Numerical study on the unsteady rotating detonation flow-field interacted with turbine guide vane

Dawen Shen, Miao Cheng, Kevin Wu, Zhaohua Sheng, Jianping Wang*
Center for Combustion and Propulsion, CAPT & SKLTCS, Department of Mechanics and Engineering Sciences, College of Engineering, Peking University
Beijing 100871, China

1 Introduction

Pressure gain combustion promises to be an alternative to conventional isobaric combustion due to reduced entropy generation and higher thermodynamic efficiency. Over the last several decades, the rotating detonation engine (RDE) using this novel combustion concept has attracted worldwide attention. Among several practical applications, attempts have recently been made to realize its integration with turbine-type engines [1], [2]. However, characterized by strong high-frequency pressure, temperature, and velocity fluctuations, the unsteady exhaust flow-filed in RDEs poses a threat to the downstream turbomachinery. An RDE equipped with turbine guide vanes (TGVs) has been proposed to alleviate these fluctuations, with its feasibility verified numerically [3]–[5] and experimentally [6]–[8]. Additionally, the presence of a set of TGVs serves to condition the flow angle before impacting on the rotor and extract the inherent tangential kinetic energy in RDEs.

The current study focuses on the effects of three kinds of TGV configurations with different inclination angles on the flow-field in RDEs. Besides, the aerodynamic performance between every configuration is compared and analyzed in terms of total pressure loss and damping of fluctuations.

2 Numerical method

RDE combustor chamber is typically coaxial annular, where rotating detonation waves (RDW) propagate circumferentially. Considering the radial dimension is rather smaller compared to the azimuthal and axial dimensions, the effect of chamber width can be neglected and the flow-field in RDE can be treated as two-dimensions. In this study, the computational domain is 125.66 mm in circumferential and 90 mm in the axial direction, configured with turbine guide vanes of different angles of attack. The unstructured grid size is 0.15 mm in every case, with a total of around 1.2 million in each case.

Premixed kerosene surrogate fuel (C10H20)/air mixture is injected into the combustor with equivalence ratio $\varphi = 1$, total temperature T_{inlet} = 1300 K, and total pressure P_{inlet} = 0.6 MPa. Two-dimensional Euler equation is solved through an in-house solver, BYRFoam [9], based on the open-source computational fluid dynamics platform OpenFOAM®.

Correspondence to: wangjp@pku.edu.cn

3 Results and discussion

As shown in Fig.1, four cases have been numerically simulated, namely base case, case 1, case 2, and case 3. Specifically, base case is simply a rotating detonation wave (RDW) propagation without any TGV. Case 2 is configured with a row of 9 TGVs inclined by an angle of 0^0. While for case 2 and case 3, 9 TGVs are both inclined 10^0, but the detonations propagate in opposite directions, corresponding to the "misaligned" and "aligned" configuration (named by Bach et al. [6]). Note that Blue, red, black, and green solid lines represent axial position = 15 mm, 30 mm, 45 mm, and 85 mm respectively. The pressure fluctuations at 4 different axial positions are first space-averaged and then integrated over an RDW propagation period, eventually tabulated in Tab.1.

Where the amplitude of pressure fluctuations in a period is defined as:

$$A = \frac{p_{Max} - p_{Min}}{p_{Mean}}$$

It can be observed that the configuration in case 3 has the most significant damping effect on pressure fluctuations, showing an agreement with practical experiments [6].

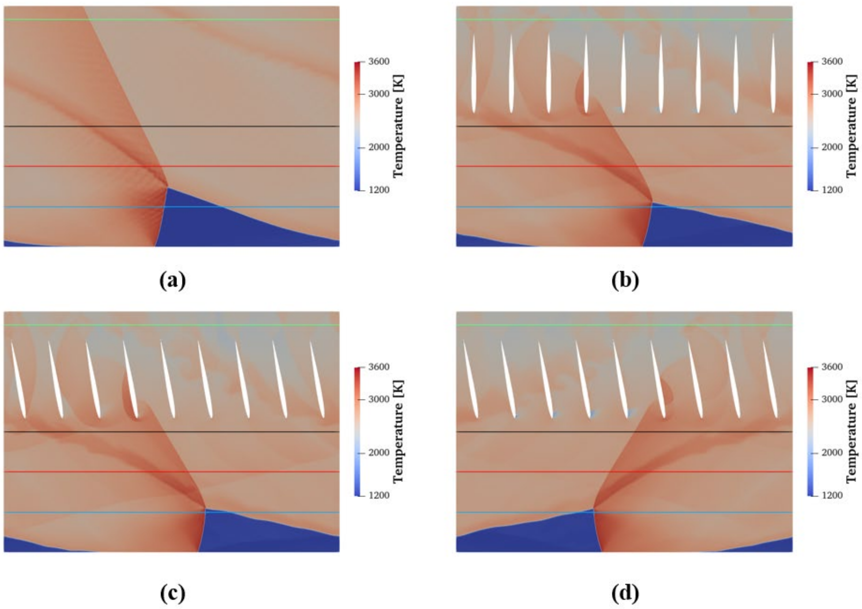

Figure 1: Temperature contour in (a) base case (b) case 1 (c) case 2 (d) case 3.

Table 1: The amplitude of pressure fluctuations in different cases

Cases \ Axial Position	15 mm	30 mm	45 mm	85 mm
Case 1	5.51	1.31	1.06	0.89
Case 2	5.87	1.37	1.02	0.92
Case 3	5.76	1.30	1.10	0.73

In all three cases equipped with TGVs, a novel shock wave system is generated and termed rake-type shock envelope. Since the formation and evolution of this shock system are similar in the 3 cases, here we specifically analyze that in case 1, as shown in Fig.2. The flow-field structure near the injection plane contains a detonation front, the attached oblique shock, and post-detonation expansion fans. While in the flow-field upstream of the leading edge of TGVs, a rake-type shock envelope is formed continuously and propagates towards the head end.

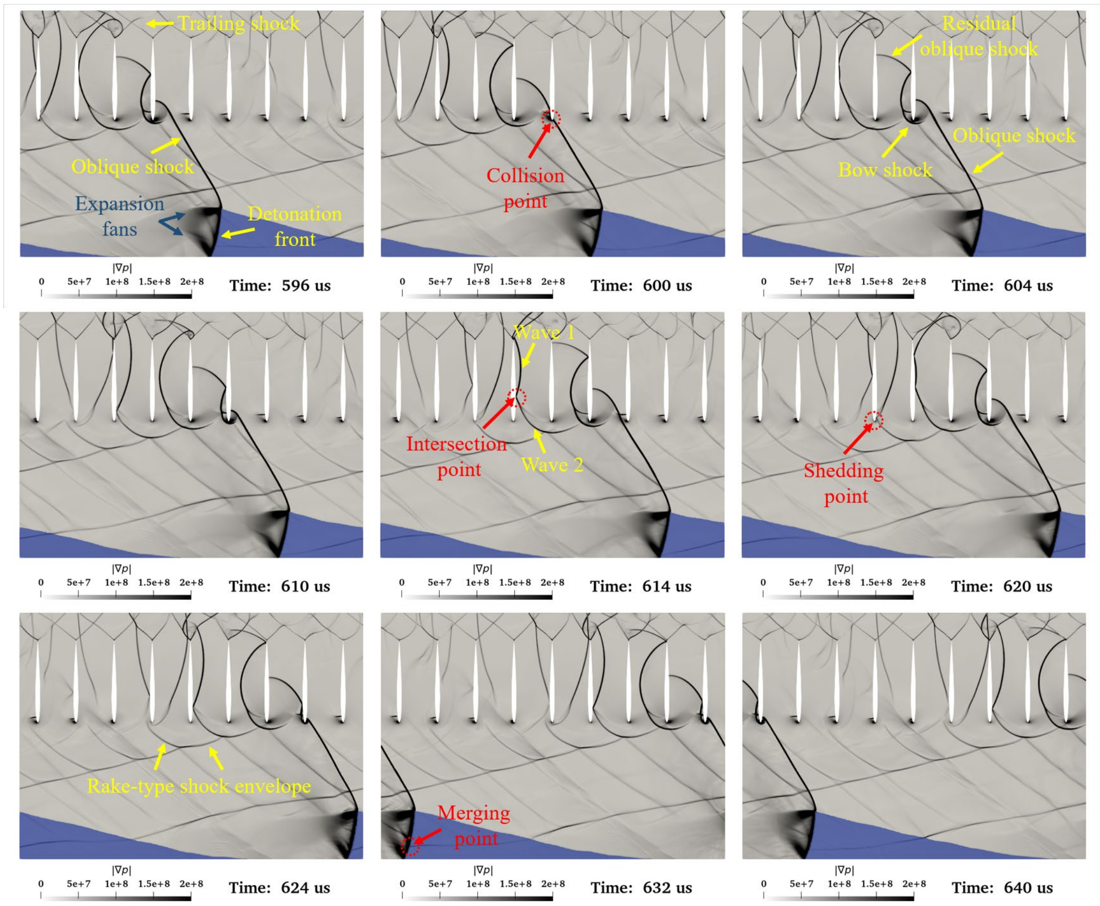

Figure 2: The formation and evolution of rake-type shock envelope.

Total pressure ratio is first instantaneously mass-flow-averaged and then time-averaged over a periodic cycle, calculated by the following equation.

$$\varepsilon = P_{t,average}^{MFA} / P_{t,average}^{MFA,inlet}$$

Where the superscript "MFA" denotes mass-flow-averaged.

It can be seen in Fig.3 that the aligned configuration (case 3) outperforms the others (case 1 and case 2). The weaker RDW intensity in case 1 causes poorer self-pressurized capacity, yielding consistently lower total pressure than the other two cases. For case 2 and case 3, the RDW of comparable intensity contributes to the virtually equal total pressure upstream of the TGVs' leading edges; while in the TGV passage region, the shock system in each case develops uniquely, yielding different intensity and existing time. Overall, the difference in formation and evolution of this shock system generated by the interaction between oblique shock and downstream TGVs results in different extents of total pressure loss in TGV passages, which will be discussed in the future study.

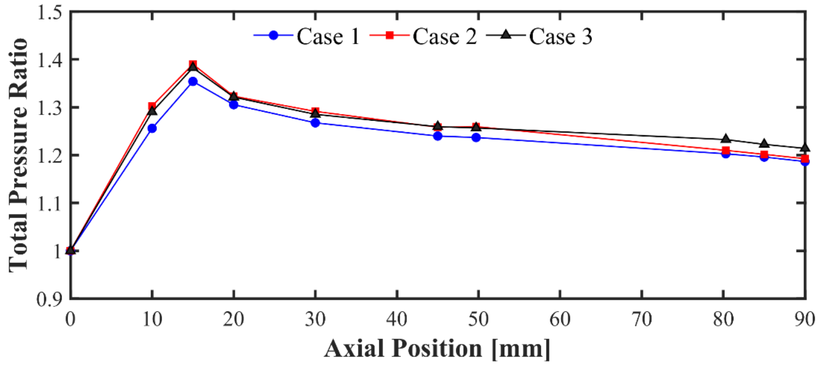

Figure 3: Profiles of total pressure ratio along RDE axial positions in 3 cases equipped with TGVs.

4 Conclusions

Two-dimensional Euler-equation simulations in RDEs fueled by C10H20/air mixture have been performed to provide important insights into the RDE flow-field and its interaction with various instrumented TGV configurations. The main conclusions are drawn as follows:

1) TGV plays a vital role in alleviating flow-field unsteadiness in terms of pressure, temperature, and velocity fluctuations. Furthermore, TGV manages to condition flow and make full use of the circumferential kinetic energy generated by the RDW.

2) A rake-type shock envelope is obtained and this shock wave system promises to solve the typical unstarting issue in supersonic turbines.

3) RDW intensity and shock development between TGV passages are considered as the main factors resulting in the difference of total pressure loss in every case.

References

[1] A. Naples, J. Hoke, R. Battelle, and F. Schauer, “T63 Turbine Response to Rotating Detonation Combustor Exhaust Flow,” *J. Eng. Gas Turbines Power*, vol. 141, no. 2, p. 021029, Feb. 2019, doi: 10.1115/1.4041135.

[2] P. Wolański, “Application of the Continuous Rotating Detonation to Gas Turbine,” *Appl. Mech. Mater.*, vol. 782, pp. 3–12, Aug. 2015, doi: 10.4028/www.scientific.net/AMM.782.3.

[3] M. Asli, P. Stathopoulos, and C. O. Paschereit, “Aerodynamic Investigation of Guide Vane Configurations Downstream a Rotating Detonation Combustor,” *J. Eng. Gas Turbines Power*, p. 24.

[4] J. Braun *et al.*, “Characterization of an integrated nozzle and supersonic axial turbine with a rotating detonation combustor,” presented at the AIAA Propulsion and Energy 2019 Forum, Indianapolis, IN, Aug. 2019. doi: 10.2514/6.2019-3873.

[5] Z. Liu, J. Braun, and G. Paniagua, “Characterization of a Supersonic Turbine Downstream of a Rotating Detonation Combustor,” *J. Eng. Gas Turbines Power*, vol. 141, no. 3, p. 031501, Mar. 2019, doi: 10.1115/1.4040815.

[6] E. Bach, C. O. Paschereit, P. Stathopoulos, and M. D. Bohon, “Rotating Detonation Wave Direction and the Influence of Nozzle Guide Vane Inclination,” *AIAA J.*, pp. 1–12, Aug. 2021, doi: 10.2514/1.J060594.

[7] S. Zhou, H. Ma, S. Li, D. Liu, Y. Yan, and C. Zhou, “Effects of a turbine guide vane on hydrogen-air rotating detonation wave propagation characteristics,” *Int. J. Hydrog. Energy*, vol. 42, no. 31, Art. no. 31, Aug. 2017, doi: 10.1016/j.ijhydene.2017.06.115.

[8] W. Wei, Y. Wu, C. Weng, and Q. Zheng, "Influence of propagation direction on operation performance of rotating detonation combustor with turbine guide vane," *Def. Technol.*, p. S221491472030427X, Aug. 2020, doi: 10.1016/j.dt.2020.08.009.

[9] Z.-J. Xia, "Numerical investigation of pre-detonator in rotating detonation engine," p. 11.