Experimental Verification of Rotating Detonation Engine with Film Cooling

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Abstract

We conduct an experimental investigation on the integration of film cooling for thermal protection in a 72-mm cylindrical rotating detonation engine (RDE). The cooling scheme employs the injection of cooling air through a series of cat-ear-shaped film cooling holes densely distributed along the outer wall of the cylindrical combustor. Our findings reveal successful initiation of the RDE and sustained propagation of the rotating detonation wave (RDW) when film cooling is activated.

Full Text

Preamble

LETTER

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Experimental Verification of Rotating Detonation Engine with Film Cooling

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Abstract

This letter reports an experimental investigation of film cooling integration for thermal protection in a 72-mm cylindrical rotating detonation engine (RDE). The cooling scheme injects cooling air through a series of cat-ear-shaped film cooling holes densely distributed along the outer wall of the cylindrical combustor. Our findings demonstrate successful RDE initiation and sustained propagation of the rotating detonation wave (RDW) when film cooling is activated, with the outflow reaching a supersonic state. Experimental observations corroborate numerical simulations, revealing a lateral expansion tendency of the cooling jet under the influence of the high-frequency RDW.

The rotating detonation engine represents a revolutionary technology that has garnered global attention in aerospace propulsion due to its pressure gain combustion (PGC) characteristics, rapid heat release, and superior thermodynamic cycle efficiency compared to conventional deflagration-based systems [1, 2]. These attributes make RDEs highly promising for aerospace applications, as evidenced by recent experimental studies [3-8]. However, detonation constitutes an extreme combustion phenomenon, and the associated high-frequency thermal loads [9, 10] can cause severe wall ablation within the combustion chamber. Consequently, implementing effective thermal protection measures is paramount for advancing RDEs toward practical engineering applications.

Several recent efforts have addressed this challenge. Goto et al. [11] employed a sidewall injection scheme with 24 pairs of propellant injectors for temperature control. Tian et al. [12] used numerical simulation to examine interactions between cooling air from cylindrical film holes and the rotating detonation flow field, finding that while cooling air did not significantly affect RDW propagation, the RDW periodically obstructed normal cooling air outflow. Yu et al. [13] evaluated the cooling efficiency of cylindrical film holes under various primary flow (hydrogen and propellant air) and secondary flow (cooling air) mass flow rates, revealing that increased cooling air mass flow substantially expanded the axial coverage area of cooling air on the outer wall. Li et al. [14] numerically analyzed cooling performance for five cylindrical film hole configurations with different aspect ratios on both inner and outer walls of an RDE with a Laval nozzle, identifying an optimal combination of film hole arrangement, injection parameters, and nozzle configuration that balanced cooling and aerodynamic performance. Li et al. [15] further investigated two-phase RDW flow fields with film cooling. As an efficient cooling method widely used in turbine blades, film cooling offers notable advantages in flexibility and compatibility.

Despite these advances, experimental verification of film cooling feasibility for RDEs remains scarce. This study therefore conducts experiments to verify ignition and operation of a cylindrical RDE equipped with complex-shaped holes for film cooling.

The cylindrical rotating detonation combustor (RDC) has an outer diameter of = 72 mm and length of = 87.5 mm, as shown in Fig. 1 [Figure 1: see original paper]. The cylindrical configuration offers an additional advantage for film cooling implementation [15-18] by eliminating the need for thermal protection of an inner cylinder, requiring film cooling holes only on the outer wall. The RDC features a Laval nozzle with an exit-to-throat area ratio of 9. Hydrogen and air are injected at ambient temperature using a conventional orifice-slot design, comprising 200 hydrogen injection orifices (0.5 mm diameter) and an air slot measuring 0.6 mm in width. The outer wall surface (thickness $\delta =$ 1.5 mm) is machined using femtosecond laser technology to incorporate cat-ear-shaped film cooling holes, a design proven to significantly enhance film cooling effectiveness through comprehensive optimization and analysis [19]. This shaped configuration enlarges the protected area and improves cooling jet adherence to the wall through the formation of anti-counter-rotating vortices [20]. The film holes are inclined at 30° relative to the RDC axial direction, arranged in 13 circumferential rows spaced 5 mm apart vertically, with 30 holes per row. This yields 390 film holes densely distributed over the 304 stainless steel outer wall. The geometry and schematic of the cat-ear-shaped film hole are detailed in our previous study [21].

Figure 1: Cylindrical RDE with cat-ear-shaped film cooling holes: (a) front view and (b) device.

The hydrogen-fueled RDE is ignited using an automotive spark plug. Cooling air is injected for 1 s at a constant mass flow rate of approximately 100 g/s prior to ignition and maintained constant thereafter. In Shot No. 1, the RDE operates for 0.5 s post-ignition. A high-frequency piezoresistive pressure transducer mounted adjacent to the outer wall on the headwall side (see Fig. 1) acquires RDW pressure signals. In Shot No. 2, operation duration is extended to 2 s with cooling air mass flow increased to 120 g/s, though pressure transducers are removed to prevent high-temperature damage.

Test conditions are summarized in Table 1 .

Table 1: Working conditions (mass flow rates) of the test shots.

Hydrogen (g/s)	Air (propellant) (g/s)	Air (cooling) (g/s)
Shot 1		100
Shot 2		120

Pressure signals from Shot No. 1 are presented in Fig. 2 [Figure 2: see original paper], showing segments of stable detonation operation. Magnified local views of pressure traces at different stages demonstrate sustained RDE operation. Periodic peak amplitudes from the detonation wave are below 0.5 MPa initially, increasing to approximately 1.0 MPa during subsequent propagation. The pressure signals undergo high-pass filtering followed by fast Fourier transform (FFT) and short-time Fourier transform (STFT) analyses. The FFT result reveals a dominant frequency of approximately 10 kHz, corroborated by STFT results showing this frequency remains constant after RDW establishment. Combined with the phase angle from another sensor installed 90° apart azimuthally, calculations indicate a detonation wave speed of 2271 m/s in single-wave combustion mode, closely matching the 2194.6 m/s reported by Zhang et al. [22], who noted potential differences in RDW behavior between annular and cylindrical configurations, with the latter showing potential for overdriven detonation.

Figure 2: Pressure trace records and FFT analysis of Shot No. 1.

For Shot No. 2, which runs for 2 s, Fig. 3 [Figure 3: see original paper] presents the time sequence and static pressure variations in the combustor and cooling air manifold. Post-ignition, combustor static pressure remains nearly constant at approximately 0.5 MPa, while cooling air manifold pressure increases slightly until cutoff. Figure 4 [Figure 4: see original paper] compares exhaust plume photographs from both shots. Mach diamonds visible in both plumes indicate supersonic jet formation under both operating conditions.

Figure 3: Time sequence and static pressure measurements in Shot No. 2.

Figure 4: Exhaust plumes: (a) Shot No. 1 and (b) Shot No. 2.

The inner surface of the outer wall after Shot No. 2 is shown in Fig. 5 Figure 5: see original paper. Cooling air traces are clearly evident through temperature differences in burn marks (see magnified region), with wall surfaces near film cooling holes receiving better protection. Additionally, the cooling jet exhibits lateral swinging under RDW influence. These experimental findings align well with our previous numerical results [21] shown in Fig. 5(b). As the RDW passes a film hole, the cooling jet swings toward the RDW propagation direction. Since the detonation wave velocity is several times greater than the cooling air velocity, these interruptions do not significantly affect RDW velocity.

Figure 5: Film cooling air patterns within the rotating detonation flow field: (a) outer wall surface condition after operation, and (b) simulation result from Yu et al. [21].

In conclusion, our experimental investigation of film cooling integration for thermal protection in a cylindrical RDE has yielded promising results. Successful RDE initiation and sustained propagation during film cooling activation are demonstrated for both short and longer duration tests. With cooling jets entering through cat-ear-shaped film holes on the outer wall, the RDE operates stably with supersonic exhaust outflow. The experimental findings validate numerical predictions of cooling jet behavior in the RDW flow field. Future work should conduct more comprehensive investigations to evaluate film cooling performance quantitatively.

References

[1] J.Z. Ma, M.Y. Luan, Z.J. Xia, J.P. Wang, S.J. Zhang, S.B. Yao, B. Wang, AIAA Journal, 58 (2020)

[2] V. Raman, S. Prakash, M. Gamba, Annual Review of Fluid Mechanics, 55 (2023) 639-674.
[3] S. Gray, M. McLoughlin, G. Ciccarelli, Combustion and Flame, 260 (2024).
[4] S. Zhou, Y. Ma, F. Liu, N. Hu, Fuel, 354 (2023).
[5] X. Yang, Y. Wu, F. Song, J. Zhou, H. Liu, S. Xu, X. Chen, Experimental Thermal and Fluid Science, 146 (2023).
[6] Y. Wu, G. Xu, C. Ding, C. Weng, Physics of Fluids, 35 (2023) 016128.
[7] C. Knowlen, T. Mundt, M. Kurosaka, Shock Waves, (2023).
[8] M. Kawalec, P. Wolański, W. Perkowski, A. Bilar, Journal of Propulsion and Power, (2023) 1-8.
[9] Y. Qiu, Y. Wu, Y. Huang, Q. Li, C. Weng, Physics of Fluids, 36 (2024) 016131.
[10] D. Lim, S.D. Heister, J. Humble, A.J. Harroun, Journal of Spacecraft and Rockets, 58 (2021) 1444-
[11] K. Goto, K. Ota, A. Kawasaki, N. Itouyama, H. Watanabe, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, H. Kawashima, Journal of Propulsion and Power, 38 (2022) 410-420.
[12] J. Tian, Y.-s. Wang, J.-z. Zhang, X.-m. Tan, Aerospace Science and Technology, 122 (2022).
[13] J. Yu, S. Yao, J. Li, Y. Huang, C. Guo, W. Zhang, International Journal of Hydrogen Energy, 48 (2023) 9082-9094.
[14] R. Li, J. Xu, H. Lv, D. Lv, J. Song, Aerospace Science and Technology, 136 (2023) 108221.
[15] J. Li, J. Yu, J. Li, Y. Lei, S. Yao, W. Zhang, Physics of Fluids, 36 (2024).
[16] R. Wiggins, A. Gaetano, T. Pritschau, J. Betancourt, V. Shaw, V. Anand, E. Gutmark, AIAA Journal, (2022) 1-11.
[17] S.-Y. Huang, J. Zhou, S.-J. Liu, H.-Y. Peng, X.-Q. Yuan, H.-L. Zhang, Combustion and Flame, 248 (2023).
[18] G. Rong, M. Cheng, Z. Sheng, X. Liu, Y. Zhang, J. Wang, Physics of Fluids, 34 (2022) 056104.
[19] K. Kusterer, N. Tekin, D. Bohn, T. Sugimoto, R. Tanaka, M. Kazari, in: ASME Turbo Expo 2012: Turbine Technical Conference and Exposition, 2012, pp. 1299-1310.
[20] K. Kusterer, A. Elyas, D. Bohn, T. Sugimoto, R. Tanaka, M. Kazari, in: ASME 2011 Turbo Expo: Turbine Technical Conference and Exposition, 2011, pp. 303-313.
[21] J. Yu, S. Yao, J. Li, J. Li, C. Guo, W. Zhang, Aerospace Science and Technology, (2023) 108642.
[22] H. Zhang, W. Liu, S. Liu, International Journal of Hydrogen Energy, 41 (2016) 13281-13293.

Note: Figure translations are in progress. See original paper for figures.