A Review of Recent Advances in the Combustor and Blade Cooling Methods for Pressure Gain Applications

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Abstract

This paper presents a review of the recent advances in the gas turbine combustor and blade cooling methods in order to identify the most promising thermal management solutions for pressure gain combustors (PGCs) and their integration into gas turbine cycles. PGCs have recently acquired renewed interest due to their considerably higher theoretical potential for performance improvements in gas turbines compared to the conventional constant pressure combustors. However, their challenging thermal management impedes practical realization and integration with turbomachinery due to their high wall heat fluxes, fundamentally unsteady operation, spatially non-uniform outflow and non-negligible backward impact on compressor operation. The review explores various proposed and realized cooling methods for different deflagrative and detonative pressure gain approaches. PGC cooling requirements, experimental values, and implemented cooling strategies from past research are described. Ongoing efforts towards increasing the convective cooling effectiveness for blade cooling are discussed and innovative cooling concepts such as propellant injection cooling, pulse impingement cooling and bladeless turbine are analyzed. Additionally, the development of cooling models for cycle analysis and the cooling-associated performance losses are also investigated. Special consideration is given to the PGC application in land-based power generation application. Potential performance improvements in PGC-based combined cycle (CC) are discussed and the feasibility of various steam cooling methods for combustor and turbine are analyzed. Finally, it has been argued that the implementation of steam cooling in the combined cycles powered by PGC, at least in the initial turbine stages, is a practically viable approach for the development of a feasible PGC system for high efficiency and clean power generation.

1. Introduction

Gas turbines (GTs) operating with steady constant pressure combustion have been enormously successful in propulsion and power applications due to several decades of incremental developments, but the potential for further improvements in Brayton cycle GTs has plateaued, necessitating substantial cycle-level improvements in the next generation GTs to meet the ever-increasing performance and emission goals. Pressure Gain Combustors (PGCs) that ideally operate on the Humphrey cycle with constant volume combustion have acquired a renewed interest in recent decades due to their considerable theoretical potential. PGCs can provide higher cycle efficiency, higher power output, combustor pressure rise of 15-20% and fuel reduction by 4-9% [1]. The practical realization of the theoretically attractive PGC is impeded by significant challenges related to fuel injection, ignition, mixing, ducting, valving, deflagration to detonation transition, wave directionality, turbine integration, and thermal management. In particular, the thermal management in PGCs is more challenging than conventional combustors due to high power density, high peak temperatures, unsteady heat transfer, compactness, autoignition and near stoichiometric operation due to scaling and size limitations. Moreover, the cooling approaches for detonative PGC are more difficult than deflagrative PGC due to strong pressure waves. Compared to Pulse Detonation Combustors (PDCs), Rotating Detonation Combustors (RDCs) have captured more research interest due to high-frequency operation, absence of moving parts, continuous detonation and relatively steadier inflow and outflow than PDCs.

Most modern GTs operate with Turbine Inlet Temperature (TIT) in the range of 1400°C - 1600°C, which is expected to increase to 1700°C in the near future. The modern nickel-based turbine materials can only perform prolonged operation below TIT of 1200°C without active thermal management [2]. With TIT in GTs increasing at an average rate of 20°C per year, while the allowable superalloy material temperature increasing only at 8°C per year [3], advanced materials, innovative cooling systems and accurate cooling models are required to realize stable and prolonged PGC operation in future.

The paper reviews recent developments, challenges and proposed concepts for thermal management in PGC to identify the potential solutions for the development of practical PGC systems. Firstly, experimental thermal loads in PGC along with developments in convective cooling, film cooling, turbine integration and cooling models are described in section 2. Subsequently, the cooling-associated performance trade-offs are discussed in section 3. Finally, the application of PGC in land-based power generation utilizing steam cooling is discussed in section 4. The review is vital in selecting cooling systems for cycle-level performance analysis of PGCs in combined cycle applications.

2. Thermal Management in Pressure Gain Combustion

2.1 Cooling requirements in PGC

In conventional GTs, the combustor liner is air-cooled and the turbine blades are usually subjected to a Reynolds number of 1,000,000, convective heat transfer coefficients of 2,000 W/m^2K and heat fluxes of 1 MW/m^2 [2]. However, experimental measurement of thermal loads in PGC tests is inhibited by its high-power density, short burn duration and high-frequency operation. Falempin et al. reported peak wall temperatures exceeding 700°C and 1000°C for RDC fueled with H_2-O_2 and Kerosene-O_2, respectively, in tests lasting 0.5 seconds [4]. The maximum heat fluxes measured were 12 MW/m^2 and 17 MW/m^2, and the hottest sections were near the injection within the detonation height [4]. The authors also suggested the use of C/SiC composite materials capable of withstanding 1800°C in an oxidizing environment [4]. Similarly, Theuerkauf et al. measured heat flux up to 9 MW/m^2 in H_2-air fueled RDC through high frequency (100 kHz) thin film heat flux sensors [5]. Bykovskii et al. studied heat fluxes of deflagrative and detonative combustion in identical combustors with the same flow conditions and observed the same average heat flux of 1 MW/m^2 in both modes, with a peak heat flux of 2.5 MW/m^2 in detonative mode [6]. It was also reported that the injection of the fresh mixture at the inlet wall provided some regenerative cooling which receded in the axial direction due to increasing product temperature. Lastly, Theuerkauf et al. has reported a peak heat flux of 100 MW/m^2 at start-up, with an average value of 10 MW/m^2 [7]. Due to such high heat fluxes, experimental RDC and PDC setups require extensive water cooling and heat resistive materials, even for an operating duration of 0.5-3 seconds.

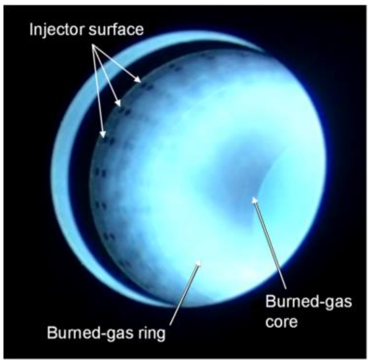

Figure 1. Propellant injection active cooling in cylindrical RDC [8]

Conventional annular RDCs require cooling for both inner and outer walls. Therefore, a cylindrical RDC with discrete reactant injection from combustor sidewalls is proposed to reduce the cooling requirements. In this configuration, referred to as propellant injection active cooling (shown in Fig. 1), the detonation wave is detached from the wall, which reduces the heat transfer to the wall substantially [8]. Goto et al. demonstrated this technique in a 24 mm diameter cylindrical RDC at a mass flow rate varying from 24 to 62 g⁄s [8]. The combustor attained stable detonation, and the flame stand-off from the injector side wall was verified through chemiluminescence images. Also, the less cooling requirements were evident by heat flux increase of only 18-25% on doubling the flow rate [8], which is otherwise roughly proportional to the flow rate.

2.2 Internal Blade Cooling

Practical GTs employ various cooling methods of the convective, film, impingement, transpiration, and effusion types through a series of internal serpentine passages and thermal barrier coatings (TBCs). The internal convective blade cooling has been highly effective in GTs, particularly the double wall cooling approach characterized by secondary cooling channels with pin-fins and rib-turbulators within the blade. Turbulators and ribs are the small structures protruding in the flow channels meant to induce turbulence and achieve heat transfer enhancement from 2-3.5 times. Several configurations of turbulators have been investigated, however, recent studies have shown that the discrete W-Shaped and discrete V-shaped types have the best heat transfer characteristics [9]. Also, pin-fins with three-dimensional geometry have been shown to generate more vortices and turbulence with heat transfer enhancement of 4-5 times [10]. Furthermore, diamond and cubic-shaped pin-fins have shown better performance than widely used circular geometries [11]. However, as pin-fins incur higher pressure loss, they are mostly used in trailing edges. Lastly, a combination of pin-fins and turbulators has been shown to perform better than single geometry [12], an approach that is practically possible now due to manufacturing advancements and is apparently feasible for blade cooling in future PGCs.

Conventionally, steady jet impingement cooling has been used for the most thermally stressed blade section, the leading edge. Recently, a new approach referred to as Pulsed Impingement Cooling has been shown to perform better than conventional steady jet impingement. Neumann et al. showed cooling efficiency improvement by 15 p.p. and cooling flow rate reduction by 10% with the pulsed impingement technique through a set of 49 nozzles on a curved surface at frequencies from 0 to 1000 Hz [13]. Such improvements in the internal blade cooling can substantially reduce the cooling airflow and allow higher TIT.

2.3 Film cooling

Traditionally implemented external film cooling for the turbine is also an attractive cooling technique for PGC, however, it is extremely complicated due to flow pulsations and shock waves, which induces lift-off and reduces cooling efficiency. For instance, Zhou et al. investigated the influence of mainstream flow oscillations on cooling film cooling effectiveness at frequencies from 0–20 Hz and observed a 35% reduction in cooling effectiveness [14]. Similarly, Heinrich et al. showed a strong impact of pulsations on film cooling effectiveness at frequencies from 1-5 Hz [15]. These detrimental effects of pulsating flow on film cooling warrant further studies.

Combustor film cooling through liner holes cannot be directly implemented in PGC due to chamber pressure rise and pulsations unless an external air pressure booster is employed. To understand the film cooling performance in the PGC combustors, Tian et al. numerically investigated the film characteristics in a 27 mm diameter hydrogen-air RDC through single row film cooling [16]. Although the film cooling effectively reduced the time-averaged temperature on the RDC wall, significant cooling disruption was observed near the inlet in the form of blocking of cooling jets and invasion of combustion gases into cooling nozzles with sweeping detonation waves [16]. Furthermore, Tan et al. numerically studied the film cooling stability in 40 mm diameter and 500 mm long H_2-Air fueled PDC [17]. They found that the film could be effectively sustained for a considerable cycle duration in PDC. The film's dynamic interaction with the detonation wave momentarily affects the film structure and stability, but it re-established itself quickly post-detonation [17]. Subsequently, they also experimentally showed a decrease in wall temperature with increasing film cooling airflow in a 60 Hz PDC. Temperature reduction up to 300K could be achieved, which highlights the applicability of film cooling in PDC. Alternatively, unlike air film cooling, liquid film cooling, characterized by fuel injection in the form of film, unlike conventional spray injection, is also a promising cooling technique, especially for detonation-based liquid rocket engines.[18].

2.4 Integration

The thermal management in PGC is coupled with turbine integration, necessitating a review of integration strategies, which is challenging due to unsteady supersonic outflow in PGCs. Among the various PGC approaches, deflagrative combustion-based Internal Combustion Wave Rotor (ICWR) and Ejector Enhanced Resonance Pulse Combustor (EERPC) can be more easily integrated into turbomachinery than PDC and RDCs, due to relatively steadier outflow and less cooling requirements.

The combustor outer wall cooling by bypass flow followed by downstream mixing can also be implemented in PGC, with additional compression due to pressure gain. Downstream of the combustor, ejectors with well-known pumping and mixing characteristics are very effective in reducing the combustor outflow temperature and unsteadiness in the tube-based PGC to ensure optimum turbine performance. For instance, Yungster et al. numerically studied shrouded ejector-based RPC and demonstrated pressure gain up to 3.6 % [19]. Moreover, Paxson et al. have experimentally demonstrated up to 83% reduction in exit velocity fluctuations with ejector entrainment ratio up to 18:1 [20]. The bypass flow inside the shroud effectively cools the combustor and dilutes the products to acceptable levels for the turbine to attain high turbomachinery performance. Since the turbine structural integrity and nozzle performance are adversely affected by the repeated impingement of unsteady high-pressure waves, combustor bypass cooling with product dilution is potentially a viable strategy for RPC and PDC integration.

For the integration of PDC, Rasheed et al. have experimentally demonstrated the effectiveness of secondary air cooling through a coaxial liner in a multitube-PDE integrated with a single-stage axial turbine fueled by C_2H_4–air mixture [21]. The cooling air was subsequently mixed with products in the transition duct before entry into the turbine. The 560-kW system consisted of 8 PDE tubes of diameter 49.3 mm and length 800 mm, arranged in can-annular configuration and was operated for burn duration exceeding 5 minutes at 3.5 kg/s airflow. To further enhance the heat transfer from PDC tubes, the use of cooling fins on the outside tube surface is also suggested [22]. It is worthwhile to mention that multitube PDEs operating in sequential mode with detonations occurring in some tubes while others are being filled will have more steady output, less peak shock overpressure and less tube interaction than simultaneous operation, and thus, is practically a more promising approach. Finally, several researchers have studied the performance of RDC with turbomachinery. Naples et al. demonstrated successful operation of ejector-based air-cooled hydrogen-air RDC integrated with Allison T63 engine [23]. The dilution of RDC exhaust by cooling air in the ejector reduced the temperature of gases to the allowable value of 1300K for the T63 turbine, permitting the system to operate continuously for up to 6 minutes. The ejector also reduced the pressure wave magnitude by 60-70%, allowing the turbine to perform nominally.

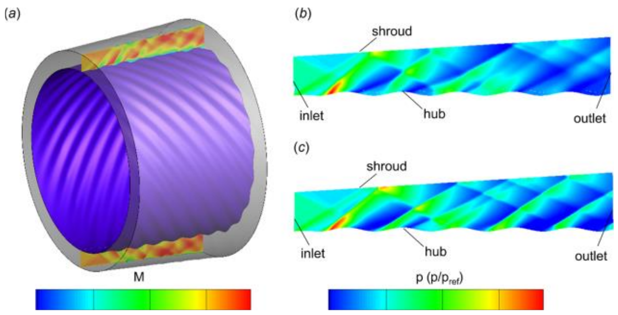

Figure 2. Bladeless turbine with Mach number contours [24]

The pressure losses and poor turbine performance from supersonic pulsating flow in detonation-based PGCs has motivated research toward a novel bladeless turbine that uses tangential viscous drag forces in the flow instead of pressure forces on the conventional blades. Vinha et al. [24] numerically demonstrated the effectiveness of bladeless turbines (shown in Fig. 2) in supersonic flow, but the 0.45 MW power extracted by bladeless wavy configuration was considerably less than 3.5 MW and 21.2 MW extracted from different bladed configuration at similar conditions indicating low efficiency of the bladeless turbine. Despite the low efficiency, the authors argued that the bladeless design can be managed to extract useful work with substantially reduced shock-related pressure losses. It was also claimed that the design can reduce cooling requirements considerably, due to much lower wetted area and reduced mechanical complexity [24], compared to conventional turbines, where 60-70% of the total coolant air is consumed by stator and rotor blades [25]. Although in principle, this novel design is promising from the cooling perspective, further studies are necessary to understand its cooling requirements and work extraction capability for PGC systems.

2.5 Development of Cooling Models

Estimation of heat transfer, cooling flow requirements and coolant pressure drop is critical for the preliminary assessment of PGC cycles, and thus, significant efforts have been devoted to the development of reliable and accurate cooling and heat transfer models [22,26–30]. Jordal et al. developed a computational convective cooling model by incorporating a cooling technology parameter that facilitated the determination of cooling requirements and pressure drop with different blade geometries and cooling fluids [29]. Subsequently, Torbidoni et al. extended the model to incorporate the film cooling over the blade [28] and developed a more detailed model incorporating a chordwise local variation of the blade temperature [30]. These models were subsequently incorporated into the thermoeconomic code (WTEMP), enabling a comprehensive analysis of innovative GT cycles [31]. Likewise, Chiesa et al. have developed a thermodynamic code (GS) for detailed analysis of various open and closed loop blade cooling configurations in combined cycles (CC) with industrial GTs [32]. Such cooling models, which were primarily developed for the conventional GTs, can be extremely useful for the performance evaluation of PGC cycles with little modifications. For the PGC applications., the quasi-one-dimensional, unsteady time-accurate CFD code with viscous and heat transfer loss models has been used to predict heat transfer with sufficient accuracy for detonative systems [8,22,26,27]

3. Effect of Cooling on PGC Cycle Performance

Conventional blade cooling techniques in PGC require higher cooling airflows with additional compression [33,34]. It has been shown in the water-cooled RDC experiments that the heat transferred to the combustor walls can range from 8-15% of the fuel calorific value [7]. Such extensive cooling requirements can reduce the idealized performance gains from PGC, and hence the practically possible performance potential of PGC is contentious [35,36]. Paxson et al. showed that up to half of the ideal reduction in specific fuel consumption could be lost as a performance penalty due to thermal management in the study of a turbomachinery-integrated PDE with realistic component efficiencies [22]. Similarly, Stathopoulos showed that a sufficiently poor turbine efficiency resulting from the pulsating flow can completely eliminate the ideal performance gains of PGC [37]. However, these cooling-associated performance penalties can be mitigated with innovative cooling techniques. For instance, Neumann et al. estimated that in the case of pure convective cooling without TBC, pulse impingement cooling can increase the cycle efficiency by 1 p.p. in the Brayton cycle and 0.5 p.p. in the PGC cycle, as compared to steady impingement cooling [13].

4. PGC application in Combined Cycle for Power Generation

Interestingly, the efficiency of the land-based CCs can be increased by incorporating both, PGC and steam cooling from the bottoming cycle. Several theoretical studies have shown the possible improvements in the CC efficiency by the independent implementation of either PGC [38–41] or steam cooling [31,32,42], in the conventional CCs with air-cooled GT operating on the Brayton cycle. The efficiency increments from these studies are graphically represented in Fig. 3. It is important to mention that all PGC-related studies in Fig 3 have been conducted with air-cooled blades, and all the steam cooling studies have been performed with conventional constant-pressure combustors, with steam cooling implemented only in initial two or three turbine stages.

To understand the impact of PGC on the CC cycle, Gulen conducted a real cycle analysis of PDC in 505 MW CC with an air-cooled J-class industrial GT at a pressure ratio of 23 and TIT of ~1600 °C at different conditions. The study showed efficiency rise up to 3.3 p.p. and combustor pressure gain up to 1.85 times compared to the baseline Brayton cycle CC [40]. Likewise, Holley reported an efficiency increase of 3.55 p.p. and 4.45 p.p., and an increase in air-cooled CC power output of 3.1% and 4.1%, with PDC and RDC, respectively [41].

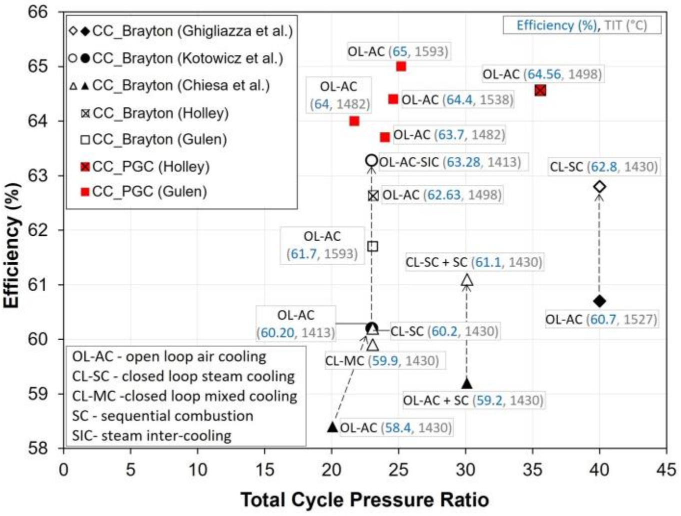

Figure 3. Potential efficiency increase in CC through steam cooling and PGC.

The thermal management in PGC-based combined cycles can be easier than in aerospace applications due to steam availability from the bottoming cycle. Steam has superior heat exchange properties and lower entry temperature than air, and can reduce the cooling requirements and coolant pressure loss by half [29,43]. It can be used for direct blade cooling, cooling air inter-cooling, and combustor cooling. Moreover, the recovered heat from cooling can be used to increase the steam turbine output. Several researchers have demonstrated performance enhancement with steam cooling in conventional constant-pressure GT based CCs, as shown in Fig. 3. Ghigliazza et al. have demonstrated an efficiency rise from 60.7% to 62.8% by using closed-loop steam cooling instead of open-loop air cooling for turbine blades [31]. Similarly, Kotowicz et al. theoretically showed an increase in CC efficiency from 60.20 % to 63.28 % by inter-cooling the cooling air to 100°C by an additional closed-loop steam cycle at a GT pressure ratio of 23 [42]. Also, Chiesa et al. showed an efficiency increase of 1.8 p.p. by closed-loop steam cooling and an additional increase of 0.9 p.p. by implementing sequential combustion alongside steam cooling [32]. Interestingly, apart from blade cooling, Mitsubishi has also demonstrated the use of steam cooling for combustor liner in its M501G GT unit [44], but the approach was later discontinued due to the reduced ramping rate due to coupling with the steam cycle. Nearly all the GT combustors at present employ air cooling through liner holes. Even though steam cooling is advantageous, it does present some corrosion related challenges for long-term operation, but the ongoing metallurgical advancements are expected to provide the solution by the time the emerging PGC technology is practically realized.

Even though the steam-based turbine cooling studies discussed above have shown the cycle efficiency rise in conventional GTs, similar performance enhancements can also be expected in the PGC-based CCs. While the studies related to steam cooling in PGC powerplants are not available in the open literature, to the best of author's knowledge, the simultaneous implementation of PGC and steam cooling in future CCs provides a promising pathway towards high efficiency and clean power generation.

For the sake of perspective, typical literature values of the TIT and the cycle pressure ratio in various cycle analysis studies are provided in Fig. 4. Since the usual pressure gain in PGC is 1.5-3 times the inlet pressure [38–41], the value of the compressor pressure ratios for PGC-based CC are in the range of 10-20, to maintain the total cycle pressure ratio of around 25 which is equivalent to modern CCs. With manufacturers continuously striving for higher TITs, Mitsubishi has already claimed to have commercialized the CC with TIT of 1650°C in the year 2020 [45], and a powerplant with TIT of 1700°C can be expected in the near future. Therefore, real cycle analysis of future PGC-based CCs should be performed at higher temperatures by incorporating steam cooling as discussed above, extending the state of the art knowledge.

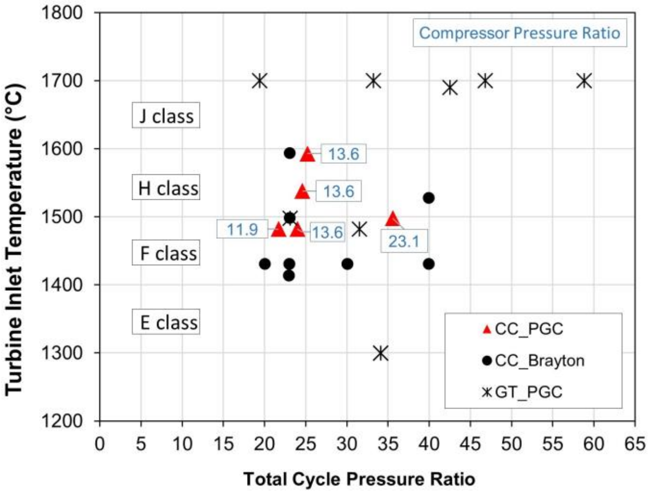

Figure 4. The typical value of TIT and cycle pressure ratio in literature.

5. Conclusion

The study reviews recent developments in the cooling and turbine integration strategies for the fundamentally different PGC technology that requires advanced combustor and blade cooling techniques for practical realization.

It has been shown that the film cooling for the combustor is feasible in RDC and PDC, despite the local disruption and slight cooling effectiveness reduction due to unsteady shocks. The convective blade cooling effectiveness can be increased by using more complex internal configurations of ribs and turbulators, and by implementing the novel pulse impingement cooling that enables cooling efficiency augmentation by 15 p.p. over the conventional steady impingement. For the RDC, a novel cylindrical configuration with propellant injection cooling can significantly reduce the thermal load and cooling requirements. Moreover, ejector-based entrainment and dilution, downstream of the combustor is extremely effective in reducing the combustor outlet temperature and flow unsteadiness. Additionally, recently conceptualized bladeless turbines can also be used for high-efficiency work extraction from the unsteady and supersonic PGC outflow. Although, in principle, the pulse impingement cooling and bladeless turbines appear promising, further experimental and theoretical work is required to understand their practical viability and to evaluate the associated performance losses.

For the power generation application of PGC in CCs, direct steam cooling in turbine and indirect coolant inter-cooling by steam offers significant and practically attainable cooling potential with efficiency improvements of 3-4 p.p, compared to the air-cooling solution. Consequently, it is also argued that, due to less size, volume and operational constraints than aerospace applications, land-based CCs employing steam cooling from the bottoming cycle, at least in the initial stages, have the potential to represent the first practical implementation of PGC due to the expected higher efficiency. Therefore, further studies are recommended to understand the characteristics of various steam cooling techniques in PGC-based CCs.

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