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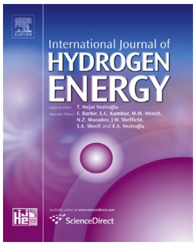

Adaptive simulations of detonation propagation in 90-degree bent tubes

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ABSTRACT

The open-code adaptive mesh refinement program AMROC was adopted to conduct numerical simulations of detonation propagation in 90° bent tubes. Propagation modes in bent tubes, the mechanism of detonation restored to stable propagation and effects of curvature radius on detonation restoration were explored in depth. Results indicate that with the increase of initial pressure and inner wall curvature radius, detonation propagation undergoes a transition from the unstable mode to the transition mode, and finally the stable mode. The critical conditions for mode transition among the unstable mode, the transition mode and the stable mode are $r_0/\lambda = 13.7$ and $r_0/\lambda = 22.3$, respectively, where λ is the cellular width. In the unstable and transition modes, when the detonation crosses through the bent section, the detonation structure is destroyed. However, the generated Mach reflection can induce the formation of new transverse waves to realize re-initiation and the collision between two triple points can enhance the strength of the detonation gradually, which can cooperatively promote detonation restoration to self-sustained propagation. The curvature radius not only has an influence on the formation of the transverse wave, but also makes an impact on the position where the triple point of Mach reflection collides on the outer wall. The colliding position has an effect on collisions among triple points, which can influence detonation restoration eventually.

Introduction

Detonation is a self-sustaining supersonic combustion wave where the shock and the reaction front are coupled together. It holds almost the same thermodynamic characteristics as constant-volume combustion [1], and the thermodynamic efficiency is much higher than that of constant-pressure combustion, which contains good application prospects in hypersonic propulsion systems [2–4]. Detonation initiation has always one of the key points of detonation investigation. There are two main methods to initiate detonation: direct initiation [5,6] and DDT (Deflagration-to-Detonation Transition) [7]. Compared with direct initiation, the DDT process needs lower ignition energy. Therefore, the DDT is extensively applied for detonation initiation.

To achieve detonation initiation through the DDT process, a long straight tube is usually necessary for the full flame acceleration. Recently, the high-energy hot jet in straight tubes has been generally applied to shorten the distance of flame acceleration and realize rapid initiation [8,9]. However, this straight tube design has little flexibility for assembling, which greatly imposes restriction on experimental research and application of detonation engine. For comparison, a bent tube is more flexible, and the assembly space can be utilized

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more reasonably. Considering this situation, if detonation can be realized and stabilized in a bent tube, or recuperated to stable propagation after exiting the tube, then a bent detonation tube can be employed in engineering application.

Some studies on detonation propagation have been carried out in bent tubes. In experimental researches, Thomas et al. [10] observed the detonation cellular pattern for a stoichiometric C_2H_2/O_2 mixture in 90° bent tubes with different curvature radius. The results showed that when detonation propagated into the bent section, Mach reflection was formed. When the curvature radius was small enough, the detonation wave near the inner wall would be strongly affected by expansion waves and finally the detonation failed. Frolov et al. [11–15] designed a pulse detonation engine which firstly used a spiral tube as initiator and its performance was tested. Through the test, they showed that this kind of design can shorten the engine length and needs evidently less energy for successful ignition. Kudo et al. [16] and Nakayama et al. [17,18] conducted a series of experiments in rectangular-cross-section bent tubes. They visualized the cell structure of a curved detonation using multi-frame short-time open-shutter photography (MSOP), obtained the critical condition when the detonation was stabilized in the bent tube and formulated an approximation of the curved detonation wave shape. In numerical simulations, Lee et al. [19] conducted numerical investigations of detonation propagation in annular tubes with varied radius. The results indicated that when the radius was larger than a critical value, the detonation could propagate steadily in the tube. Otsuka et al. [20] carried out simulations of detonation initiation and propagation in U-shape bent tubes to analyze the influence of tube width and curvature radius on the initiation rate. Li et al. [21] studied detonation propagation numerically by setting various bend angles and obtained the critical angle for detonation wave to propagate stably.

The related experimental observations above can provide limited insight, and meanwhile it is hard to analyze the development process of detonation wave after exiting the bent section. For detonation calculations, chemical reaction generally introduces additional temporal and spatial scales. It normally requires finer meshes than studies of nonreactive Euler equations alone. However, only a small area near the detonation front where the chemical reaction is severely accumulated needs a very high-resolution mesh, whereas other areas with relatively mild flow behavior can be resolved coarser due to the compromise of resolution and efficiency. In this paper block structured adaptive mesh refinement (SAMR) is adopted for high-resolution simulations while improving the efficiency. The structured adaptive mesh refinement technique was first proposed by Berger and Oliger [22,23], and has achieved a wide range of applications and development [24–26]. Initially developed from the DAGH code [27], AMROC [28–32] supports several Euler solvers based on total variation diminishing (TVD) and weighted essentially non-oscillatory (WENO) schemes. It has been integrated in the VTF software [33], and widely applied in multi-dimensional detonation simulations [34–39].

Here, we will employ AMROC for high-resolution simulations of detonation propagation in 90° bent tubes. By changing the initial pressure and inner wall curvature radius of the bent section, the detonation propagation modes in bent tubes will be analyzed and the critical conditions of mode transition will be investigated. Furthermore, the mechanism of detonation restored to stable propagation after exiting the bent section will be explored, and the effect of curvature radius on detonation restoration will be discussed.

Calculation model and numerical scheme

Calculation model

Two-dimensional simulations of detonation propagation are conducted in 90° bent tubes, as shown in Fig. 1 It consists of a straight inlet section, a bent section, and a straight outlet section. The width of the tube is $d = 40$ mm, the inner and outer wall of the bent section are concentric, and the bend angle is $\phi = 90°$. The length of the straight inlet section is $l_1 = 130$ mm, and the straight outlet section is long enough for detonation evolution after propagating through the bent section. The initial pressure p_0 and inner wall curvature radius of the bent section r_0 are variables. Reflecting boundary with slip conditions are used on the tube walls, and zero-order extrapolation boundary conditions are adopted on both the inlet and the outlet. The tube is filled with $H_2/O_2/Ar$ mixture with the molar ratio 2:1:7, under the condition of temperature 298 K. The detailed reaction model of 9 species (H_2, H, O, O_2, OH, H_2O, HO_2, H_2O_2, Ar) and 34 elementary reactions [40] is employed. In order to shorten the calculating time, the 2D self-sustained state of detonation under the specified initial pressure has been achieved in advance. Each parameter of the resulting detonation is imposed on the inlet domain as the initial condition. Fig. 2 shows the temperature contour and

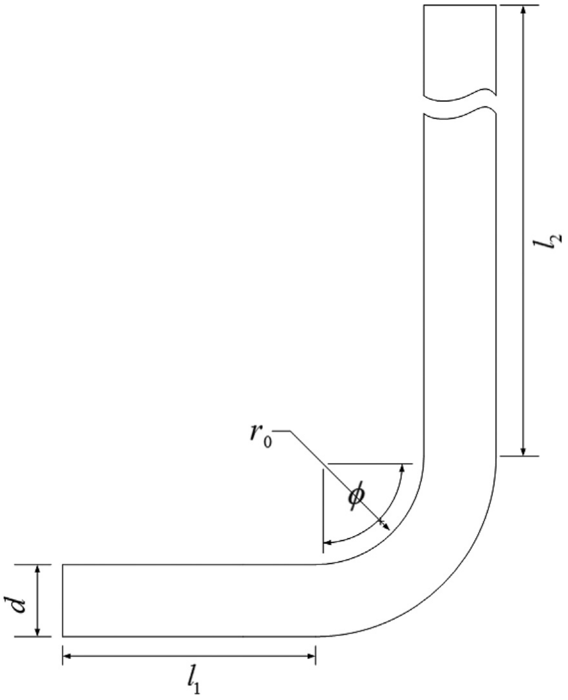

Fig. 1 – Schematic of calculation domain.