Comparative Performance Analysis of Hollow and Annular Combustors in Rotating Detonation Engines

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Rotating detonation engines (RDEs) have emerged as a promising propulsion technology, offering superior thermodynamic efficiency over conventional Brayton-cycle engines due to their utilization of detonation combustion. Annular combustors (with inner and outer walls) are typically used in RDEs. However, hollow—lacking an inner wall—combustors are emerging as a promising alternative due to their potential mitigation of the thermal heating problem in RDEs, as well as reduced weight and structural complexity. This study conducts a literature review comparing the performance of hollow and annular combustors. Performance metrics analyzed include specific impulse, specific thrust, characteristic velocity efficiency, pressure gain, and thrust vector efficiency metrics. The results, though varied, indicate that the hollow combustor usually achieves similar or lower performance compared to the annular combustor. The performance deficit in the hollow combustor is mainly attributed to the recirculation/deflagration region in the core, along with study-specific amplifiers. Mitigation strategies such as optimizing operating conditions and flow-through combustors may allow the hollow combustor to achieve similar or even exceed the performance of annular combustors. Lastly, this study proposes tangential swirl injectors as a novel solution to suppress the recirculation issue and enhance performance. Despite some performance deficits, the hollow combustor remains a promising alternative.

Keywords: rotating detonation engine, hollow combustor, centerbody-less, annular combustor, performance.

Introduction

The primary form of propulsion in jets and rockets has been Brayton-cycle combustion. It involves four thermodynamic stages: isentropic compression, constant-pressure heat addition, isentropic expansion, and exhaust. In modern engines, the air is compressed, mixed with the fuel, and ignited, where it burns through deflagration[1]. Deflagration combustion is a type of subsonic combustion where the flame propagates through the fuel and oxidizer at subsonic speeds[2]. Since it operates at a constant pressure, no pressure gain is achieved and energy conversion efficiency is limited[3].

Detonation, by contrast, is where the flame propagates through the propellants at supersonic speeds, much faster than deflagration combustion[2]. This results in a more rapid and powerful combustion process, characterized by higher pressure gain and faster energy release. As a result, thermal efficiency is improved, yielding a performance improvement of at least 20%[4,5]. There has been a growing interest in using detonation or pressure gain combustion as a form of propulsion due to its higher thermal efficiency, performance, and reduced weight[6,7].

A few engines have been developed that utilize detonation combustion. The most extensively studied engine over the last few decades has been the pulse detonation engine (PDE). The PDE was developed in the early 2000s and was demonstrated in flight in 2008. It uses detonation waves that propagate axially numerous times per second along a long detonation tube[8,9]. A less studied engine is the standing detonation engine (SDE). The SDE aims to maintain a stationary detonation wave inside a combustor to produce thrust. However, a major limitation is its limited range of operating conditions[6].

In recent years, research efforts have shifted to the rotating detonation engine. The RDE utilizes a continuous rotating detonation wave (CRDW) that propagates around a cylindrical combustor which continuously produces thrust[10]. This allows the RDE to be more compact and efficient than conventional engines. They enable a wide range of applications from military applications to rocket engines[11,12]. The RDE offers several advantages over the PDE. It is more compact due to the absence of the long detonation tube and the compact cylindrical combustor. Moreover, it provides continuous detonation and thrust. Due to the continuous detonation, RDEs can further increase performance gains[13,14]. Additionally, it removes the necessity for periodic ignition. RDEs are generally considered more efficient by researchers, as they have demonstrated

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higher specific impulse. However, their design is more complex[6,13,14].

The conventional rotating detonation engine typically uses an annular combustor with an inner and outer wall[15,16]. However, it comes with significant thermal management issues due to the high temperatures and thermal stress from combustion, which prevent it from operating for a long duration[17]. Additionally, it was found that the inner wall experiences significantly higher temperatures than the outer wall[18,19]. In annular RDEs, the detonation wave repeatedly propagates across both the inner and outer walls. The inner wall of an annular RDE experiences higher heat flux and significantly greater thermal loading. Theuerkauf et al. found that the outer wall absorbed approximately 2.5% of the propellants' Lower Heating Value (LHV), corresponding to an average heat flux of 2.2 MW/m^2. In contrast, the inner wall absorbed about 7.1% LHV with an average heat flux between 5.0 and 6.7 MW/m^2 during steady-state RDE operation[18]. This would necessitate extra structural elements and added complexity to manage the heat, increasing weight, cost, and reducing reliability during long-duration operation[19].

A plausible explanation for this is that in conventional annular rotating detonation engines, the inner wall of the annulus is where the rotating detonation wave and its associated shock reflections concentrate the hottest, highest-pressure products. As a result, it naturally becomes an area of concentrated thermal stress. Repeated passage of the detonation front and reflected shocks near this small-radius wall keeps high-temperature combustion products pressed against the surface. This causes large convective heat transfer and rapid wall heating. From a fundamental heat-transfer perspective, the local wall heat flux can be approximated as $q'' = h(T_g - T_s)$, where T_g is the gas temperature right next to the wall, T_s is the surrounding or in this case, the wall temperature, and h is the convective heat-transfer coefficient, which increases with local gas density and velocity. In an annular combustor, both T_g and h at the inner wall are high because the gas there is repeatedly re-energized by detonation and shock interactions, so q'' on the inner cylinder can reach extreme values and drive ablation and very demanding cooling requirements.

When the inner wall is removed to form a "hollow" combustor, the region where this energy focusing used to occur is no longer a solid boundary but a gas core. Consequently, the detonation products and shock structures expand inward into the center rather than impinging on metal, and the strongest shockwave interactions occur within the flow instead of at a wall. This change redistributes the thermal energy because the hottest gas now occupies the interior core and exits through the nozzle instead of being between two close walls. Meanwhile, the remaining outer wall is shielded by a thicker, partially cooled boundary layer with lower near-wall gas temperature and reduced local mass flux, which lowers both T_g and h in the expression for q''. As a result, removing the inner wall largely eliminates the severe inner-cylinder heat load characteristic of annular RDEs.

For these reasons, a hollow combustor has been considered as an alternative design[20,21]. In contrast to the annular combustor, the hollow combustor has no inner wall and only has an outer cylindrical wall (see Figure 1 for comparison of hollow and annular geometries). With the elimination of the inner wall, only cooling for the outer wall is necessary. This significantly simplifies RDE design, reduces cooling requirements, and improves reliability.

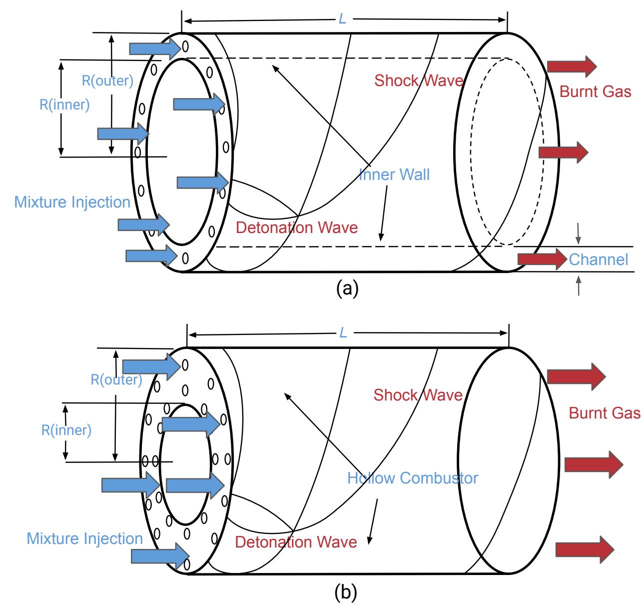

Fig. 1 Schematic of (a) annular and (b) hollow rotating detonation combustor geometries showing detonation and shock wave propagation[21].

The results of many studies have experimentally validated the hollow combustor for successful generation and propagation of a detonation wave. Bykovski et al. first demonstrated continuous detonation in a hollow combustor with hydrogen, methane, kerosene and diesel with air in 1997[22]. They observed two different propagation modes, with one mode having the characteristics of spinning detonation and the other having a complex combination of oblique shock waves, detonation fronts, and reflected waves without a Mach stem. Tang et al. aimed to verify the hollow combustor and found that there are no repeated reflected shockwaves and a deflagration zone in the core[21]. Moreover, numerous studies report higher detonation wave velocities than annular configurations[23–27]. Additional studies have shown the hollow combustor to reduce injection pressure losses[23,28]. As illustrated in Fig. 8

of Zhang et al. (2023), the hollow configuration maintained detonation at visibly lower injection pressure ratios, on the order of 1.5 to 2.0, compared to values above 2.5 for the annular case. This indicates a notable reduction in pressure loss across the injectors[28]. Reducing injection pressure losses in rotating detonation engines has been a topic of major interest in the scientific community recently. Researchers are making efforts to reduce injection pressure losses to prevent engine performance degradation[29–31]. Moreover, the hollow combustor has been observed to have additional operational benefits such as operating successfully at a broader range of equivalence ratios[25,32,33] and higher detonation probability[23]. It has also demonstrated shorter transition time and easier detonation initiation[25], and a greater allowance for fresh mixture injection[26].

Despite growing research in hollow combustors, there is varied and limited literature comparing their performance to annular combustors. This paper aims to address this gap by providing an in-depth comparative performance analysis of the hollow and annular combustors. The two combustor geometries are compared under similar operating conditions and a normalized relative performance metric is developed for comparative analysis across studies.

Methodology

Data Selection and Analysis

This study conducts a comprehensive literature review on comparing the performance of hollow and annular combustors in rotating detonation engines using peer-reviewed sources from academic journals. Databases include AIAA, ResearchGate, Google Scholar, and ScienceDirect. Keywords include ‘rotating detonation engine,’ ‘hollow combustor,’ ‘annular combustor,’ ‘centerbody-less,’ ‘performance,’ ‘comparison.’ Computational and experimental studies were utilized.

Given the significant variation in operating parameters across studies, cross-study quantitative comparisons are excluded except in cases where authors directly referenced annular combustor data from their own or other studies under comparable conditions. Such comparisons would ignore the impacts of the varying operating parameters. Hence, this study focuses on within-study comparisons to isolate the impact of combustor geometry, hollow and annular, while controlling operating parameters. Sources that directly tested hollow and annular combustors within the same experiment were prioritized. However, due to the limited availability of literature, sources that were used to test the performance of hollow combustors while referencing past annular configurations with similar operating parameters from their own work or other works were also included. Some important operating parameters, performance metrics, and qualitative factors impacting the relative performance are noted.

Table 1 Operating parameters, performance metrics, and qualitative factors affecting performance noted.

Operating Parameters	Examples
Geometry / Dimensions	Length, inner/outer radius, channel width, nozzle
Injection	Configuration, injection area ratio, number of orifices
Propellants	Fuels, oxidizer/air
Operating Conditions	Mass flow rate, equivalence ratio, backpressure, premix
Performance Metrics	Specific impulse, specific thrust
Qualitative Factors	Deflagration/recirculation zone, mixing inefficiencies

Studies comparing hollow and annular combustors with fundamentally different nozzle configurations were excluded from propulsive performance. This is because nozzle design strongly influences expansion efficiency and would confound geometric comparison. Combustion performance metrics that are independent of nozzle effects were unaffected. These include characteristic velocity efficiency, n_{c^*} (discussed in 2.2.1).

Both experimental and numerical studies were included in this review because the objective of the analysis is to compare the relative performance of hollow and annular combustors within each individual study, rather than to aggregate absolute performance across different sources. For each study, the relative performance difference (δ_X) was computed only from cases that shared the same numerical framework or the same experimental facility, ensuring that modeling assumptions or facility-specific biases remained internally consistent. Because δ_X is a normalized, within-study metric, systematic differences between experiments and simulations (such as idealized boundary conditions or neglected heat losses) do not affect the comparative geometry trend, and no direct averaging was performed between experimental and numerical datasets. Instead, simulation and experimental results contribute separately to the overall trend analysis, consistent with standard comparative methodology in propulsion literature.

Performance Metrics

Overall Propulsive Performance

The two key parameters in assessing the overall propulsive performance of rotating detonation engines are specific impulse and specific thrust[34]. The specific impulse, I_{sp}, is the amount of thrust produced per unit of weight of propellant consumed. It measures the effectiveness of the engine in using propellant to produce thrust. However, its use varies between air-breathing and rocket engines since the propellants are slightly different. Air-breathing engines only carry fuel, while rocket engines carry both the fuel and oxidizer. Hence, the fuel-based specific impulse is primarily reported in air-breathing engines, while the total propellant-based specific impulse is reported in rocket engines. The specific impulse is given by

$$I_{sp} = \frac{F}{\dot{m}_p g_o}, \tag{1}$$

Where F is the total thrust, m_p is the mass flow rate of the propellant, and g_o is the acceleration of gravity.

For this study, specific impulse is discussed separately as total-propellant-based and fuel-based metrics, reflecting differences in reporting conventions between rocket and air-breathing RDE studies.

The specific thrust, F_{sp}, is the amount of thrust produced per unit of mass of air consumed. It is primarily used in air-breathing applications to measure the effectiveness of the engine in utilizing airflow to produce thrust. It is computed using the following expression.

$$F_{sp} = \frac{F}{\dot{m}_{air}}, \tag{2}$$

where m_{air} is the air mass flow rate.

Combustion Performance

While the specific impulse and specific thrust measure the efficiency of the entire engine, the characteristic velocity efficiency, n_{c^*}, is used to assess only the performance of the combustion, independent of nozzle effects. It is given by

$$n_{c^*} = \frac{c^*_{\text{exp}}}{c^*_{theo}}, \tag{3}$$

where c^*_{exp} is the experimentally obtained characteristic velocity, and c^*_{theo} is the theoretical characteristic velocity[35]. Where the experimental characteristic velocity is given by

$$c^*_{\text{exp}} = \frac{p_c A_t}{\dot{m}}, \tag{4}$$

where p_c is the stagnation pressure in the combustion chamber, A_t is the nozzle throat area, and $\dot{m}$ mass flow rate; and the theoretical characteristic velocity is given by

$$c^*_{\text{theo}} = \frac{\sqrt{\gamma R T_c}}{\gamma \sqrt{\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}}, \tag{5}$$

where T_c is the combustion chamber temperature, R is the universal gas constant, and γ is the ratio of specific heats[35].

Pressure gain is a key metric for evaluating the performance of rotating detonation engines, quantifying their advantage over conventional Brayton-cycle engines. Higher pressure gain reduces energy losses, and improves engine efficiency and thermodynamic performance. It is essentially the net increase in total pressure achieved across the combustor through detonation combustion. However, the methods to calculate it vary across studies.

Thrust Vector Efficiency Metrics

The kinetic energy proportion in the axial direction (E_w) is the effective energy proportion for thrust, since at the chamber exit, only the axial velocity w can produce thrust. It is given by

$$E_w = \frac{\int \rho\, w^2\, dA}{\int (u^2 + v^2 + w^2)\, dA}, \tag{6}$$

where ρ is the density of the gas at the chamber exit, w is the velocity in the axial direction, u and v are the velocity components along the x-axis and y-axis, respectively, and dA is the differential area of the exit plane[24,36,37].

The ratio of thrust generated by momentum to total thrust (f_{mv}) is given by

$$f_{mv} = \frac{\int \rho\, w^2\, dA}{\int (\rho\, w^2 + p - p_b)\, dA}, \tag{7}$$

where ρ is the density of the gas at the chamber exit, p is the pressure at the chamber outlet, p_b is the ambient (back) pressure, w is the velocity in the axial direction, and dA is the differential area of the exit plane[24].

Wave Speed

While it is commonly believed that wave speed positively correlates with performance, its effect on performance is inconsistent. Paxson et al. found that wave speed had a negligible impact on performance as measured by the specific impulse[38]. Additionally, Zhang et al. and Bigler et al. found a negative correlation between wave speed and performance[23,38,39], although it is worth noting that these findings emerged from investigations using different combustors and operational modes. Moreover, for this study specifically, the data does not demonstrate a correlation between wave speed and performance. Thus, wave speed will not be considered a primary performance metric in this paper due to the lack of demonstrable and reliable correlation with performance.

Detonation Probability

Detonation probability, defined as the likelihood that a detonation wave can be initiated or sustained, is not included as a performance metric in this study. Although relevant to operability, it is not a measure of propulsive or combustion performance, unlike specific impulse, specific thrust, characteristic velocity efficiency, or pressure gain. Additionally, the available data are far too limited to support a meaningful comparative evaluation. For these reasons, detonation probability is excluded from the performance assessment.

Comparison Protocol

This paper compares studies on their individual reported data. Studies were evaluated on the relative performance data of the hollow compared to the annular combustor reported. The relative performance from each study was synthesized across studies, respecting the context of each individual study's operating parameters. To evaluate the relative performance within a metric, the performance difference of the hollow and annular configurations was calculated relative to the annular combustor. To quantify the relative performance difference between the combustor geometries with the annular as a baseline, a normalized performance metric will be defined δ_X.

$$\delta_X = \frac{\bar{X}_{\text{hollow}} - \bar{X}_{\text{annular}}}{\bar{X}_{\text{annular}}} \times 100\% \tag{8}$$

Where, $\bar{X}_{\text{hollow}}$ denotes the mean value of the general performance metric X (such as I_{sp} or F_{sp}) for hollow combustor cases, while $\bar{X}_{\text{annular}}$ represents the corresponding mean value for annular combustor cases. The quantity δ_X indicates the signed relative difference of a metric, where a negative value of δ_X signifies a performance deficit in the hollow combustor, and a positive value indicates a performance gain in the hollow combustor. The values of each metric reported by individual studies ranged from single-case results to multi-case parametric sweeps. For studies reporting only one hollow–annular pair, the mean corresponds directly to the single available measurement. For studies reporting multiple cases under closely matched operating conditions, using the mean reduces random variability while preserving the underlying geometric effect. Because the number of cases per configuration was small in several studies (typically 1–5), median and mean values are effectively identical in all included datasets. Therefore, the mean was used consistently for δ_X to maintain a uniform comparison framework across studies.

Direct Experimental Investigations

Within-study comparisons were made for studies that directly tested hollow and annular configurations within the same investigation. For studies with multiple cases and closely matched operating conditions for the hollow and annular configurations, the relative performance difference δ_X between the means of the hollow and annular cases was calculated.

In this work, a *tolerance* is defined as the maximum allowable relative deviation between the hollow and annular cases for a given operating parameter. Because published RDE experiments and simulations rarely match every parameter exactly, small deviations must be permitted. A tolerance therefore sets an upper limit on how much variation is acceptable before a difference in geometry, mixture preparation, or injection characteristics would begin to influence detonation behavior.

Table 2 Tolerances for Operating Parameters

Operating Parameter	Tolerance (%)
Geometric dimensions	1
Equivalence ratio	10
Mass flow rate	10
Injection area	1

For each parameter X (such as geometric dimensions, equivalence ratio, or mass flow rate) the mismatch between the hollow and annular configurations was computed as

$$\Delta_X = \frac{|X_{\text{hollow}} - X_{\text{annular}}|}{\frac{1}{2}(X_{\text{hollow}} + X_{\text{annular}})} \times 100\% \tag{9}$$

Here, Δ_X represents the percent difference based on the mean of the two values. The numerical tolerances τ_X listed in Table 2 specify the largest Δ_X that is still considered negligible for each parameter. Accordingly, two operating points were classified as operationally equivalent within prescribed tolerances only if

$$\Delta_X \leq \tau_X, \tag{10}$$

for every reported parameter X. Within this framework, two operating points are treated as operationally equivalent only when all reported parameters fall within their respective tolerance ranges. This ensures that any performance differences observed between hollow and annular combustors arise from the configuration itself and not from changes in mixture state, mass flow rate, injection design, or geometric layout. The relative performance difference δ_X of the means of the hollow and annular pairs was then calculated.

Table 3 Example of tolerance-based pairing of hollow and annular operating points taken from Kawasaki et al., using run 1 (hollow) and run 2 (annular) as the paired cases[27].

Parameter	Hollow (run #1)	Annular (run #2)	Mismatch (Δ_X)
Mass flow rate (g/s)	130 ± 13	138 ± 14	5.97
ϕ (dimensionless)	1.19 ± 0.1	1.13 ± 0.1	5.17
Chamber pressure (kPa)	47 ± 3	47 ± 3	0

This example demonstrates how tolerances were applied when determining whether hollow and annular cases were comparable. Mass flow rate and equivalence ratio fall within the allowable difference, and chamber pressure is fully matched. By establishing tolerance bounds, paired cases can be considered operationally equivalent, ensuring that observed performance differences originate from geometry rather than uncontrolled variation in input conditions.

Cross-Study References

Cross-study comparisons were restricted to studies that referenced a previous annular configuration, whether in the same team or another laboratory. Comparisons were undertaken when operating conditions could be matched as closely as possible to preserve the fairness of the comparison. When operating parameters matched, the relative performance difference δ_X was calculated between the means of the cases of each geometry. However, if the operating parameters differed or varied within a study, individual cases for the two geometries were paired based on the closest matching operating parameters to ensure fair comparison, and the δ_X was evaluated.

Interpretation of Conflicting Results

Because the literature reports divergent findings, particularly in propulsive performance, conflicting results were not weighted or forced into a single averaged trend. Instead, discrepancies were analyzed mechanistically. When studies disagreed, differences were interpreted in the context of operating conditions and known amplifying factors. Direct within-study comparisons were treated as the most reliable, while cross-study comparisons were used only when operating parameters were closely matched. Rather than prioritizing any single data source, conflicting studies were incorporated to reveal the physical mechanisms that govern performance variation between hollow and annular combustors.

Data Synthesis

Although the literature is limited and the data is varied, synthesis of collected data was taken to identify and analyze trends. The diversity and variation of operating parameters across studies posed a significant challenge to aggregating data for a unified comparative assessment and conducting cross-study comparisons. Nevertheless, to synthesize data for comparative analysis, this study uses the relative performance difference δ_X as a normalized metric across studies, quantifying how the hollow combustor performs relative to the annular one. Studies were grouped and analyzed by performance metric to allow metric comparisons. For the propulsive performance, they were further categorized based on the quantified performance differences δ_X —within 5%, 5-15% lower, over 15% lower, or even higher—compared to the annular. For other metrics, studies were simply categorized as reporting higher or lower performance compared to the annular combustor due to the very limited data available.

For instance, in Xu et al., the hollow configurations produced a mean I_{sp} of 255*s* compared to the corresponding annular cases of 250*s*. Using Eq.(8). $\delta_{I_{sp}} = 2\%$, which falls in the within 5% category of propulsive performance.

Graphs were developed for primary performance metrics, especially the propulsive efficiency, as these metrics contained sufficient data to support visual analysis. These graphs quantified the performance of each combustor within individual studies, as well as the relative performance of the hollow combustor compared to the annular one. Additionally, graphs were made to highlight specific trends and observations in the data.

Synthesis also focused on identifying underlying reasons why the hollow exhibited lower performance across studies compared to the annular combustor. Primary causes such as the deflagration/recirculation zone, as well as study- specific factors for investigations that reported significantly lower propulsive performance—over 15% lower specific impulse and specific thrust—were identified and analyzed to explain the observed performance disparity. Several studies reported qualitative physical phenomena that contributed to performance differences. To ensure consistency across studies, qualitative factors were included only when explicitly identified by the original authors. Additionally, the phenomenon had to be known from RDE literature to directly affect performance and to correspond with a quantifiable performance deficit. Each factor was classified as an 'amplifier' only when it satisfied these criteria and represented a mechanism capable of increasing the magnitude of the performance deficit. This framework ensured that qualitative judgments were standardized and not inferred subjectively.

Finally, this study includes a review of proposed solutions aimed at mitigating the performance deficit in the hollow combustor. This includes proven remedies from existing research, as well as a new potential solution—tangential swirl injectors—proposed by the author for future research.

Results

Overall Propulsive Performance

Studies show that the specific impulses of the hollow combustors indicate mainly similar (±5%) or lower (>5% lower) performance than the annular combustors. The primary reason for this performance deficit in the hollow combustors is a recirculation region (further discussed in Section 4.2.1).

Total-Propellant-Based Specific Impulse (Isp)

Most studies reported similar total-propellant-based Isps for the two combustors within a difference of 5%[24,40–44]. Xu et al. reported that the hollow combustor reached up to a specific impulse of 260*s*, consistently 1-3% higher than the

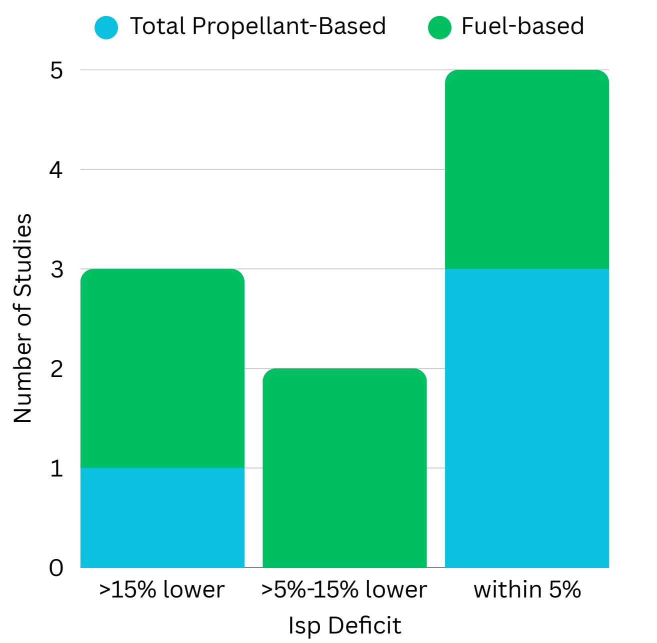

Fig. 2 Distribution of $\delta_{I_{sp}}$ across studies

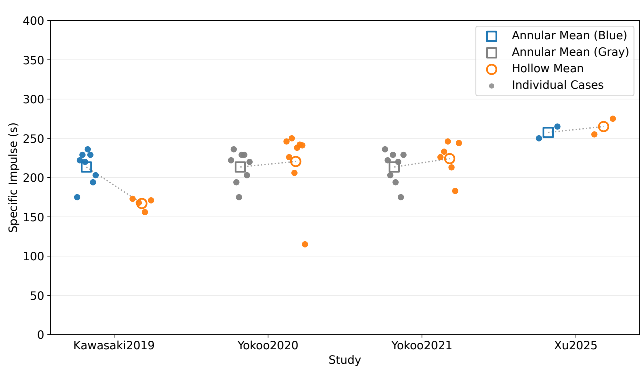

Fig. 3 I_{sp} (total propellant-based): hollow vs annular across studies

annular combustor for all diameters tested, which attained up to 253s[24]. Yokoo et al. found that the hollow combustor achieved similar specific impulses to the previous annular combustor tested by the same group, ranging from 115s to 242s[27,42–44]. On average, the hollow combustor showed a 3.3% higher specific impulse than the previous annular configurations tested.

However, one study reported significantly lower total-propellant-based I_{sp}, with a deficit of over 15% for the hollow combustor compared to the annular[27]. Kawasaki et al. found that the hollow configurations achieved specific impulses ranging from 150s to 180s, which was 25-30% lower than the annular configurations of 170s to 240s[27]. However, it is important to note that this performance deficit was mitigated by the same group in later studies[42–44] by adjusting the mass flux and operating conditions (discussed further in Section 4.3.1).

Fuel-based Specific Impulse (I_{sp})

Some studies reported similar fuel-based I_{sp} for the two combustors within a difference of 5%. Tang et al. in 2013 reported a specific impulse of 1900s for the hollow combustor, which was 5% lower than the annular[40]. Yao et al. tested four cases of the hollow combustor with different injection surface ratios varied from 56 to 84% and reported a specific impulse of $6700-7800s$[41], which falls in the range of previous annular results reported by Fotia et al[45] and Yi et al[46]. However, it is important to note that the range given by Yao et al. is wide, from 5300s by Fotia et al. to over 8000s by Yi et al.

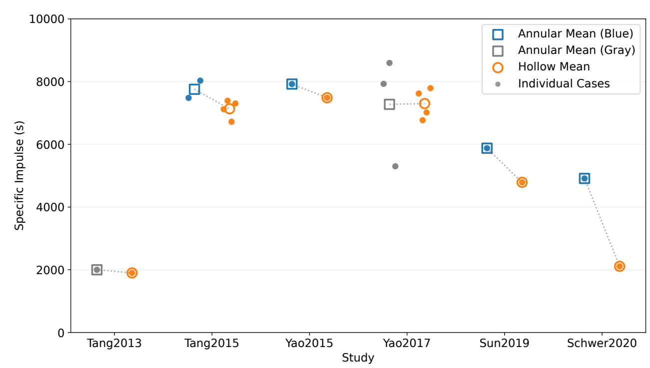

Fig. 4 I_{sp} (fuel-based): hollow vs annular across studies

Two studies also reported slightly lower fuel-based specific impulse with a difference of over 5 to less than 15% deficit for the hollow compared to the annular[21,47]. Tang et al. found that the hollow combustor cases showed specific impulses from 6720 to 7390, which was on average 8% lower than the annular cases[21]. Yao et al. tested a hollow and annular RDE with a de Laval nozzle and found that the hollow RDE reached up to a specific impulse of 7484s, which was 5.5% lower than the annular RDE of 7921s[47].

However, two studies reported significantly lower fuel-based specific impulse over a 15% deficit for the hollow combustor compared to the annular[26,36]. Schwer et al. reported that the hollow combustor showed a fuel-based specific impulse of 2110s, 57% lower compared to the annular combustor of 4912s[26]. Sun et al. found that the hollow combustor showed a fuel-based specific impulse of 4788s, which was 18.5% lower compared to the annular at 5877s[36].

Specific Thrust (F_{sp})

The hollow combustor usually performs worse than annular. The results for the specific thrust align closely with those of the fuel-based specific impulse.

Tang et al. showed that the hollow configurations achieved specific thrusts ranging from 1829 to 2012, around 8% lower than the annular configurations of 2034 and 2195[21].

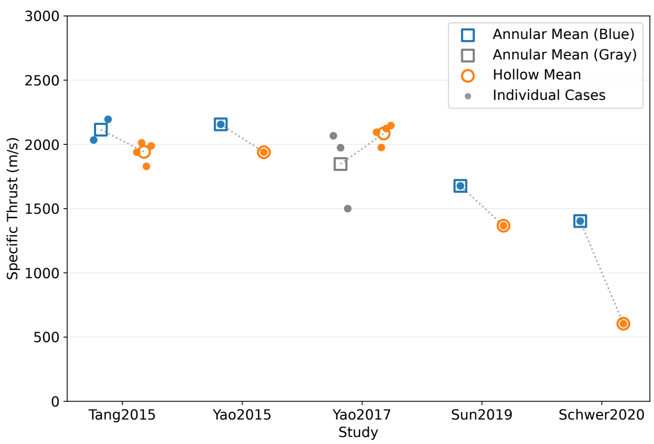

Fig. 5 Specific thrust: hollow vs annular across studies

Most studies, however, show greater deficits. Schwer et al. and Sun et al. showed significantly lower specific thrust[26,36,47]. Schwer et al. showed that the hollow had a specific thrust of 604, which was 57% lower than that of the annular combustor of 1403[26]. Yao et al. found that the hollow configurations attained a specific thrust of up to 1939, around 10% lower than the annular, which was calculated at around 2156[47]. Sun et al. found that the hollow combustor achieved a specific thrust of 1367, which was 18.5% lower compared to the annular at 1677[36].

Combustion Performance

Characteristic Velocity Efficiency n_{c^*}

Zhang et al. was the only study that reported the characteristic velocity efficiency n_{c^*} found that the hollow showed a slightly lower n_{c^*} for the hollow combustor compared to the annular[23,28]. For the two exit throat area ratios tested by Zhang et al., the hollow combustor reached a n_{c^*} of 0.70 at Ath/Ain of 2.7 and 0.79 at Ath/Ain of 5.3, whereas the annular reached 0.75 and 0.84 respectively, which was around 5-6% higher in each case than the hollow.

Pressure Gain

Two studies report pressure gain in comparisons. Schwer et al. reported similar pressure gain[48]. Schwer et al. tested the hollow and annular combustors with CD-nozzles and reported a pressure gain of 0.87—1.08 for the hollow RDE, where the 0.87 was an outlier, and 0.93—1.10 for the annular RDE. Wang et al. reported a pressure gain of 20—58% in the hollow configuration compared to less than 13% in the annular configuration[49].

Other data reports peak static pressures in hollow and annular combustors. Xu et al. reported that the hollow had a significantly lower average peak pressure of 0.42 MPa compared to 0.92 MPa of the annular[24]. Tang et al. also reported lower average static pressure at 0.60 MPa for hollow compared to 0.92 MPa for the annular[21]. A cause for this could be the lack of an inner wall, which creates a greater volume and cross-sectional area, which in turn decreases static pressure (discussed in section 4.1.2).

Thrust Vector Efficiency

Kinetic Energy Proportion in the Axial Direction: (E_w)

Xu et al. reported E_w values of 64.4%, and 66.2% for the hollow configurations, which is on average a 31% relative decrease compared to 92.9% and 95.7% for the corresponding annular configurations of the same diameters[24]. Schwer et al. reported an E_w of 85% for the hollow combustor which is a 7.6% relative decrease compared to 92% for the annular combustor. Tang et al.[21] and Yao et al.[41] reported an E_w of 89.1% for the hollow combustor which is only a 0.9% relative decrease compared to 89.9% for the annular configuration.

Momentum Thrust Contribution: (f_{mv})

Xu et al. also measured the ratio of thrust generated by momentum to the total thrust and found that the hollow showed around 8—13% lower f_{mv} values than the annular[24]. Xu et al. report that the hollow combustor delivers f_{mv} of 20.8% and 23.6% for an outer diameter of 40 and 60 mm, versus 22.7% and 27.0% for the annular at those respective diameters.

Discussion

Performance Comparison Analysis

Propulsive Performance

The results, while varied, indicate that the hollow combustor usually exhibits propulsive performance comparable to or lower than that of the annular combustor. The hollow combustor frequently shows a similar or reduced specific impulse. However, results are varied. The hollow combustor showed

Table 4 Summary of experimental and numerical studies on hollow and annular rotating detonation rocket engines

Study (Author, Year)	Geometry	Injection	Propellants	Mass Flow Rate ($\dot{m}$)	Equivalence Ratio (ϕ)	δI_{sp}
Xu et al. (2025)	Annular: $R_i = 27$ mm, $R_o = 30$ mm ($\Delta = 3$ mm); Hollow: $R_o = 30$ mm; Length = 36 mm	O_2: annular slit ($\Delta = 0.24$ mm) H_2: 90 holes ($d = 0.48$ mm); Slit-hole injection; non-premixed	H_2/O_2	Not specified	0.5 ± 0.06	+2–4
Kawasaki et al. (2018)	Annular: $r_i = 9$–31 mm, $r_o = 39$ mm; Length = 70 mm	Doublet impinging injection; non-premixed; 120 holes ($d = 1$ mm), $r_{\text{inj}} = 35$ mm	C_2H_4/O_2	130–142 g/s	1.01–1.34	–25–30
Yokoo et al. (2020)	Hollow ($r_i = 0$); $D_o = 20$ mm ($R_o = 10$ mm); Length = 20/40/70 mm	24 doublet pairs; Fuel ring: diameter = 9 mm; Ox ring: diameter = 15 mm; Impingement angle (θ) = 45°	C_2H_4/O_2	22–41 g/s	1.3–1.8	± 5
Yokoo et al. (2019)	Hollow ($r_i = 0$); $D_o = 20$ mm ($R_o = 10$ mm); Length = 70 mm	24 doublet holes; Fuel ring: diameter = 9 mm; Ox ring: diameter = 15 mm; $\theta = 90°$	C_2H_4/O_2	8–45 g/s	N/A	± 5

Table 5 Summary of studies on hollow and annular air-breathing rotating detonation combustors.

Study (Author, Year)	Geometry	Injection	Propellants	Mass Flow Rate ($\dot{m}$)	Equivalence Ratio (ϕ)	$\delta_{I_{sp}}$	$\delta_{F_{sp}}$
Tang et al. (2013)	Hollow combustor: Outer radius: 6 cm; Length: 12 cm	Type: Continuous, premixed; Area: Outer ring (r $\geq R_{inner}$)	H_2/Air	450 kg/m²·s (surface-specfic)	Stoichiometric ($\phi = 1$)	-5	–
Tang et al. (2015)	Hollow combustor: Outer radius: 6–12 cm; Length: 12 cm	Type: Continuous, premixed; Area: r $\geq R_{inner}$	H_2/Air	3.63–15.25 kg/s	Stoichiometric ($\phi = 1$)	-8	-8
Yao et al. (2017)	Hollow combustor: Outer radius: 6 cm; Length: 12 cm	Type: Continuous, premixed; Injection surface area ratio = 55.6–88.9% (varied)	H_2/Air	Not explicitly stated	Stoichiometric ($\phi = 1$)	-11 to +36	+12 to +15
Schwer et al. (2020)	Annular: D_{inner} = 9 cm, D_{outer} = 10 cm; Hollow: R_{outer} = 10 cm; Length: 12 cm	Ideal injector (Laval nozzles), choked flow modeled;	H_2/Air (premixed)	Annular: 0.488 kg/s; Hollow: 0.574 kg/s Flow-through: 0.460 kg/s	Stoichiometric ($\phi = 1$)	-57	-57
Yao et al. (2015)	Hollow combustor: Inner radius: 0 mm; Outer radius: 6 cm; Length: 12 cm	Premixed, injected via micro nozzle inlets	H_2/Air (stoichiometric)	3.63–6.68 kg/s	Stoichiometric	-5.5	-10
Sun et al. (2019)	Hollow combustor: Inner radius: 0 mm; Outer radius: 6 cm; Length: 12 cm	Non-premixed injection Air: annular slot (throat width = 1 mm)	H_2/Air	500 g/s total H_2: 14.15 g/s Air: 485.85 g/s	Stoichiometric ($\phi = 1$)	-18.5	-18.5

mostly similar propellant-based specific impulse, with one exception by Kawasaki et al., which was later mitigated in subsequent experiments by the same group, Yokoo et al. However, the hollow combustor frequently showed lower fuel-based specific impulse. Additionally, the trends observed in specific thrust closely align with those of the fuel-based specific impulse. This is because the mass flow rate ratio of fuel to total propellant was kept constant across hollow and annular configurations within most studies. The primary cause of the performance deficit in hollow configurations compared to annular configurations is the deflagration/recirculation zone (discussed in Section 4.2.1). However, there are additional study-specific factors that amplified the performance deficit in the hollow combustor reported (discussed in section 4.2.2).

Combustion Performance

The primary metrics reported by studies to evaluate combustion performance are the pressure gain and characteristic velocity efficiency. While these metrics are important in assessing the combustion performance for this study, there is very limited data on combustion-specific performance metrics reported by studies comparing hollow and annular combustors. Only one study reports the characteristic velocity efficiency, showing slightly lower values for the hollow combustor.

For pressure-related performance, four studies report data with mixed outcomes. The results indicate that the hollow combustor achieves similar or higher pressure gain but exhibits lower peak static pressures. A likely explanation for this contrasting behavior is that, while the detonation still induces a strong rise in total pressure, the removal of the inner wall increases the effective flow area and permits inward radial transport of the burned products. This reduces local static pressure, even as the overall pressure gain remains high, because the pressure generated by the detonation is distributed through a larger volume rather than confined between two walls.

Thrust Vector Efficiency

The metrics assessed in this section are the kinetic energy proportion in the axial direction, E_w, and the ratio of thrust generated by momentum to total thrust, f_{mv}. Results indicate that the hollow combustor exhibits similar or lower E_w values.

A possible reason for the E_w deficits reported in the hollow combustor is the presence of a deflagration-dominated core, driven by inward radial transport of burned products and reactants following removal of the inner wall. From Eq. (6), E_w decreases when axial velocity w contributes less to the total kinetic energy relative to the transverse components. In the central region of the combustor, inward-directed radial transport and partial stagnation lower w^2 while increasing u^2+v^2. Consequently, this core region adds minimally to the numerator of Eq. (6) but contributes significantly to the denominator, yielding a net reduction in E_w.

However, in Fig. 6, it can be seen that hollow configurations which were premixed demonstrated E_w values closer to those of annular configurations. This shows that premixed fuels may enable hollow combustors to convert kinetic energy into thrust more efficiently, offering potential for greater performance and efficiency.

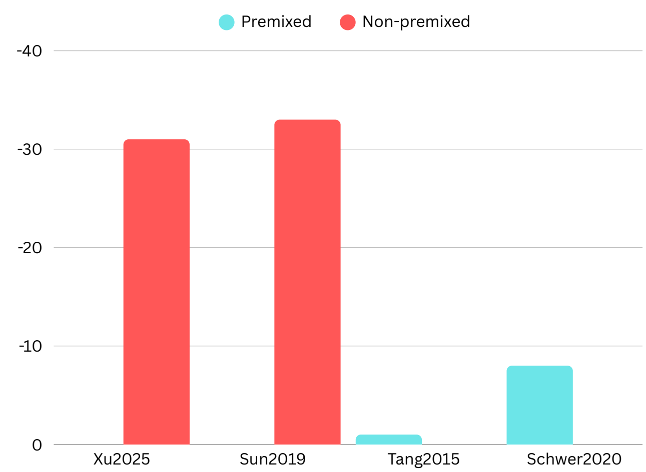

Fig. 6 Comparison of δ_{E_w} in hollow vs annular combustors across premixed and non-premixed conditions. The x-axis lists individual investigations (Xu2025, Sun2019, Tang2015, Schwer2020), and the y-axis represents the δ_{E_w}

.

A possible reason for this is that premixing helps mitigate the deflagration core that lowers E_w efficiency. A uniformly premixed flow promotes continuous annular detonation, reducing the formation of low-reactivity pockets that otherwise drive radial inflow toward the centerline. In the context of Eq.(6), these conditions increase axial velocity w while reducing transverse kinetic components u^2+v^2, resulting in an increase in E_w.

Additionally, only one study reports the momentum thrust contribution f_{mv}, showing lower values for the hollow combustor. A possible reason for this deficit is also the recirculation core. From Eq.(7), f_{mv} decreases when the exit-plane axial momentum flux, $\int \rho w^2 dA$, is reduced relative to the total thrust $\int(\rho w^2+(p-p_b))dA$. In the hollow geometry, inward expansion and the recirculation core produce a larger region with weakened axial transport, which directly lowers the momentum term through both reduced w (decreased quadratically) and reduced density in the expanded and heated products. Because the denominator still contains the pressure-thrust contribution, the total thrust does not decrease proportionally to the loss in ρw^2, so the fraction of thrust attributable to momentum is lower. This is consistent with the reduced f_{mv} reported for hollow configurations.

Problems Degrading Performance in Hollow Combustors

There are critical issues observed that have contributed to performance deficits in the hollow combustor relative to the annular. The primary issue is the deflagration/recirculation region in the hollow core. However, there are other factors that exacerbated the performance deficit in studies that reported large propulsive performance deficits (characterized by $\delta_{I_{sp}}$ or $\delta_{F_{sp}}$ values less than 15% relative to annular combustors). This section summarizes these issues and the mechanisms through which they degrade performance in the hollow combustor.

Recirculation Region

The primary mechanism degrading performance in hollow combustors is the recirculation/deflagration region that forms in the core with the removal of the inner cylinder. In an annular RDE, the inner wall blocks inward expansion and confines the detonation products to a narrow annulus, so most of the injected mixture is directed azimuthally through the detonation front and then accelerated toward the exit. However, in a hollow combustor, the absence of the inner wall allows a low-pressure channel to develop along the centerline. High-pressure burned products and unburned reactants expand radially inward into this core, where the flow decelerates and travels into a recirculation cell. Within this cell, propellants undergo inefficient mixing and predominantly subsonic, near-constant-pressure deflagration instead of detonation, as reported in multiple numerical and experimental studies of hollow configurations[21,26,27,41,50].

This recirculating core likely degrades performance through several coupled effects. First, propellant that is diverted into the core is no longer processed efficiently by the rotating detonation wave. Because the combustion in this region is slower and closer to constant-pressure heat addition, it increases entropy without generating a commensurate rise in stagnation pressure. As a result, a significant portion of the propellant's chemical energy is converted into thermal energy that does not yield additional pressure gain or useful thrust. This behavior is consistent with the lower performance observed in many studies that observed a recirculation region.

Amplifiers for Significant Performance Deficits

While the recirculation region is the central issue negatively impacting performance in the hollow combustor, it alone does not fully account for the significant performance deficits—over 15% lower specific impulse and specific thrust— observed in some studies. Other study-specific factors exacerbated the performance deficit in the hollow combustor.

Physical phenomena observed in these studies may have amplified the deficit. Schwer et al. observed that there was lower pressure in the fill-zone ahead of the detonation[26]. Kawasaki et al. found that the detonation wave detached from the wall[27]. Sun et al. found that the hollow had reduced mixing quality and backflow in the inner core[36]. It is important to note that for Kawasaki et al., subsequent experiments by the same group, Yokoo et al., managed to mitigate the performance deficit and achieve similar performance to the annular by adjusting and optimizing the operating parameters (discussed further in Section 4.3.1)[42–44].

Additionally, the operating parameters and methodologies in these studies may have influenced results. The 57% performance deficit observed by Schwer et al. is not an inherent limitation of the hollow combustor geometry, but rather a result of the specific numerical and operating conditions used in their simulation. The authors had to artificially reduce the induction time to sustain a stable detonation and introduced a large dump region and exhaust plenum for numerical stability. These modeling choices depressurized the fill region ahead of the wave. This lowered the stagnation pressure available for pressure gain and thereby reduced the exit pressure-thrust contribution and overall propulsive performance. Therefore, the 57% deficit reported in their study reflects computational and configuration-specific limitations rather than an inherent geometric deficiency. Sun et al. used a low quantity of injector orifices for the combustors, 60, compared to most studies, which used over 90, which may have degraded mixing efficiency.

Proposed Solutions

Several studies have proposed solutions to mitigate the performance deficit in hollow combustors. These include properly matching the exit areas to the injection flow rates, adjusting mass flux, operating under proper conditions— such as optimizing the ratio of injector area to combustor area or the arrangement of injectors—increasing injection surface area ratio, and flow-through combustors[26,42–44,48]. Additionally, this study proposes a novel solution: tangential swirl injectors.

Optimizing Operating Conditions

Subsequent studies by the same group, Yokoo et al.[42–44], successfully mitigated the performance deficit in the hollow from their previous research by Kawasaki et al.[27]. While Kawasaki et al. reported a 25-30% propulsive performance deficit in the hollow combustor, Yokoo et al. managed to achieve similar performance to the annular. They found that

Table 6 Summary of performance deficit amplifiers and methodological issues for studies reporting significantly lower performance.

Study	$\delta_{I_{sp}}$	Amplifying Factors	Physical Performance Mechanism	Methodological Concerns
Schwer et al.	−57%	Low pressure in fill-zone ahead of detonation	Lower fill-region pressure → reduced pressure gain and exit thrust	Artificially reduced induction time
Kawasaki et al.	−25–30%	Detonation wave detachment from wall	Destabilized combustion → inefficient energy release	No major methodological concerns
Sun et al.	−18.5%	Reduced mixing quality and inner core backflow	Increased unburned fuel → axial momentum loss	Low injector count (60 vs. typical > 90) → degraded mixing

adjusting the mass flux and operating under proper conditions, such as optimizing the ratio of injector area to combustor area and the arrangement of injectors, can help the hollow combustor achieve similar performance to the annular combustor. Specifically for injection configuration, they switched from 120 1mm diameter injector holes to 24 double pairs of 0.8mm injection holes impinged at an angle of 45 degrees on the bottom surface. Additionally, the mass flow rate was lower, ranging from 8 to 45 g/s compared to 130 - 140 g/s in Kawasaki et al. The performance data of the annular combustor in Kawasaki et al., along with the retested hollow configurations in Yokoo et al., are shown in Figure 7[42].

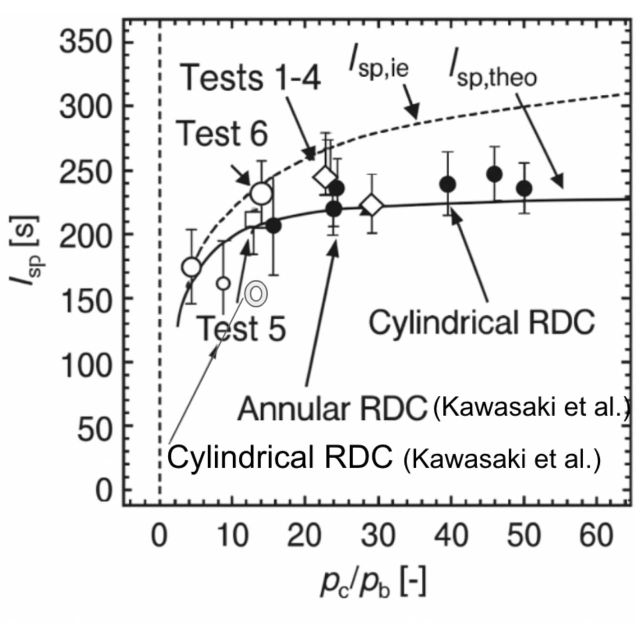

Fig. 7 Specific impulse results of Yokoo et al. compared to Kawasaki et al. Figure adapted from Yokoo et al[42]

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Furthermore, Schwer et al.[48] also mitigated the performance deficit in an earlier study[26]. Schwer et al. reported similar pressure gain and thrust performance for the hollow RDEs compared to the annular RDEs. They reported that properly matching the exit areas to the injection flow-rates for the hollow RDE should produce similar performance as an annular RDE[48].

Flow-Through Combustors

One study by Schwer et al. mitigated the deficit and even surpassed the performance of annular configurations using flow-through combustors—hollow combustors with a high-velocity airflow in the center. Schwer et al. found that the flow-through hollow combustors showed higher propulsive performance than the annular combustor[26]. Schwer et al. tested four cases of flow-through combustors with core temperatures ranging from 325 K to 650 K and airflow speeds from 150 m/s to 450 m/s. They found that the flow-through combustors showed specific impulses ranging from 4000s to over 9000s and specific thrusts ranging from 1100 m/s to over 2600 m/s. The highest performing flow-through configuration had the densest (coldest) flow at high velocity. This significantly outperformed the annular configurations by up to 85% higher specific impulse and specific thrust. Additionally, it was found that the E_w was similar to the annular combustor, suggesting most of the energy remains axial compared to the hollow, which showed 7% lower E_w.

Moreover, Schwer et al. stated that the high-pressure relief wave that penetrated into the core dump region for the hollow combustor was pulled back for the flow-through cases. This suggests that the deflagration/recirculation region may be mitigated in the flow-through combustors. A possible explanation is that the core flow prevents the propellants from expanding radially into the core. The higher density and velocity aid this. However, some problems with the flow-through combustor observed include weaker and slower detonation waves, a limited detonation range, and a lower range of fuels, as it could not realize detonation with ethylene/air mixtures[51].

Given that only one study has systematically examined the propulsive characteristics of flow-through combustors relative to annular configurations, the current research base is insufficient to draw broad conclusions about their performance. Future experimental and numerical investigations are needed to validate their potential, characterize their operating limits, and assess whether the observed performance gains generalize across propellant combinations and geometries.

New Proposed Solution: Tangential Swirl Injectors

Tangential swirl injectors help divert gas from the core and prevent recirculation into the center region, potentially mitigating the deflagration region. They impart a strong rotational momentum to the flow, creating a radial pressure gradient that pushes fresh reactants toward the combustor walls[52,53]. Yuasa et al. found that the combustion reaction does not develop in the core region when the swirl injectors are applied[54,55]. This could suggest that swirl injectors could suppress the Brayton-cycle reaction in the core by imparting flow radially and outward. Future experiments should investigate the effect of tangential swirl injectors on the performance of hollow combustors.

Conclusion

While literature is limited and the data is significantly varied, overall findings indicate that the hollow combustor generally achieves comparable but often lower performance than the annular combustor. Performance deficits are more evident in fuel-based specific impulse, specific thrust, and certain combustion and thrust vector efficiency metrics. The hollow combustor usually shows similar or lower propulsive performance. Specifically, the hollow combustor usually shows similar total propellant-based specific impulse, but frequently shows lower fuel-based specific impulse and specific thrust. While the data is limited and varied for combustion performance, the hollow combustor showed lower characteristic velocity efficiency, but varied results on pressure characteristics, with studies reporting similar or higher pressure gain and some reporting lower peak stagnation pressures. In terms of thrust vector efficiency, the hollow combustor has shown lower E_w and f_{mv}, but similar E_w values when operating under premixed conditions.

The primary reason for performance deficits is the recirculation/deflagration zone in the core. However, other physical factors and methodological inconsistencies may have exacerbated the performance deficit in studies reporting significant performance loss. Hollow combustors have shown to match or even exceed annular configurations when optimizing operating conditions and utilizing flow-through combustors. Additionally, tangential swirl injectors are proposed to mitigate the recirculation issue in the core of the hollow combustor. Nevertheless, the comparative assessment in this work is constrained by inconsistent operating parameters and limited cross-study data avail- ability. Future investigations with controlled, standardized operating conditions would enable more definitive quantitative comparison between hollow and annular combustors. While annular combustors are conventionally used in RDEs, hollow combustors present a promising alternative due to their significant thermal management benefits, reduced weight, and simplicity. Future experiments should focus on optimizing hollow combustors for performance.

References

1 S.R. Turns. *An Introduction to Combustion: Concepts and Applications*. McGraw-Hill, 3rd edition.

2 J.E. Shepherd and J.H.S. Lee. On the transition from deflagration to detonation. In *Major Research Topics in Combustion*, page 439–487. Springer.

3 Y.B. Zeldovich and A.S. Kompaneets. *Theory of Detonation*. Academic Press.

4 R.A. Schneider, C. Celis, and A.Z. Mendiburu. Detonation processes application to increase thermal efficiency in gas turbine cycles: Case study for hydrogen enriched fuels. *International Journal of Thermofluids*, 25:101010,. Online]. Available:.

5 M. Zhao, L. Zhang, W. Huo, H. Yang, and Y. Yuan. Performance analysis of a rotating detonation model for future thermal power system using hydrogen as fuel. *2021 6th International Conference on Clean Energy and Power Generation Technology*, 8:66–74,. Available:.

6 P. Wolanski. Detonation engines. *Journal of KONES Powertrain and Transport*, 18(3):7,.

7 Y. Wang, C. Huang, R. Deiterding, H. Chen, and Z. Chen. Numerical studies on detonation propagation in inhomogeneous mixtures with periodic reactant concentration gradient. *Journal of Fluid Mechanics*, 955:23,.

8 T. Bussing and G. Pappas. An introduction to pulse detonation engines. In *32nd Aerospace Sciences Meeting and Exhibit*. AIAA.

9 G. Roy, S. Frolov, A. Borisov, and D. Netzer. Pulse detonation propulsion: Challenges, current status, and future perspective. In *Progress in Energy and Combustion Science - PROG ENERG COMBUST SCI*, volume 30, pages 545–672,.

10 F.K. Lu and E.M. Braun. Rotating detonation wave propulsion: Experimental challenges, modeling, and engine concepts. *Journal of Propulsion and Power*, 30(5):1125–1142,.

11 B.A. Rankin, M.L. Fotia, A.G. Naples, C.A. Stevens, J.L. Hoke, T.A. Kaemming, S.W. Theuerkauf, and F.R. Schauer. Overview of performance, application, and analysis of rotating detonation engine technologies. *Journal of Propulsion and Power*, 33(1):131–143,.

12 R.D. Smith and S.B. Stanley. Experimental investigation of rotating detonation rocket engines for space propulsion. *Journal of Propulsion and Power*, 37(3):463–473,.

13 K. Kailasanath. The rotating-detonation-wave engine concept: A brief status report. In *49th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, Orlando, Florida. American Institute of Aeronautics and Astronautics. Online]. Available:.

14 T.-H. Yi, J. Lou, C. Turangan, J.-Y. Choi, and P. Wolanski. Propulsive performance of a continuously rotating detonation engine. *Journal of Propulsion and Power*, 27(1):171–181,.

15 J. Nicholls, R. Cullen, and K. Ragland. Feasibility studies of a rotat-

ing detonation wave rocket motor. *Journal of Spacecraft and Rockets*, 3:893–898,.
16 T.-H. Yi, C. Turangan, J. Lou, P. Wolanski, and J. Kindracki. A three-dimensional numerical study of rotational detonation in an annular chamber, 2012. Available:.
17 S. Theuerkauf, P. King, F. Schauer, and J. Hoke. Thermal management for a modular rotating detonation engine.
18 S. Theuerkauf. Heat exchanger design and testing for a 6-inch rotating detonation engine. *Air Force Institute of Technology (AFIT) Thesis*.
19 S. Randall, V. Anand, A.C.S. George, and E.J. Gutmark. Numerical study of heat transfer in a rotating detonation combustor, 2015. Available:.
20 Ye-Tao and Jian-Ping. Three dimension numerical simulation of rotating detonation engine without the inner wall. In *Proceedings of the 23rd International Colloquium on the Dynamics of Explosions and Reactive Systems (ICDERS*, page 1–6. Online]. Available:.
21 X. Tang, J. Wang, and Y. Shao. Three-dimensional numerical investigations of the rotating detonation engine with a hollow combustor. *Combustion and Flame*, 162(4):997–1008,.
22 F. Bykovskii, V. Mitrafanov, and E. Vedernikov. Continuous detonation combustion of fuel-air mixtures. *Combustion, Explosion and Shock Waves*, 33(3):344–353,.
23 Y. Zhang, Z. Sheng, G. Rong, D. Shen, K. Wu, and J. Wang. Experimental research on the performance of hollow and annular rotating detonation engines with nozzles. *Applied Thermal Engineering*, 218:119339,.
24 H. Xu, F. Wang, and C. Weng. Investigation on h2/o2 rocket rotating detonation engine with annular and hollow combustors. *Aerospace Science and Technology*, 159:109981,.
25 H. Zhang, W. Liu, and S. Liu. Effects of inner cylinder length on h2/air rotating detonation. *International Journal of Hydrogen Energy*, 41(30):13 281–13 293,.
26 D.A. Schwer, R.F. Johnson, A. Kercher, D.A. Kessler, and A.T. Corrigan. Numerical investigation of centerbody-less rotating detonation combustors. In *AIAA SciTech 2020 Forum*.
27 A. Kawasaki, T. Inakawa, J. Kasahara, K. Goto, K. Matsuoka, A. Matsuo, and I. Funaki. Critical condition of inner cylinder radius for sustaining rotating detonation waves in rotating detonation engine thruster. *Proceedings of the Combustion Institute*, 37(3):3461–3469,.
28 Y. Zhang, J.Z. Ma, Z. Sheng, G. Rong, D. Shen, J. Wang, and K. Wu. Experimental research on the performance of hollow and annular rotating detonation engines. In *AIAA SciTech 2023 Forum, National Harbor, MD*. paper No. AIAA 2023-1105.
29 J. Han, Q. Bai, S. Zhang, M. Wu, S. Cui, H. Chen, and C. Weng. Experimental study of h2/air rotating detonation wave propagation characteristics at low injection pressure. *Aerospace Science and Technology*, 126:107628,. Online]. Available:.
30 A. Baratta and J.B. Stout. Demonstrated low loss and low equivalence ratio operation of a rotating detonation engine for power generation. In *AIAA Scitech 2020 Forum*. Orlando, FL. Online]. Available:.
31 T. Suzuki, A. Matsuo, Y. Daimon, H. Kawashima, A. Kawasaki, K. Matsuoka, and J. Kasahara. Prediction of pressure loss in injector for rotating detonation engines using single-element simulations. In *AIAA Propulsion and Energy Forum, Virtual Event*. Online]. Available:.
32 Q. Xie, H. Wen, W. Li, Z. Ji, B. Wang, and P. Wolanski. Analysis of operating diagram for h2/air rotating detonation combustors under lean fuel condition. *Energy*, 151:408–419,.
33 Y. Wu, J. Guo, G. Xu, C. Ding, Q. Li, T. Jiang, and C. Weng. Wave mode observation of hydrogen/oxygen driven rotating detonations in the hollow and annular rotating detonation rocket engine. *Physics of Fluids*, 36(11):115105,.
34 D. Schwer and K. Kailasanath. Numerical investigation of the physics of rotating-detonation-engines. *Proceedings of the Combustion Institute*, 33(2):2195–2202,. Online]. Available:.
35 L. Werling, M. Haßler, F. Lauck, H. Ciezki, and S. Schlechtriem. Experimental performance analysis (c* c* efficiency) of a premixed green propellant consisting of n 2 o and c 2 h 4.
36 J. Sun, J. Zhou, S. Liu, Z. Lin, and W. Lin. Numerical investigation of a non-premixed hollow rotating detonation engine. *International Journal of Hydrogen Energy*, 44(37):20 557–20 566,. Online]. Available:.
37 A. Dubrovskii, V. Ivanov, and S. Frolov. Three-dimensional numerical simulation of the operation process in a continuous detonation combustor with separate feeding of hydrogen and air. *Russian Journal of Physical Chemistry B*, 9:104–119,.
38 D.E. Paxson. Examination of wave speed in rotating detonation engines using simplified computational fluid dynamics, 2018. Available:.
39 B.R. Bigler, J.R. Burr, J.W. Bennewitz, S. Danczyk, and W.A. Hargus. *Performance Effects of Mode Transitions in a Rotating Detonation Rocket Engine*. Online]. Available:.
40 X.-M. Tang, J.-P. Wang, and Y.-T. Shao. 3-d simulation of rotating detonation wave in combustion chambers without inner wall. *Journal of Aerospace Power*, 28(4):792–799,. Online]. Available:.
41 S. Yao, X. Tang, M. Luan, and J. Wang. Numerical study of hollow rotating detonation engine with different fuel injection area ratios. *Proceedings of the Combustion Institute*, 36(2):2649–2655,.
42 R. Yokoo, K. Goto, J. Kasahara, V. Athmanathan, J. Braun, G. Paniagua, T.R. Meyer, A. Kawasaki, K. Matsuoka, A. Matsuo, and I. Funaki. Experimental study of internal flow structures in cylindrical rotating detonation engines. *Proceedings of the Combustion Institute*, 38(3):3759–3768,.
43 R. Yokoo, K. Goto, J. Kim, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, and I. Funaki. Propulsion performance of cylindrical rotating detonation engine. *AIAA Journal*, 58(11):4901–4913,.
44 K. Goto, R. Yokoo, J. Kim, A. Kawasaki, K. Matsuoka, J. Kasahara, A. Matsuo, and I. Funaki. Propulsion performance of inner-cylinder-less rotating detonation engine. In *AIAA SciTech 2019 Forum*. San Diego, CA, USA. paper No. AIAA 2019-1500.
45 M. Fotia, F. Schauer, and J. Hoke. Experimental study of performance scaling in rotating detonation engines operated on hydrogen and gaseous hydrocarbon fuel, 2015. Available:.
46 T.-H. Yi, C. Turangan, J. Lou, P. Wolanski, and J. Kindracki. A three-dimensional numerical study of rotational detonation in an annular chamber.
47 S. Yao, X.-M. Tang, and J.-P. Wang. Numerical study of the propulsive performance of the hollow rotating detonation engine with a laval nozzle. *International Journal of Turbo Jet-Engines*, 34.
48 D.A. Schwer and R.F. Johnson. Performance of centerbody-less rotating detonation combustors for an rde concept. In *AIAA Propulsion and Energy 2021 Forum*.
49 Y. Wang and J. Le. A hollow combustor that intensifies rotating detonation. *Aerospace Science and Technology*, 89:1–12,.
50 W. Lin, Y. Tong, Z. Lin, W. Nie, and L. Su. Propagation mode analysis on h2–air rotating detonation waves in a hollow combustor. *AIAA Journal*, 58(12):5052–5061,.
51 R. Wiggins, A. Gaetano, T. Pritschau, J. Betancourt, V. Shaw, V. Anand, and E. Gutmark. Rotating detonations through hydrogen-air and ethylene-air mixtures in hollow and flow-through combustors.
52 R. Cheng. Lean premixed combustion stabilized by low swirl: A promising concept for practical applications. Technical report lbl–44776,, Lawrence Berkeley National Laboratory, Berkeley, CA. environmental Energy Technologies Division, MS70-108B, 1 Cyclotron Rd.
53 N. Banga and K. Kanika. Design and study of swirl injector of pulse detonation engine. *International Journal of Advanced Engineering Research and Science (IJAERS*, 4(4):79–82,.
54 S. Yuasa, T. Ide, M. Masugi, T. Sakurai, N. Shiraishi, and T. Shimada. Visualization of flames in combustion chamber of swirling-oxidizer-flow-type hybrid rocket engines. *Journal of Thermal Science and Technology*, 6(2):268–277,.
55 S. Yuasa, N. Shiraishi, and K. Hirata. Controlling parameters for fuel

regression rate of swirling-oxidizer-flow-type hybrid rocket engine. In *48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference Exhibit*.