Investigations of Film Cooled Rotating Detonation Combustor

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Abstract
Detonative combustion offers a pathway to developing high-power-density combustors, such as the Rotating Detonation Combustor (RDC). In RDCs, the combination of high mass flow rates and intense heat release from detonation waves occurring near the narrow annulus walls generates substantial thermal loads. Effectively managing these thermal loads is critical for the successful integration of RDCs into gas turbine systems. While prior studies have indicated that film cooling could be a promising method for mitigating these thermal stresses, the influence of the coolant injection location on RDC performance remains not fully understood.

This work investigates four film-cooled RDC configurations, varying the coolant hole locations along the outer wall—from near the reactant injection zone to farther downstream in the oblique shock region. Due to significant circumferential and axial pressure fluctuations, coolant flow patterns varied, and the addition of coolant mass raised the overall chamber pressure. This rise in chamber pressure notably altered the fresh reactant refill process and affected the detonation wave height. In terms of cooling effectiveness, each configuration showed differing impacts on wall temperature reduction. It was found that placing coolant injections further downstream provided the most efficient overall wall cooling. However, introducing coolant within the detonation region disrupted the initial mixture conditions, thereby influencing detonation combustion behavior. Across all configurations, the injected coolant interacted with the unburned fuel, triggering additional secondary deflagration, which in turn decreased the amount of unburned hydrogen exiting the chamber.

Introduction

Annular RDCs are promising for gas turbines but face severe thermal loads from high mass flow rates, intense heat release, and shock interactions [1]. Experimental and computational studies report heat fluxes far exceeding conventional combustors [2,3]. Film cooling offers potential protection despite shockwave disruptions. This study uses high-fidelity simulations to evaluate how coolant injection at different axial locations impacts detonation dynamics, mixing, heat release, and wall cooling, aiming to optimize thermal management.

Four film-cooled configurations were tested: PC40 (cooling holes starting 4 cm from the injector), PC23 and PC10 (cooling shifted closer to the injector at 2.3 cm and 1 cm), and FC22 (full wall coverage from 2.2 to 8 cm) as shown in **Figure 1**. All used a 3 bar air coolant. LES simulations with the AVBP solver employed WALE turbulence modeling, localized artificial diffusivity, and a validated hydrogen-air 4S1R mechanism to accurately capture detonation behavior.

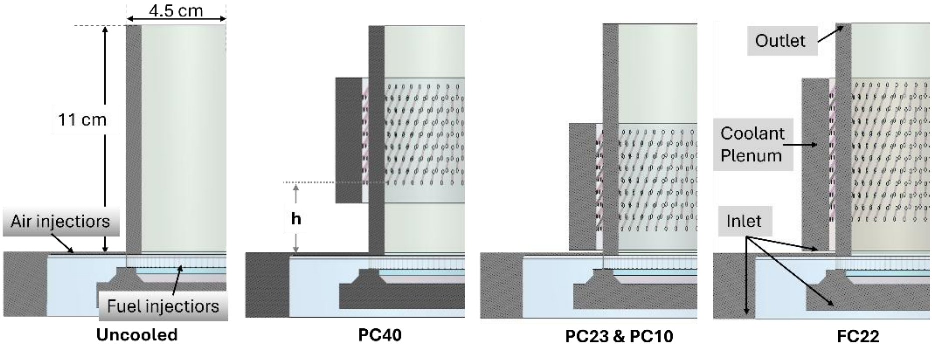

Figure 1 Film cooled TU Berlin RDC geometry.

Results

The distribution of fresh gases is highly dependent on chamber pressure. The height of the fresh gas region dictates the shape and height of the detonation wave, which, in turn, influences overall chamber pressure variations. The impact of coolant mass addition on the detonation wave is evident in the phase-averaged temperature distributions shown in **Figure 2** As observed, the shape of high-pressure regions differs in the film-cooled cases. At an axial position of 5 cm, oblique shocks in the cooled cases lag behind those in the uncooled case due to the reduced detonation height and variations in its shape.

Additionally, the lower gas temperature caused by coolant injection reduces the speed of sound, leading to faster-moving shocks near the outer wall. With the same detonation speed and oblique shock angle but a reduced detonation height, the phase shift between the detonation and oblique shock positions at a given axial location increases due to geometric effects.

Placing coolant holes in the detonation region promotes burnt gas recirculation; however, the burnt gas composition is lower due to the increased coolant volume in the plenum. Additionally, injecting coolant closer to the injectors can help mitigate rich-zone formation.

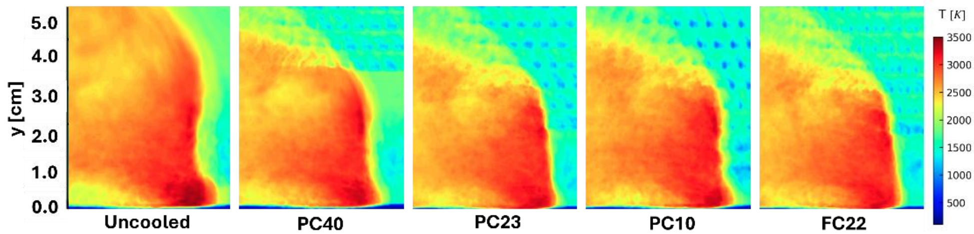

Figure 2 Phase-averaged temperature distributions of the detonation wave obtained closer to the outer wall

The circumferentially averaged temperature and heat release rate profiles for two radial spans are presented in Figure 3. The primary heat release is associated with the detonation wave occurring below an axial length of 4 cm. Due to the presence of unburnt hydrogen, the oxygen in the coolant interacts with the burnt products, leading to secondary heat release. Interestingly, despite this secondary combustion, a reduction in temperature across the combustor axis is observed.

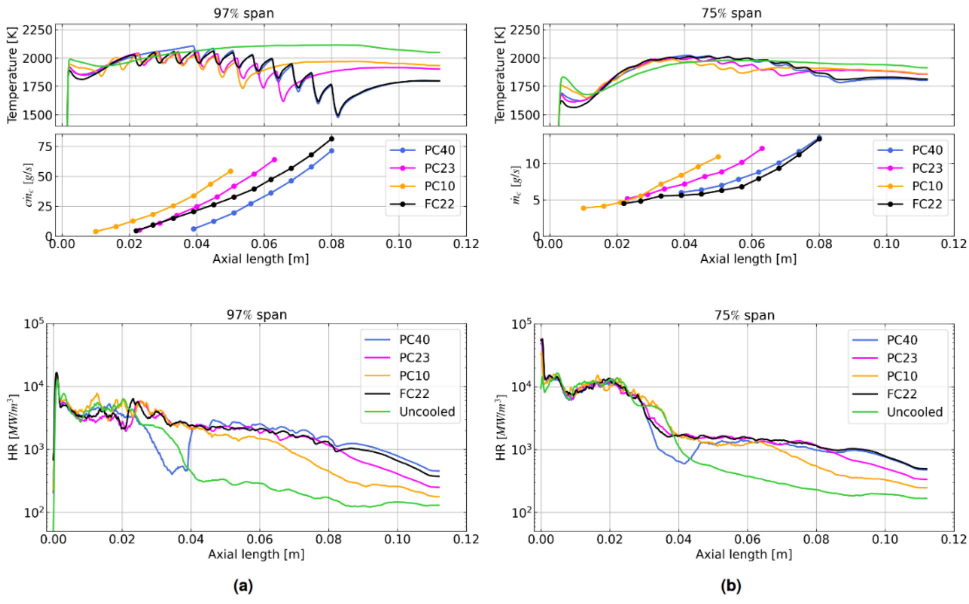

Figure 3 The circumferentially averaged temperature is shown at the top, cumulative and local coolant mass flow in the middle, and heat release profiles at the bottom row, obtained for (a) 97% span and (b) 75% span.

References

[1] J. Braun, J. Sousa, G. Paniagua, Assessment of the boundary layer within a rotating detonation combustor, 52nd AIAA/SAE/ASEE Jt. Propuls. Conf. 2016. (2016) 1–13. https://doi.org/10.2514/6.2016-4557.

[2] K. Goto, R. Yokoo, J. Kim, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, I. Funaki, D. Nakata, M. Uchiumi, Experimental performance validation of a rotating detonation engine toward a flight demonstration, in: AIAA Scitech 2019 Forum, American Institute of Aeronautics and Astronautics Inc, AIAA, 2019. https://doi.org/10.2514/6.2019-1501.

[3] S. Ramanagara Sridhara, U. Sandri, P.C. Nassini, M.D. Polanka, M. Bohon, A. Andreini, Quantification of Heat Loads for Rotating Detonation Combustors with Gas Turbine Conditions, in: AIAA SCITECH 2024 Forum, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2024: pp. 1–12. https://doi.org/10.2514/6.2024-2433.

[4] S. Ramanagar, A. Andreini, M.D. Polanka, M.D. Bohon, The impact of film cooling on the heat release within a rotating detonation combustor, Appl. Energy Combust. Sci. 20 (2024) 100300. https://doi.org/10.1016/j.jaecs.2024.100300.

[5] S. Ramanagar Sridhara, A. Andreini, M.D. Polanka, M.D. Bohon, LES Investigation of Film Cooling in Rotating Detonation Combustors, in: Vol. 7 Heat Transf. Combustors; Heat Transf. Film Cool., American Society of Mechanical Engineers, 2024: pp. 1–14. https://doi.org/10.1115/gt2024-123796.

[6] P.C. Nassini, A. Andreini, M.D. Bohon, Characterization of refill region and mixing state immediately ahead of a hydrogen-air rotating detonation using LES, Combust. Flame. 258 (2023) 113050. https://doi.org/10.1016/j.combustflame.2023.113050.