The 8th International Conference on Jets, Wakes and Separated Flows, ICJWSF-2024
September 23-25, 2024, Firenze, Italy

The Effect of Compound Angled Holes on a Film Cooled Rotating Detonation Combustor

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Abstract

Rotating detonation engine due to its high thermal load posses a challenge in maintaining a suitable wall temperature. Film cooling is a promising solution aiding in handling the harsh thermal load. However, the RDC flowfields impose greater challenges for film cooling. The shockwaves disrupt the coolant film and the strong tangential velocity component of the rotating detonation wave induces compound angle to the coolant creating non-uniformity in the coolant distribution. This study investigates the possibility of mitigating those coolant compound angles to obtain a well distributed and properly developed film layer.

In this study, three hole configurations were tested namely holes with negative and positive compound angles along with axial cylindrical hole. The results have shown that holes with negative compound angles obtain better cooling behind the detonation wave while the positive compound angled hole provided better coolant spreading ahead of the shock wave. On the other hand, the axial hole performance fall in between the negative and positive compound angles.

Keyword:*Rotating Detonation Combustor, Film Cooling, Reactive Film Cooling)*

1. Introduction

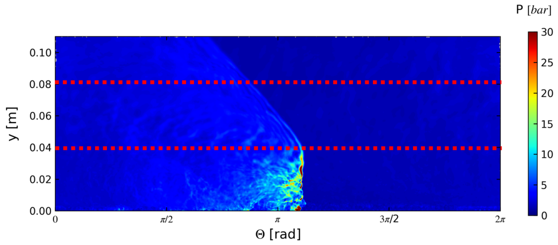
The Rotating Detonation Combustor (RDC) is one of the most advantageous implementations of PGC because of lower unsteadiness and easier integration with no moving parts [1]. There are several configurations of rotating detonation combustors, with different shapes [2] and sizes [3]. One of the most used configuration is an annular RDC where the combustion process happens in a narrow annulus with fuel and air supplied from the head end and the burnt products are expanded out of the aft end. The detonation wave continuously loops around this circular annulus. A sufficiently high mass flow rate of detonatable mixture is required to sustain the detonation wave due to its high consumption speed.

The structure of the flow field is characterized by a detonation front with a trailing oblique shock. This oblique shock extends to the outlet and travels with the same speed in the laboratory frame of reference as the detonation, however the shock strength and relative Mach number is significantly lower. The bulk flow exiting the combustor is mainly axial with minimal tangential component. This configuration presents essentially two distinct regions in the combustion chamber with respect to consideration of the cooling requirements. One is characterized by the passage of the detonation front, while the other, further downstream, is characterized by burnt gas expansion and the passage of the oblique shock wave.

Considering all the available thermal loads from the literature, Sandri et al. [4] performed a preliminary cooling requirement analysis. The outcome of their analysis showed that the combustion air alone as a coolant is no longer sufficient to optimally cool the RDC with convective cold side cooling strategies due to its thermal capacitance. They suggested that air can be used as a barrier to protect and cool the walls, and when provided as a film can protect the walls from the hot gases and even if it is disrupted by the shock wave it can rebuild itself. Hence, film cooling can be a possible solution to reduce the thermal load on the RDC walls.

2. Film Cooling configuration

The non premixed TU Berlin RDC architecture [5] was implemented with film cooling to perform high fidelity simulations. The pressure contour for the same rig without film cooling obtained by Nassini et al. [6] is depicted in Figure 1a. The region below 0.04 m is termed as the detonation region because of the presence of the high pressure detonation wave. The region above 0.04 m is called the the oblique shock region. In the current film cooling design, the film holes are distributed only in the oblique shock region, highlighted by the red dotted lines in Figure 1a, at locations from 0.04 m to 0.08 m. The detonation region was excluded from film cooling to reduce the possibility of detonation quenching due to reactant dilution caused by coolant mixing. Moreover, Tien et al. [7] observed hot gas ingestion into the coolant plenum in the detonation region.



(a)

Fig. 1: (a) Pressure contour of uncooled TU Berlin RDC. The highlighted region represents the film cooled region.

The highlighted region was populated with typical film cooling holes with a diameter (Φ) of 1 mm and an inclination of 30°along with a wall thickness of 3 mm corresponding to an L/D ratio of six. A classical staggered arrangement with pitch of 5.8 Φ in X and 4.7 Φ in the Y direction was applied. By implementing this distribution scheme, the combustor was covered with a total of 480 holes. These holes were fed from a common coolant plenum. The coolant plenum pressure (Pcool) was chosen based on the circumferential distribution of static pressure at the axial position of 0.04 m where the first row of film cooling holes are situated.

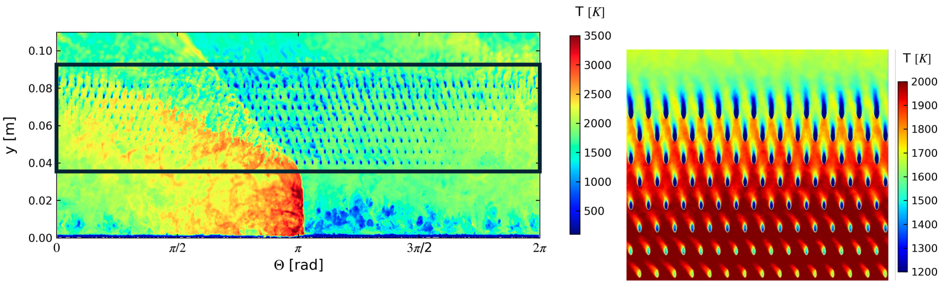
3. Numerical model

In this investigation, Large Eddy Simulations are performed using the AVBP code developed by CERFACS. AVBP solves fully compressible, multispecies, reactive Navier-Stokes equations[8]. It uses different solving schemes like Taylor-Galerkin TTG4A (Fourth order in time and third order in space) and Lax Wendroff (second order in space and time). AVBP is extensively validates for all kinds of flows including film cooling [8].

The explicit time integration is carried out enforcing a dynamically maximum CFL of 0.7 resulting in a timestep of 6 x 10^{-9} s. The WALE LES model along with the localized artificial diffusivity model is used to stabilize the solving scheme. The hydrogen air detonation is modelled using 4S1R single step reaction scheme developed by Nassini et al. [6]. The current reaction mechanism is compatible with the Lax Wendroff convection scheme. The single step reaction mechanism uses four species H_2, O_2, H_2O, and N_2 in a single reaction. The solver setup along with the time step convergence and the reaction mechanisms used for the simulation were validated by Nassini et al. [6].

4. Results

The flowfields of a film cooled RDC is similar to the uncooled RDC shown in the previous section. The flowfiels include a detonation and a shock wave rotating around an annulus at a frequency of 7 kHz with a maximum tangential velocity of 1200 m/s. The coolant entering the combustor follows the same path of main stream gases as seen in the instantaneous temperature contour obtained on the outer wall shown in Figure 2a. The detonation wave is travelling from left to right and the film cooling region is highlighted by the dark black rectangle. The region ahead of the oblique shock where maximum coolant flow is expected due to the lower chamber pressure shows a clear trace of coolant flow and its trajectory. The main stream flow angles vary along with the detonation wave leading to different coolant trajectories at different locations of the combustor. For instance, the coolant flow within the region π and $3\pi/2$ is tilted towards the left while the region with in $\pi/2$ and π is tilted towards the right. In rest of the regions the coolant flow follows a partial axial direction. The change of mainstream flow angles influencing the coolant flow trajectory has a huge impact on the wall temperature distribution.



(a) (b)

Fig. 2: (a) Temperature contour obtained on the outer wall and (b) average temperature contour.

The average gas temperature distribution obtained on the outer wall is shown in Figure 2b. The averages are performed for 30 detonation cycles. The temperature contour clearly shows the distribution of coolant flow. As reported by Ramanagar et al. [9] for the current scenario with a coolant plenum pressure of 3 bar the, coolant flow experiences a compound angel of -35°, -30°, -25° -15° for the first four rows respectively. For the rest of the rows, the flow is mostly axial in direction. These non axial coolant trajectories might diminish the film formation. To investigate the possibility of uniforming the temperature distributions by altering the coolant trajectories, compound angled holes are tested for the TU Berlin RDC. The compound angle holes alter the flow angles and help in uniforming the coolant distribution. Moreover, the compound angle hole help in reducing the amount of hot gas ingestion to the coolant plenum.

The configurations investigated in the current study are shown in Figure 3. Configuration ”b” corresponds to the baseline case with axial holes. While configuration ”b” and ”c” are with compound angle holes. In configuration ”a” the holes are rotated against the direction opposite to the rotation of the detonation wave while in configuration ”c” the holes are rotated towards the direction of the detonation wave. In both the configurations, the first four rows are tilted and the rest of the holes are axial in direction. The compound angle of first four rows are selected based on the previous study performed by Ramanagar et al.[9]. The prescribes angles are reported in Table 1. The first row experience greater tangential component from the detonation wave hence it is rotated with an angle of 25°. The compound angles of the other rows are decreased as it experiences weaker tangential component from the oblique shock.

Case	**Hole 1**	**Hole 2**	**Hole 3**	**Hole 4**
CA -X°	-25	-20	-15	-10
Axial	0	0	0	0
CA +X°	25	20	15	10

Tab. 1: Prescribed hole compound angles for the film cooling geometry.

The closeup contours of instantaneous temperatures and heat release rate for the three cases are shown in Figure 4. As observed, the detonation shape and the heat release profiles in the detonation region are similar to all the three cases. The angel of the oblique shock was observed to remain the same. Interestingly for the case CA -X°, it can be observed that the coolant flow is active in large number of holes behind the shock wave. It can be further confirmed by the heat release contours, behind the shock wave higher heat release is observed across most of the holes. Ahead of the shock wave, it seams that more coolant is entering the combustor with CA +X° holes. When comparing the heat release of all the cases, it can be observed that the coolant deflagration happens right behind the shock wave.

To understand in detail the response of the holes and the effect of compound angle on the flowfields near the wall, the mass flow inside each hole and the respective flow angels ahead of the holes are averaged for 30 detonation cycles. The mass flux of all the holes varying with the position of the detonation wave is reported

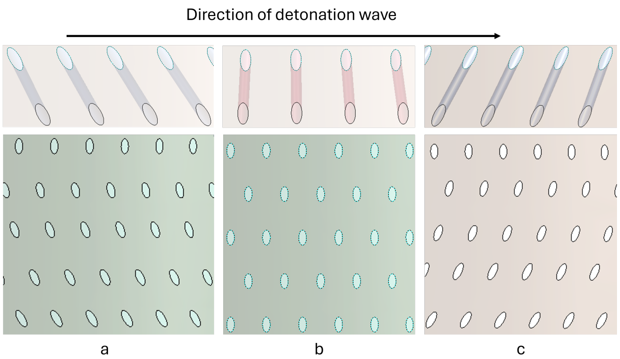


Fig. 3: (a) holes with negative compound angle, (b) axial holes and (c) holes with positive compound angles.

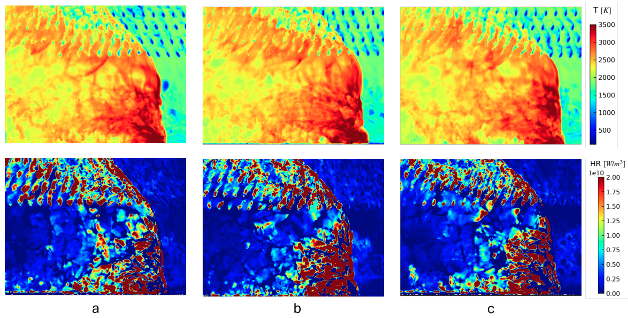
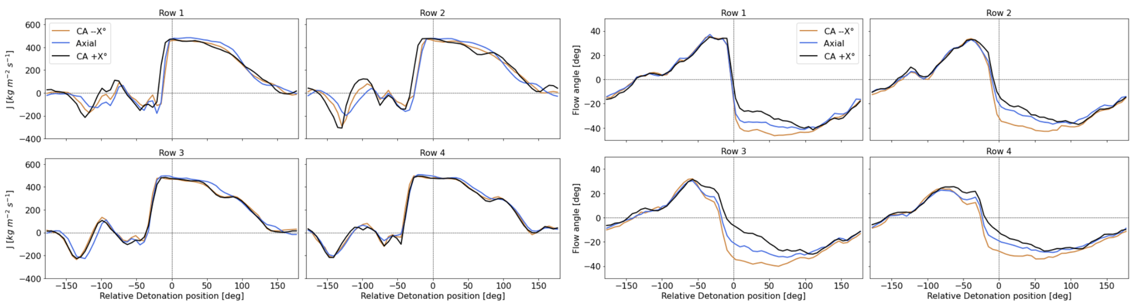


Fig. 4: Closeup Temperature contours on the top and heat release contours on the bottom for the three cases.

in Figure 5a. Only the first four rows are reported since the rest of the rows are without compound angles. For all the rows, it can be observed that the shock wave and the increase of chamber pressure behind the shock wave decreases the mass flow. For example, the shock wave is located at a relative detonation position of 0 for row 1, the coolant mass flux in the region -180 to 0 is reduced due to the shock wave and the increased local chamber pressure. The region ahead of the shock wave is where the coolant flow recovers due to lower chamber pressure. The maximum mass flow occurs right in front of the shock wave where the local chamber pressure is lower than the other regions.



(a) (b)

Fig. 5: (a) Mass flux of first four rows and (b) flow angles ahead of the film cooling holes for four rows.

The hole blockage due to the shock wave and its recovery depends on the coolant plenum pressure. For all the cases the coolant plenum pressure is set to 3 bar hence the recovery of the holes is globally similar. However, the response to the shock wave is different for the three cases. For instance, in row 1 the compound angled holes are tilted with an angle of 25°. It can be observed that the mass flux of the of compound angled cases are in offset with the axial hole case. This offset in mass flow decreases as the compound angle decreases. As observed in row 4, with a compound angle of 10° the offset between the cases are negligible. Furthermore, the compound angle holes behave differently at certain regions. In row 1 and row 2, the region between -100° and -50° the compound angle cases supply more mass flow than the axial case while the region between -150° and -100° receive greater hot gas injestion. For rows 3 and 4, due to the decrease of compound angle the region between -150° and 100° the compound angle holes are similar to the axial holes.

The compound angle holes alter the flowfiels ahead of the hole. The coolant ejected out at different direction interacts with the hot gases in a particular way leading to an change in flow direction. This can be studied in detail by looking at the flow angels. The obtained average flow angle in the regions ahead of the holes are reported in Figure 5b. For row 1, the holes are tilted with a compound angle of 25°. In baseline axial case we observe a flow angle of -35° ahead of the shock wave while the CA -X° case the flow angle reduces to -45°. In case CA +X°, the flow angles reduce to -25°. The 25° compound angle induce a change of 10 degrees with respect to the baseline axial case. For row 2, CA -X ° case induce a greater change in flow angle than compared to CA +X°. While in rows 3, a greater change in compound angles is observed however, ahead of the shock wave the differences are minimal. Moreover, a greater period of the wave is affected when compred to first two rows. Similar features are observed for row 4. The greater regions are affected in the row 3 and 4 due to that fact that the holes experience less blockage when compared to first two rows.

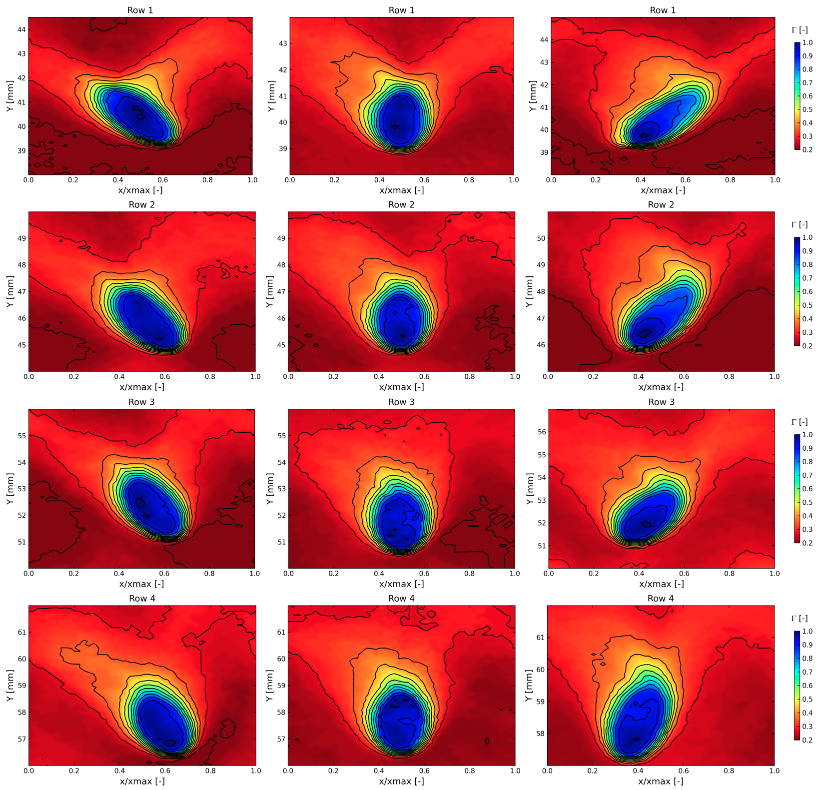


Fig. 6: Normalized averaged temperature profiles for each case.

To assess the final temperature distributions across each hole the average gas temperature near the wall is averaged along each hole. In each row there are 60 holes providing 60 sample points for the statistics. The average temperature profiles normalised with the maximum gas temperature and the prescribed coolant temperature are shown in Figure 6. For CA -X° configuration, the temperature profile for row 1 shows low temperature distributions in two directions while in the base line case most of the coolant is oriented towards the left. This is due the higher coolant flow occurring behind the shock wave which can be confirmed from the mass flux plots shown in Figure 5a and from the temperature and heat release contours shown in Figure 4. The coolant injected during the cycle where the flow angels are positive create the low temperatures which are oriented towards the right side. On the other hand in the CA +X° configuration, few holes are active behind the shock wave hence, the leaser area of low temperature region is oriented towards the right. Interestingly, the positive compound angle holes in the region ahead of the shock wave, inject coolant in the opposite direction of the flow creating a wider spread of coolant. Hence the coolant is greatly distributed across the hole.

5. Conclusion

Thermal management of the Rotating detonation combustor is a challenging task due to the combustion process leading to higher wall heat transfer. Film cooling technique can be used to isolate the walls from the harsh hot gases to protect the wall. The presence of the shockwaves in the RDC flowfield posses a challenge in developing an efficient film layer. In this regard, three film-cooled RDC configurations were tested, namely holes with negative and positive compound angles, as well as axial cylindrical holes, to assess the film's behavior. The results showed that holes with negative compound angles obtain better cooling behind the detonation wave while the positive compound angled hole provided better coolant spreading ahead of the shock wave. On the other hand, the axial holes performance falls in between the negative and positive compound angles.

The average wall temperature for negative compound angle obtain coolant spreading in two opposite directions creating a uniform y shape distribution. For the axial holes, greater coolant is spread towards the left. While the positive compound angles provide circular distribution. Overall, all the three cases provide the same coolant film development.

6. Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie grant agreement No 956803. The authors also thank Pier Carlo Nassini for his support.

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