving the reactive Navier-Stokes equations can give a better understanding of the detonation initiation in supersonic combustible mixtures.

In the present study, in order to investigate detonation initiation and propagation with the influence of the boundary layer in a stoichiometric $H_2/O_2/Ar$ supersonic mixture, the reactive Navier-Stokes equations are solved with detailed reaction model [48] utilizing the adaptive mesh refinement program AMROC. This work is part of an ongoing research program, aiming at providing information to help and to improve the comprehensive understanding of detonation initiation and propagation in supersonic combustible mixtures using a hot jet.

The remainder of this paper is organized as follows: the calculation method is presented in Section "Calculation method". The verification of adaptive mesh refinement is given in Section "Verification of adaptive mesh refinement". Results of detonation simulation are discussed in Section "Results", in which the initiation process and propagation character in supersonic mixture with the influence of boundary layer are studied. Finally, Section "Conclusions" presents the conclusions of the paper.

Calculation method

Mathematical model

As shown in Fig. 1, numerical simulations of detonation initiation in the supersonic combustible mixture with a hot jet are conducted in two-dimensional channel. In Fig. 1, X1 = 8 cm, Y1 = 3 cm, X2 = 3.1 cm, X3 = 0.4 cm. The lower wall adopts the nonslip adiabatic wall condition. The inflow of the hot jet is embedded within the upper domain boundary. From previous experiment observation [35], a hot jet which ejects into the supersonic flow will induce a bow shock. The boundary layer on the upper wall has little influence on the initiation process. The detonation is initiated via the reflecting of the bow shock on the lower wall. Here we focus on the influence of boundary layer on the lower wall and ignore the boundary layer on the upper wall. Therefore, for the economy of grid resolution spending for the upper wall, the upper wall here adopts the slip adiabatic wall condition for simplify. The left boundary models the ideal outflow condition, which ignores the influence of backpressure. The right boundary models the supersonic inflow condition.

Numerical simulations [56] and experimental observations [57–59] indicate the existence of two types of detonation structures which are usually classified as regular (weakly

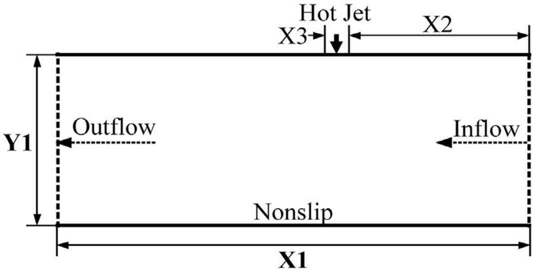

Fig. 1 – Schematic of calculation domain.

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