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Numerical investigation of the effect of inlet mass flow rates on H_2/air non-premixed rotating detonation wave

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ABSTRACT

In this paper, a three dimensional numerical investigation was carried out to study the formation and propagation characteristics of non-premixed rotating detonation wave using H_2/air as reactive mixtures. At a constant global equivalence ratio, the effects of inlet mass flow rates of H_2 and air on various performance parameters of rotating detonation wave and based on it combustor were analyzed in detail. On this basis, the mode switching process of rotating detonation wave caused by transiently changing the inlet mass flow rates was also discussed. The numerical results showed that inlet mass flow rates of H_2 and air played a very critical role in the formation, propagation and mode switching of rotating detonation wave. With the increase of inlet mass flow rates, rotating detonation wave could be switched from single wave to double waves. The propagation direction of double waves depended on the changing process of inlet mass flow rates. Meanwhile, compared to the single wave, double waves or its based combustor had the obvious advantages in formation time, stability and thrust, but had disadvantage in pressure ratio. In addition, both fill characteristics and mixing quality of fresh reactive mixtures are the underlying important mechanisms to explain the effects of inlet mass flow rates on rotating detonation waves.

Introduction

Deflagration combustion is a main form adopted in many existing propulsion and power systems (such as rocket engine, aeroengine and gas turbine). In recent years, with the increasingly stringent requirements on environmental protection and energy conservation, the conventional deflagration combustion has the limited potential for significantly increasing fuel efficiency and decreasing pollutant emission because of its high pressure loss, high entropy generation and low reaction rate [1,2]. How to develop the effective alternative technology to deflagration combustion has become an urgent concern.

Detonation combustion, which is a strong couplings of shock waves and chemical reactions, provides an unprecedented opportunity for combustion enhancement owing to its

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unique capabilities of low entropy generation, pressure gain, rapid chemical energy release, etc. [3–5]. Nowadays, according to the propagation characteristic of detonation wave, there are three typical forms to achieve the applications of detonation combustion in propulsion, which are named pulsed detonation engine (PDE) [6], oblique detonation engine (ODE) [7] and rotating detonation engine (RDE) [8]. Compared to the former two, RDE is a novel propulsion concept which utilizes one or multiple detonation waves propagating around the annular channel continuously to produce steady thrust. Because of its obvious advantages in high thermal efficiency [9,10], continuous presence after one ignition [11,12], uniform exhaust gas [13], easy for integration and control [14], RDE attracted a great deal of attentions over the past decades. Lu and Braun [8], Kailasanath [15], Zhou et al. [16], Rankin et al. [17] and Nejaamtheen et al. [18] respectively reviewed the research progress of RDE from different views. As shown in their studies, most of the published research indicated that RDE had the attractive thermal cycle performance when compared with the traditional Brayton cycle based engine. For example, the researchers from U.S. Naval Research Laboratory reported that RDE had the potential to meet 10% increased power requirements as well as 25% reduction in fuel cost for future navy application, which could save approximately 300–400 million dollars a year [19].

Essentially, rotating detonation is a kind of supersonic combustion involving the complex chemical reactions and wave series [20,21]. The strong coupling interactions between detonation waves, shear layer and oblique shock waves leading to the propagation stability and control of rotating detonation wave (RDW) have become one of the biggest challenges for RDE application [22]. Kindracki et al. [23], Liu et al. [24], Lin et al. [25,26], Yang et al. [27], Anand et al. [28], Wang et al. [29], Rankin et al. [30], Wang et al. [31], Naples et al. [32], Deng et al. [33] experimentally investigated the propagation characteristics of various RDW under different operating conditions. Their results consistently showed that the formation, propagation and evolution of RDW were closely related to both the injection configuration of reactants (mass flow rate, equivalence ratio and mixed uniformity, etc.) and the geometrical structures of combustor (channel width, nozzle obstacle shape). And the unstable propagating processes of RDW were observed when the operating conditions were changed transiently. On these basis, Anand et al. [34], Wang et al. [35], Zhang et al. [36], Zhou et al. [37] respectively studied the effects of various reactant or geometry parameters on RDW instability. They experimentally found that the changing of RDW number was one of the most typical instability phenomena for the annular RDE. Further, the experiments of Bykovskii et al. [38], Falempin et al. [39] and Suchocki et al. [40] revealed that with the increase of inlet mass flow rate, the propagation modes of RDW could be switched from single wave to multiple waves. However, it is worth pointing out that due to the lack of sufficient visual experiments, few studies presented the available explains for the above phenomena.

As an effective computational approach, numerical simulation can help to further understand the effects of various factors on RDW performance by analyzing the detailed combustion field information. Considering the non-premixed process of fuel and oxidant in RDE, Driscoll et al. [41,42] numerical analyzed the injection flow field characteristic of combustor under different reactant flow rates, injection areas, and fuel injection placement. Their results showed that all of the above three factors could significantly affect the local equivalence ratio and the propagation of RDW. Deng et al. [43] conducted a two-dimensional simulation model to study the degeneration problem of H_2/Air RDW from two waves to single wave and thought that the decrease of fuel supply played a key role. Also selecting the two-dimensional numerical approach, Xia et al. [44] presented a detailed analysis to understand the effects of geometry parameters and stagnation pressure on propagation mode of RDW. As shown in their investigation, the changing of operating condition could cause the unstable propagation of RDW and re-initiation. Based on the three dimensional numerical simulations, Wu et al. [45,46] studied the transition process of RDW using the premixed stoichiometric H_2/Air mixtures as reactant. It was found that the sudden changing of inlet parameters had an obvious influence on RDW propagation modes, and the increase of detonation wave numbers could enhance the stability and repeatability of detonation initiation. Using the same numerical approach and reactant, Yao et al. [47,48] discussed the possible ways to form the multiple detonation wave fronts in RDE and pointed out that the local explosion caused by the complex collisions between detonation waves might be a very important mechanism. Based on the experiment of Rankin et al. [49], Yellapantula et al. [50] numerically studied the effects of inlet mass flow rates of H_2/Air on propagation modes of RDW. Their results indicated that at a constant global equivalence ratio of 1, the higher inlet mass flow rates of H_2/Air could increase the filling height in the annulus channel, which leaded to a bifurcation of one detonation front into two detonation fronts. Moreover, to the best of authors' knowledge, although many available papers have been published to investigate the propagation characteristics of various RDW, very limited three dimensional numerical studies were performed to discuss the formation and propagation characteristics of non-premixed RDW under different H_2/air injection conditions. This leads that the following three questions are still not be answered clearly. (1) For the non-premixed RDW, really can its number be affected by the inlet mass flow rates of reactive mixtures (especially for the transient variation) as same as the premixed one? (2) If so, how it will be changed for the typical parameters of non-premixed RDW and its based combustor? (3) What are the main mechanisms that can be explained the formation, propagation and mode switching characteristics of RDW? In view of these, a three dimensional numerical investigation which could reflect the actual injection of reactive mixtures in RDE experiment or application was carried out in the present study. Then, considering the effects of inlet mass flow rates of reactive mixtures at a constant global equivalence ratio, much detailed information of RDW involving the formation and propagation process, the characteristics and mechanisms of single and double RDW were discussed. On this basis, the performance of combustor with different RDW numbers was also compared and discussed.