Numerical Investigation on Pylon and Flush Wall Injection in Cold Coaxial Jets

J. Sarathkumar Sebastina, S. Jeyakumara, K. Karthika, R. Sivakumb

a Aeronautical Engineering, Kalasalingam Academy of Research and Education, Krishnankoil, India – 626126.
b School of Mechanical Engineering, VIT University, Chennai, India.

*corresponding author: sjeyakumar1974@gmail.com

Abstract. The dual combustion ramjet (DCR) engine is considered one of the promising engines for the hypersonic missile propulsion system. This paper reveals the non-reacting flow characteristics of the DCR engine with the influence of pylon and wall injections in coaxial jets using numerical investigation. The supersonic combustor of the DCR engine is modeled and analysed using the commercial CFD software ANSYS 18.0. The three-dimensional compressible Reynolds-averaged Navier-Stokes (RANS) equations coupled with the SST k − ω turbulence model have been used to analyse the coaxial mixing characteristics of the jets. The numerical study is validated with the experimental data and agrees with it for further investigation. The pylon and wall injectors are located symmetrically at the gas generator's nozzle exit, and the air is used as the injectant to simulate gaseous fuel. The pylon and wall injection results are compared with the actual DCR engine. In a typical DCR engine, the shock waves generated from the gas generator nozzle enhance the mixing of the coaxial jets with minimum total pressure loss. The pylon injection induces more shock interactions along the flow direction within the supersonic combustor leading to higher total pressure loss than the wall injection. The pylon injection provides the spatial distribution of fuels compared to the wall injection in the coaxial supersonic flow field.

1. Introduction

The scramjet engines are the propulsion systems for the hypersonic airbreathing vehicle[1–3]. The scramjet engine's key features are fuel injection, air-fuel mixing, and combustion, particularly for heavy hydrocarbon fuels that need a relatively long time for chemical reactions to continue. The well-known propulsion concepts pursued in scramjet applications are the Dual-mode Combustion Ramjet (DMCR) and Dual Combustion Ramjet (DCR). In DMCR, subsonic and supersonic combustion modes occur within a solitary combustor itself; however, the DCR consists of a gas generator and the supersonic combustor[4]. Billig[5] and Waltrup[6] proposed the DCR engine concept for hypersonic missile applications in the 1980s. The DCR engine combines the advantages of both ramjet and scramjet combustion modes of operation. The DCR engine schematic illustration is shown in Figure 1.
The DCR engine operates in the ramjet mode with a limited volume (typically one-fourth) of the high-speed incoming air, which is allowed through a gas generator where the fuel is combined and ignited. The gas generator's significance is to supply the supersonic combustor with partly reacted and preheated fuel-rich streams for complete combustion than direct injection into the supersonic flow[7]. The combustion flame from the gas generator serves as a pilot flame for the supersonic combustion. A significant volume of remaining air (nearly three-fourths) flows through the annular duct between the gas generator and the outer casing of the DCR engine into the supersonic combustor at supersonic velocity. This annular duct serves as an insulator between the inlet and the supersonic combustor to avoid combustion-induced oscillations from inlet flow. The gas generator nozzle's rim helps create a recirculation zone for the coaxial jets that forms the low-speed high-temperature region to enhance the flame holding and stabilisation phenomenon. Hence, no separate flame holding device is necessary to sustain the combustion as a direct scramjet engine.

Tan et al.[8] have shown that the quasi-one-dimensional approach can be applied to evaluate various modes in the entire dual-mode scramjet combustor operation. Stockbridge[9], Waltrup, and Billig[10] studied the DCR combustor and the inlet interactions and formulated a semi-empirical relationship for the shock/boundary-layer interactions. The combustion characteristics of the DCR engine are numerically investigated by Zang et al. [11]. The authors revealed that stable combustion could be observed at the nozzle rim, and the mixing layer regimes are formed by increasing the fuel equivalence ratios. The numerical review on the analysis of splitter plate thickness[12] reveals that an increase in plate thickness (gas generator nozzle rim) improves the mixing of coaxial jets, enhancing complete combustion. Choi and Yang[13] numerically study the coupling process between the compressibility effects and the turbulent combustion in a dual combustion ramjet engine. Experimental and numerical studies by Tan et al.[14] revealed that the DCR engine achieves appreciable performance under operating conditions at Mach 4 and Mach 6.

Kurian and Habeeb[15] demonstrated that a petal nozzle could be used at the gas generator's exit instead of the conventional nozzle, which provides better mixing and combustion efficiency under the same operating conditions. However, these nozzles cause a higher loss of stagnation pressure than standard nozzles. Jeyakumar et al. [16] demonstrated that coaxial jets' mixing efficiency could be enhanced using the tandem cavities at a marginal rise in stagnation pressure loss. The authors analysed the influence of cavities in the axisymmetric supersonic field [17–22]. Byun et al.[23] developed a new correlation method to determine the pre-combustion shock train length and the combustion performance of the DCR engine.

The effect of transverse injection in the coaxial supersonic flow field has not been explored systematically. The present study investigates the characteristics of the coaxial jets in a modified DCR engine by incorporating transverse injection under the non-reacting flow field. The fuel injection schemes include flush wall and pylon injections adopted at the supersonic combustor inlet. The study details the modified DCR engine's performance parameters in terms of wall static pressure distribution, mixing, and stagnation pressure loss, and compared with the conventional DCR engine.
2. Numerical Modelling

A three-dimensional compressible Reynolds Averaged Navier Stokes (RANS) equation with a density-based double precision solver is used to resolve the flow field of the DCR engine. The RANS equation provides accurate results even with the coarse meshes and resolves the steady flow more efficiently than other models [24]. The transport equation model called Shear Stress Transport (SST) k-ω model with traditional constants have been used to solve the turbulent flow field [25]. The SST k-ω turbulence model yields accurate results in predicting mixing layers and jet flows [26]. The fluid is considered an ideal gas and the mass-weighted-mixing-law is used to compute the thermal conductivity and viscosity. For spatial discretisation, a second-order upwind system (SOU) is used along with the Advection Upstream Splitting Process (AUSM) flux splitting to provide an effective solution with reliable convergence characteristics [27]. The Courant-Friedrichs-Levy (CFL) number is chosen as 0.5 to ensure computational stability [28]. The governing equations, i.e., mass, momentum, and energy equations written for the total enthalpy are expressed as:

Continuity equation
\[
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0
\]  

Momentum equation
\[
\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) + \frac{\partial \rho}{\partial x_i} = \frac{\partial (\tau_{ij})}{\partial x_i}
\]  

Energy equation
\[
\frac{\partial}{\partial t}(\rho H) + \frac{\partial}{\partial x_i}(\rho H u_i) = -\frac{\partial}{\partial x_j}(\tau_{ij} u_i) + \frac{\partial q_i}{\partial x_j}
\]  

The turbulence kinetic energy, k, and the specific dissipation rate, \( \omega \) is obtained from the following transport equations:

\[
\frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}(\Gamma_k \frac{\partial k}{\partial x_j}) + G_k - Y_k + S_k
\]

and

\[
\frac{\partial}{\partial x_j}(\rho \omega u_j) = \frac{\partial}{\partial x_i}(\Gamma_\omega \frac{\partial \omega}{\partial x_i}) + G_\omega - Y_\omega + D_\omega + S_\omega
\]

The terms, \( G_k \) represents the production of turbulent kinetic energy and \( G_\omega \) as the generation of \( \omega \), \( \Gamma_k \) and \( \Gamma_\omega \) represent the effective diffusivity of k and \( \omega \) respectively, \( Y_k \) and \( Y_\omega \) represent the dissipation of k and \( \omega \) due to turbulence, \( D_\omega \) represents the cross-diffusion terms and \( S_k \) and \( S_\omega \) as the user-defined source terms.

3. Numerical setup

3.1. Computational domain

Figure 2(a) shows the DCR engine test facility’s schematic layout, consisting of a gas generator, isolator, and supersonic combustor. The symmetric portion of the supersonic combustor is chosen for the study to reduce the computational expense (Figure 2b). One-fourth of the incoming air is allowed to pass through the gas generator. The flow issued from the gas generator nozzle is in choking condition. The remaining air flows at a Mach number of 2.0, through the annular passage located between the outer casing and the gas generator, which acts as the isolator. The coaxial jets enter into the supersonic combustor, and the flow details are listed in Table 1.
In the supersonic combustor, a secondary fuel is injected normal to the flow direction by flush wall injection and Pylon injection. In the case of pylon injection, the fuel is injected directly to the rim of the gas generator nozzle to study the coaxial jets' flow characteristics. The air is injected to mimic gaseous fuel in the non-reacting flow study. The injection pressure ratio (= injection pressure, $P_j$/annular airflow pressure, $P_{oa}$) is 1.875 is tested, and the results are compared with the typical DCR engine.

### 3.2. Boundary Condition

The DCR experimental setup's symmetric outline is described in the experimental section. The numerical investigations are performed from the gas generator nozzle to the supersonic combustor exit to reduce the computational time. The imposed boundary conditions for the DCR engine domain are the same as that of the experimental data listed in Table 1. The mass flow inlet condition is adopted for air and fuel inlet to the DCR engine, and the pressure outlet condition is considered for the combustor exit. The wall is applied with no-slip and adiabatic boundary conditions.

| Parameters                  | Gas generator | Annular flow |
|-----------------------------|---------------|--------------|
| Stagnation pressure (MPa)   | 0.1856        | 0.8          |
| Stagnation temperature (K)  | 305           | 305          |
| Mass flow rate (kg/s)       | 0.25          | 0.75         |
| Mach number                 | 1.0           | 2.0          |
3.3. Grid generation
A 3D axisymmetric unstructured grid is generated from the gas generator nozzle to the supersonic combustor exit. Three mesh grid structures of different sizes are incorporated here, namely coarse (0.5 million), medium (0.65 million), and fine (0.75 million). The y+ value is maintained at less than 1.0 in all the simulations, where the corresponding first-row cell height is 0.001 mm. In this task, a mesh independence test is also performed to ensure and evaluate the CFD simulation features. The grid independence study reveals that the static pressure values have a variance of less than 1 percent for all the mesh sizes. However, no further error analysis is needed to illustrate grid convergence (Figure 3). Furthermore, to analyse the flow fields in the DCR combustor, the present CFD technique with medium cell size is preferred to save computational time and cost.

4. Results and Discussions
4.1. Validation of the numerical model
The numerical simulation results of the actual DCR engine wall pressure values are validated with the authors' experimental data. The experimental conditions and the computational details are reported in the preceding sections. Figure 4 illustrates the computed wall static pressure distributions with experimental data. The results indicated that the numerical results complied with the experiments' outcome (Figure 4). The small discrepancies observed in the results may be due to the model limitations, axisymmetric assumptions, and machining uncertainty.
4.2. *Wall static pressure distribution*

The coaxial jets enter the supersonic combustor at different operating conditions, which drag over the combustor’s internal surface. The static pressure distribution on the combustor wall indicates the intensity of drag generated by the flow field. The static-pressure distribution on the inner wall of the DCR engine with and without injection is shown in Figure 5.

![Figure 5: Wall pressures distribution in the supersonic combustor for various injection and no-injection cases](image)

Here, the ratio of wall static pressure (Pw) of the supersonic combustor to the annular stagnation pressure (Poa) at different axial locations of the DCR engine is represented. The Mach number contours for cases 1, 2, and 3 are presented in Figure 6. The Mach number contours from the numerical simulations are taken for 2D planes in the injection location in the combustor's flow directions.

![Figure 6. Mach number contour for various injection cases of the DCR engine](image)
The plot shows peak pressure is noted for all the injection and no injection cases at the supersonic combustor inlet. This is due to the oblique shock waves generated from the isolator exit, which interacts with the wall boundary layer creates a compressive zone. For no-injection and wall injection, static pressure profiles follow a similar pattern with a marginal variation in the pressure values compared to the pylon injection. The static pressure profile's wavy nature is due to the reflected shocks from the combustor wall and the shock to shock interactions. The Mach number of contour plots show that the shock interactions vanish downstream of the flow for the no-injection and wall injection cases. In contrast, for pylon injection, a shock to shock interactions are seen throughout the combustor with diminishing strength.

4.3. Mixing of coaxial jets

In Figure 7, planes created at various axial locations of the supersonic combustor envisage the coaxial jets' mixing mechanism with the fuel injection schemes. The streamline plots show that the active counter-rotating vortices are present at the gas generator nozzle rim to enhance mixing and flame holding. The vortex pattern is not altered with the flush wall injection, and the fuel is carried away along with the stream in the flow direction without spatial distribution. However, in the case of pylon injection, the fuel is injected directly to the nozzle rim creates an active vortex in the normal direction of the flow that increases the fuel distribution spatially and enhances the mixing along the flow direction.

Figure 7 Vortex formation at the various axial locations of combustor along with the fuel streamlines (a) case 1, (b) case 2, (c) Case 3
4.4. Total pressure loss

The Total pressure loss (TPL) of the supersonic combustor for various injection cases are calculated as,

\[ TPL = 1 - \frac{P_{oe}}{P_{oi}} \]  
(6)

\[ P_{oi} = \frac{P_{og} \times A_g + P_{oa} \times A_a}{A_g + A_a} \]  
(7)

The difference in area-averaged stagnation pressures at the inlet (\(P_o\)) to the outlet (\(P_o\)) of the supersonic combustor to the inlet stagnation pressure is termed as stagnation pressure loss. In the equations, \(A\)- denotes the areas, and the subscripts 'g' and 'a' refers to the gas generator and annular flow conditions, respectively. The stagnation pressure loss for injection and no injection cases are depicted in Figure 8. The total pressure loss for the actual DCR engine across the supersonic combustor is 6.88%. The three-dimensional shock waves emanated from the gas generator nozzle rim cause shock and shock to boundary layer interactions resulting in total pressure loss across the combustor. Figure 7 shows that in both the wall injection and no-injection cases, the coaxial jets' interactions are significantly less compared to the pylon injection. In pylon injection, active vortices in the flow's radial directions generate an additional total pressure loss compared with the other cases.

![Figure 8. Total pressure loss for with and without injection cases of DCR engine](image)

5. Conclusions

The non-reacting flow characteristics of coaxial jets with flush wall injection and pylon injection are numerically investigated. A three-dimensional RANS equation with the SST k-\(\omega\) turbulence model is used for the flow analysis. The numerical results of the wall pressures are validated with the experimental data. The major conclusions of the study are:

- The supersonic combustor's wall static pressure profile reveals that the shock to boundary layer interaction at the combustor's inlet shows peak pressure values for all the cases. The intensity of the shock interactions with the centre flow has vanished downstream of the gas generator nozzle in the flush wall and no-injection. Simultaneously, the pylon injection indicates the shock interactions with reducing intensity in the combustor.
- The mixing of the coaxial jets is enhanced by oblique shock waves formed from the gas generator nozzle rim for no injection and flush wall injection schemes. However, the fuel injection from the wall is not spatially distributed throughout the combustor. Pylon injection provides an enhancement in mixing coaxial jets with the fuel stream. The improvement in mixing is evident from the series of shock waves formed from the injection location towards the combustor's downstream.
- Pylon injection induces more stagnation pressure loss than the no injection and wall injection cases of the supersonic combustor. The pressure loss is mainly due to the shock train's strength emerges from the gas generator nozzle and the injection strategies. Further investigations on reacting flow studies would reveal the injection schemes’ performance in the DCR engine.

Nomenclature:

| Symbol | Definition |
|--------|------------|
| Ma     | Mach number |
| Po     | total pressure |
| P      | static pressure |
| ρ      | density |
| u      | velocity |
| ṁ     | mass flow rate |
| k      | turbulence kinetic energy |
| ω      | specific dissipation rate |
| Gk     | production of turbulent kinetic energy |
| Gω     | generation of ω |
| Γk and Γω | effective diffusivity of k and ω |
| Yk and Yω | dissipation of k and ω |
| Dω     | cross-diffusion terms |

Subscripts

| Subscript | Description |
|-----------|-------------|
| i         | inlet       |
| e         | exit        |
| g         | gas generator |
| a         | annular     |

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