Film Cooling Implementation in Micro Rotating Detonation Combustor

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1 Introduction

Over the past few decades, Rotating Detonation Combustors (RDCs) have garnered significant interest for their ability to improve combustion efficiency and drive advancements in high-performance propulsion and energy systems [1]. Unlike traditional deflagration-based combustors, which operate at nearly constant pressure, RDCs utilize detonation-based Pressure Gain Combustion (PGC) to achieve faster and more efficient energy conversion [2]. Their mechanically simple design and potential for integration into Gas Turbine (GT) systems make RDCs a promising technology for advanced applications [3]. Despite these advantages, the high thermal loads generated during RDC operation pose a significant challenge, particularly for the integrity and durability of combustor walls. The combination of extreme flame temperatures and compact annular geometry leads to high wall temperatures and significant thermal stresses [4]. Effective cooling strategies, such as film cooling, offer a potential solution to these issues. However, the introduction of cooling flows may influence both the stability of the detonation wave and the thermal behavior of the combustor. This work aims to investigate the effect of film cooling on the stability of the detonation wave and the wall temperature in RDCs. To this end, a Micro-RDC test rig with an integrated film-cooling hole pattern was designed and implemented. By examining the interplay between cooling flows and detonation dynamics, this study provides insights that are essential for advancing the practical application of RDC technology in propulsion systems.

2 Literature Review

Recent research on rotating detonation combustors (RDCs) has explored the design and operation of micro-scale configurations to expand their application in thrust and power generation. Smaller RDCs not only enhance volume management but also minimize the demand for oxidizers and fuel, making them suitable for diverse applications [5]. The design principles for RDCs, applicable across all scales, are often grounded in the foundational geometric and operational parameters established by the seminal works of Kudo et al. [6] and Bykovskii et al. [7]. These studies defined critical relationships between detonation channel geometry and detonation cell dimensions to ensure stable detonation wave propagation. Building on these foundations, researchers such as Dechert et al. [8] applied these relationships to develop micro-RDCs. While initial attempts resulted in unstable detonation, subsequent investigations

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by Fiorino et al. [9] and Wyatt et al. [10] introduced design optimizations—particularly in ignition and reactant injection processes— enabling stable detonation over a broader operational range.

While promising advancements have been made toward achieving stable operation in small-scale RDCs, integrating an efficient cooling system, such as film cooling, remains a significant challenge. The application of film cooling in small-scale RDCs requires further experimental investigations to assess the stability of the detonation process in the presence of an air layer along the combustor walls. Despite the complexities associated with studying film cooling under the influence of rotating detonation waves, this technique is a leading solution for thermal load management, owing to its high efficiency and well established application in aeronautical propulsion.

While film cooling has been widely employed and extensively investigated in aeronautical propulsion systems, only a limited number of studies have explored its implementation in RDCs. Preliminary findings have demonstrated its feasibility, underscoring its promise as a viable cooling method in these detonation based systems [11–14].

Tian et al. [11] were the first to conduct CFD simulations of a premixed film cooled RDC. Their model featured six film-cooling holes arranged in a single column extending from the inlet to the outlet. The initial findings indicated that film cooling had minimal impact on the detonation cycle, with the frequency observed in both cooled and uncooled cases being nearly identical. Additionally, time-averaged temperature profiles demonstrated the benefits of film cooling in reducing the thermal load. Yu et al. [15] performed similar CFD analyses, examining the effect of varying coolant mass flow in a single column of film cooling holes. Their study focused on RDC thrust performance and film cooling effectiveness. The results showed that while the cooling flow altered the detonation wave, it quickly recovered to its original profile, and the cooling did not quench the detonation. Lie et al. [13] conducted a numerical investigation on a rocket-based detonation engine with film cooling, exploring different hole shapes and varying coolant velocities.

While these pioneering studies provided valuable insights, all of them focused on premixed RDCs, solving unsteady RANS equations and modeling relatively simple film cooling configurations. In contrast, Ramanagar et al. [12] performed 3D LES simulations of a non-premixed RDC with a full coverage film cooling scheme located at the region downstream of the detonation zone. They tested the system under different cooling feed pressures. Their findings revealed that the back-pressure generated by the airflow through the film cooling holes enhanced the detonation wave, while the film cooling system significantly reduced the surface temperature of the combustor's outer body at the location of the cooling holes.

Although numerical studies on film cooling in RDCs have now been accomplished, experimental investigations remain limited. Yu et al. [14] conducted experimental investigations using a configuration analogous to those in aircraft engine combustors. Their work demonstrated the initiation and sustained propagation of detonation waves during film cooling, validating its practical applicability. These results highlight the robustness of detonation processes in the presence of air jets and represent a significant step toward integrating cooling systems into micro-RDCs.

3 Micro-RDC Facility

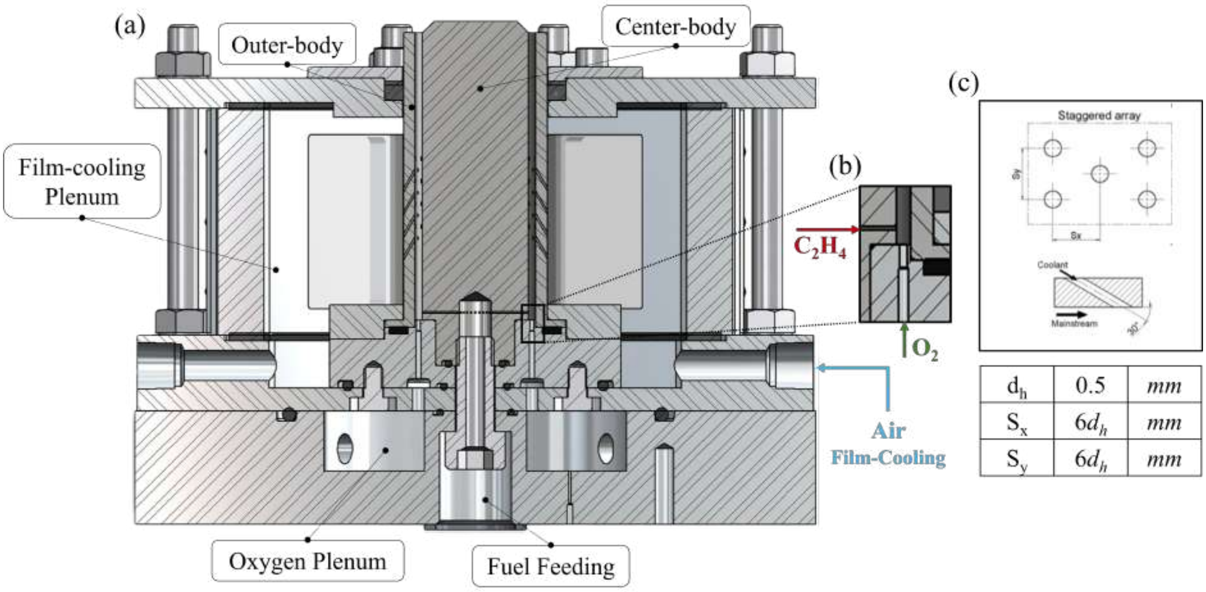
A Micro RDE facility has been established at the THT Lab of the University of Florence to enable testing of small RDC systems using ethylene and oxygen. Its development encompassed the design of the test article incorporating a film cooling system, the assembly of reactant supply lines, and the implementation of software for tests control and data acquisition. The following sections provide a detailed description of the test rig and the design of the Micro-RDE.

3.1 Micro-RDC design

Figure 1 illustrates the Micro-RDE developed in this study, which is based on the geometry originally proposed by Keller et al. [5] in their work at the Air Force Institute of Technology (AFIT). As illustrated in Figure 2, this configuration employs a Jet-in-Crossflow fuel supply system, Figure (b) 2, which distributes fuel and oxidizer through 24 injector pairs, as detailed extensively in Keller's study. Since Keller's geometry successfully produced stable detonation waves over a broad range of equivalence ratios and mass flow rates, the original injector configuration was preserved. Additionally, the 2 mm width of the annular combustion chamber was preserved, as this parameter, along with the number and arrangement of injectors, plays a critical role in achieving stable detonation wave conditions.

Figure 1: Design of the test article: (a) Micro-RDE assembly, (b) film-cooling outer-body and (b) cube-shaped air film-cooling plenum.

In the current setup shown in Figure 2, the 2 mm annular gap is realized using a 28 mm centerbody diameter and a 32 mm outerbody diameter. These dimensions align with the detonation cell size, as established by the foundational work of Bykovskii et al. [7], ensuring compatibility with the detonation wave dynamics. Figure 2 illustrates the integration of the film cooling system into the current geometry. A high density array of film cooling holes was implemented on the outer wall (Figure 1(b)). Eight staggered rows of holes was adopted each with a 0.5 mm diameter. Each hole was inclined at 30° to the axis of the Micro-RDC as shown in Figure 2c, with a total of 180 holes.



d_h	0.5	*mm*
S_x	$6d_h$	*mm*
S_y	$6d_h$	*mm*

Figure 2: Micro-RDC details: (a) Cross-section, (b) Injectors configuration, (c) Arrangement of scattered film-cooling holes.

The results from Ramanagar et al.'s [12] study indicate that film cooling located in the oblique shock region does not quench the detonation wave. While some coolant ingestion occurs, which reduces its effectiveness, the coolant is able to reestablish a film on the surface after each detonation passes. On the other hand, Yu et al. [14] demonstrated that film cooling positioned within the detonation region can still sustain stable wave propagation, despite the presence of coolant flow. Differences in design and the smaller dimensions of the current configuration motivated a more conservative approach. Therefore, the first row of cooling holes was positioned 15 mm above the expected detonation region to minimize the risk of detonation quenching. This placement was guided by the fill height estimates provided by Keller et al. [5].

A cubic plenum, as shown in Figure 1 (c), designed with four windows, enables the air pressurization required to supply the film cooling holes located in the outer wall. The four windows were specifically designed to accommodate sapphire inserts for infrared visibility or metallic inserts for the installation of thermocouples and pressure sensors. This flexible configuration supports both diagnostic and monitoring capabilities, enhancing the system's versatility for experimental investigations. The RDC will be equipped with pressure sensors positioned downstream of the film cooling region to monitor pressure variations and flow behavior. For thermal analysis, an infrared camera will capture the temperature distribution on the external surface of the combustor at the film cooling holes. Additionally, a high-speed camera will be used to view into the detonation channel from above to analyze the formation and propagation of detonation waves, both in the presence and absence of the cooling flow.

The film cooled RDC presented in this study features a modular architecture, enabling testing of various film cooling configurations. This design approach aligns with the primary objective of the research, which is to investigate film cooling in small-scale RDCs. Different configurations will be tested by varying key parameters, including the hole diameter, stagger arrangement, number of rows, hole inclination angle, and the axial positioning of the film cooling holes along the outer body.

3.2 Experimental Set Up

This rig operated with short run times, on the order of seconds. As such, fast and precise mass flow control was needed. To meet these demands, a dedicated mass flow setup was utilized, as illustrated in Figure 3. The setup features two independent flow paths for oxygen and ethylene. Each path comprises a manual ball valve (1) to open the supply, a dome-loaded pressure regulator (2), an electronic pressure regulator actuated by pressurized nitrogen, an interchangeable sonic nozzle for accurate flow control, and a check valve installed upstream of the Micro-RDC to prevent backflow.

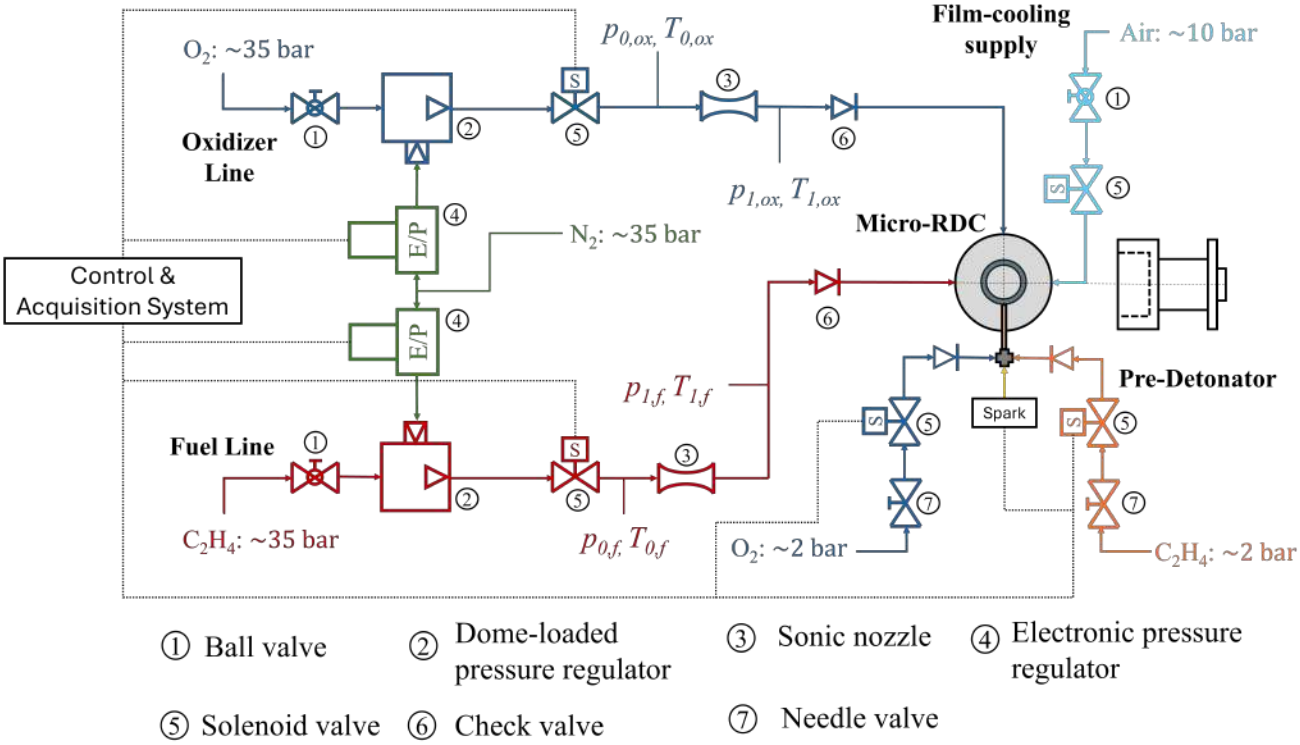


Figure 3: Schematic piping and instrumentation diagram of Micro-RDC facility, including flow control system, data acquisition system, and ignition system.

Both reactants are supplied from standard compressed gas cylinders with a rated pressure of 200 bar. A pressure regulator reduced the gas pressure to a maximum of approximately 35 bar. The Electronic Pressure Regulators (EPRs) control the pressure in the dome-loaded pressure regulators, which in turn govern the upstream pressures of the sonic nozzles. The mass flow rate can be determined using measurements of temperature and pressure upstream of the sonic nozzle as follows:

$$\dot{m} = \frac{Ap_t}{\sqrt{T_t}}\sqrt{\frac{\gamma}{R_s}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

where A represents the throat area of the sonic nozzle, p_t is the upstream total pressure, T_t is the upstream total temperature, γ is the ratio of specific heats for each reactant, and R_s is the specific gas constant. Both upstream and downstream pressures were monitored to evaluate the pressure ratio, which determines whether the flow is in a choked condition. Upstream and downstream pressures were measured using semiconductor strain gauge relative pressure sensors, while temperatures at these locations were recorded using Resistance Temperature Detectors (RTDs). By varying the diameter of the sonic nozzle throats, a wide range of mass flow rates was achieved, with a predetermined total mass flow capacity of up to 10 g/s.

3.3 Pre-Detonator and Ignition System

A pre-detonator system based on Deflagration-to-Detonation Transition (DDT) was designed as the ignition apparatus. Pre-detonators are widely utilized in research due to their ability to reliably initiate detonation waves across a broad range of operating conditions, offering a high probability of successful ignition [3, 16, 17]. Figure 4 illustrates the setup of the pre-detonator, which has been designed as a standalone test rig with dedicated oxygen and fuel cylinders. The flow of reactants is controlled by a system of components depicted in Figure 3, including a pair of flowmeters that regulate the equivalence ratio. As shown in Figure 4, the reactants are mixed in a cross-fitting, where a spark plug was positioned to initiate the ignition process within the mixing region. The deflagrating flame then propagates through the tube, where turbulence promotes the transition to a detonation regime.

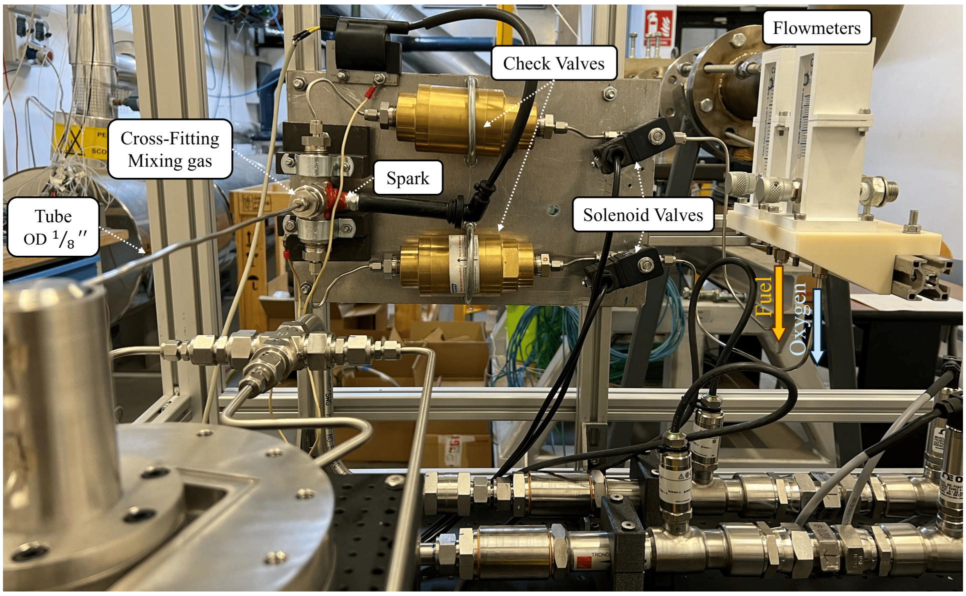


Figure 4: Pre-detonator test rig set up.

Figure 5 shows the detonation front emerging from the pre-detonator tube. Tests were conducted under identical conditions for two tubes of equal length but differing diameters. The figure displays two frames captured by a high-speed camera at 85,000 fps. As anticipated, the flow field outside the tube exhibits a diamond-shaped pattern, characteristic of the expansion of a supersonic flow at ambient pressure. Comparing Figure 5 (a) and (b), the shock-cell length was approximately halved for the smaller tube.

The pre-detonator was tested under both lean and rich combustion conditions by varying the oxygen mass flow. Preliminary results showed no significant differences in the flow field structures, even though the intensity of the detonation varied with changes in the equivalence ratio. However, a notable observation was the increased production of soot under both rich and lean conditions. The high-emissivity soot particles were clearly visible in the camera footage, particularly in the smaller diameter tube.

Prolonged operation of the smaller tube resulted in detonation attenuation, evident from the diminished

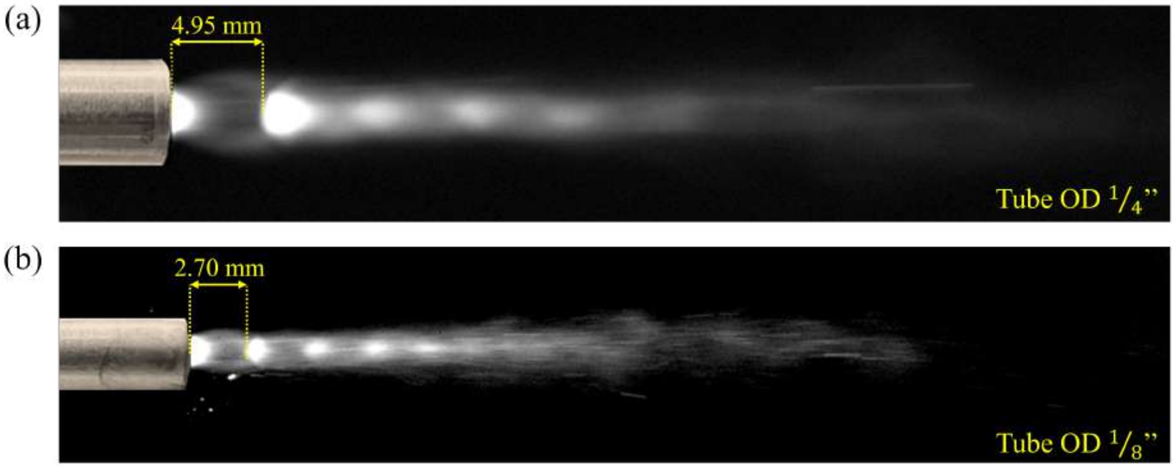


Figure 5: Frames captured by the camera at the pre-detonator output for (a) a 1/4" tube and (b) a 1/8" tube.

intensity of the shock waves at the outlet. This attenuation is likely due to soot accumulation inside the tube and the buildup of condensed particulate matter near its exit.

4 Conclusion

This paper presented the design and development of a dedicated facility for studying the effects of film cooling in Micro-RDC combustors. Key aspects of the work included the design of the combustor featuring a custom film cooling system, the assembly of the test rig, and the development of a pre-detonator based ignition system.

External surface temperature measurement via infrared (IR) imaging will provide a detailed analysis of how well the film cooling maintains the outer wall temperature and a quantification of the heat flux. Imaging within the detonation channel will reveal the impact of the film cooling on the detonation process, and the wave dynamics. These findings aim to advance the understanding and practical application of film cooling in Micro-RDC systems.

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