Predictive Numerical Analysis on the Fuel Homogeneity in a Rotating Detonation Engine (RDE) Implementing Radially-Entered Fuel Injection Scheme

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Abstract. The potential for a continuous detonation wave in rotating detonation engine (RDE) hugely rely on the homogenous fuel-air mixture within annular chamber. Using that motivation, a comprehensive numerical study on the non-reacting flow field was carried out to investigate the mixing of hydrogen (H_2)and oxygen (O_2) in a RDE, allowing this study to represent the flow behavior at the split second before ignition. A validation with the published experimental data was successfully done by comparing the predicted detonation front displacement, r and velocity, v_D. Below than 10 % error was detected from both variables. New parameter representing fuel homogeneity was introduced which is the magnitude of maximum deviation from the H_2 mean mass fraction, $|S_{\max}|$. A comparison in the $|S_{\max}|$ generated from RDE implementing axially-entered fuel (AEF) injection with RDE implementing radially-entered fuel (REF) injection was carried out. Based on the numerical results, the $|S_{\max}|$ value from AEF injection is lower than REF injection implying the capability of AEF injection to produce better fuel homogeneity. Via AEF injection, the injected fuel stream has a direct impingement with the injected oxidizer stream allowing proper mixing of the reactants. In REF injection, thedistancefrom fuel injectortooxidizerinjector, R was varied to foresee the impact of R in $|S_{\max}|$ value. The outcome shows that as the value of Rincreases, the value of $|S_{\max}|$ increases as well. Thisisduetotheformation of vortex between the reactant streams plus the increased in distance between both streams which further reduced the reactants interaction. In the cases of R3 and R4 where the values of R are 7 and 9 mm respectively, the homogeneity of fuel is severed in the upstream region. This is a major concern since the ignition happened in that particular area. Thus, it is crucial for the reactants to mix properly within the upstream region.

1. Introduction

The detonation in which combustion wave propagating at supersonic manner, provide a great potential for a notable increment in thermal efficiency. This is attributable to high work availability where the entropy generated is lower, and pressure is gained across the region of combustion [1-3, 8]. From the features of detonation wave, one of the most typical forms of achieving the utilization of detonation is rotating detonation engine (RDE) [1, 4]. RDE is a combustion engine that exploit detonation waves in which reactants are introduced from micro-nozzles, fills the annular chamber of RDE, and one ignition from pre-detonator tube will detonate the mixing reactants. Consequently, production of detonation

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waves that continuously propagates will generate consistent thrust [5]. RDE is a compelling concept and it could be the marvel of combustion technology in the near future, if several issues on RDE are solved.

In recent times, researchers have started to become aware of the importance of mixing behaviour in the annular chamber of RDE. While rotating detonation wave (RDW) propagates circumferentially around the chamber consuming the fresh mixture of oxidizer and fuel, the reactants also encounter vigorous mixing once they enter annular chamber. The intricatedflow ahead of RDW is due to the interaction between the incoming reactants and the propagation of RDW [1]. For stable RDW generation, the injection design must allow for a complete mixing of the reactants while maintaining minimal pressure losses through the injection area to preserve the detonation potential. Visualization of flow behaviour is not easily accomplished in the experiment hence, the numerical method is preferred for analysis towards the reactants mixing in RDE. One of the recent trends in RDE is the implementation of radially-entered fuel (REF) injection as shown in Wheeler's work [6]. While the Wheeler's work analyse the formation of vortices and mixing performance in the upstream of RDE, the resulting fuel homogeneity within the annular chamber is still uncertain. On that account, the present study focuses on fuel homogeneity in the annular chamber to generate stable RDWs, with particular focus on the REF injection for RDE.

2. Physical setup

The computing domain for baseline case was based on the RDE geometry employed by Shank [7] in his experimental works which used the axially-entered fuel (AEF) injection scheme. Figure 1 shows the cross-sectional view of the simplified computing domain taken from Shank's work.

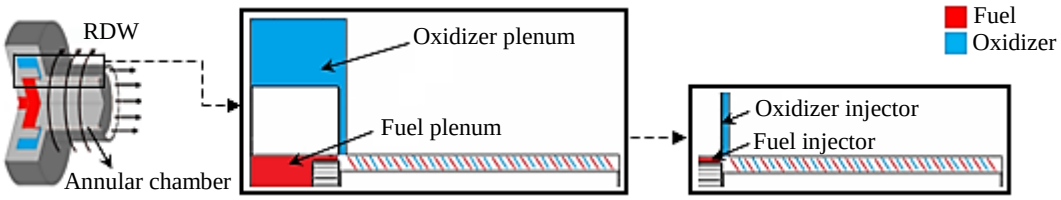


Figure 1. Cross-sectional view showing the simplification of computing domain for baseline case.

A number of simplifications were implemented from the original computing domain. Fuel and oxidizer plenums are not included as our main focused is on the mixing of reactants within the annular chamber of RDE. As shown in figure 1, RDE from the mentioned published work are considered and it is used as the baseline case and for the validation purposes. In the current contribution, the study focused on the REF injection for RDE. Using the same dimension as RDE from the baseline case, REF injection was implemented as shown in figure 2. The distance from fuel injector to oxidizer injector, *R* is also shown in figure 2.

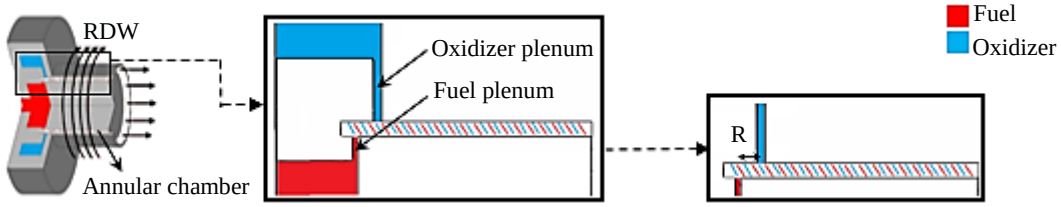


Figure 2. Cross-sectional view showing the implementation of REF injection in RDE.

In analyzing the effect of fuel injection scheme towards the fuel homogeneity in annular chamber, parameter *R* is varied and the variation of *R* for each cases are shown in Table 1.

Table 1. Variation of *R* for each cases.

Cases	*R* (mm)
R1	3
R2	5
R3	7
R4	9

3. Numerical setup

The finite volume method which is the mathematical technique used in the CFD package divides the computing domain into smaller control volumes. Compressible and steady state governing equations for fluid flow phenomenon including the conservation of mass, Newton's second law for the conservation of momentum and the first law of thermodynamics for the conservation of energy were discretized using finite volume method in ANSYS Fluent. Reynolds Average Navier – Stokes (RANS) equations as seen in eq. (1) was used to solve the turbulence flow. RANS equations were derived using Reynolds decomposition where the velocity field in Navier-Stokes equations was split into mean, $\bar{u}$ and instantaneous, u' parts and time averaging. Reynold stresses, R_{ij} which appear after the averaging operation are modelled using Boussinesq hypothesis via turbulent viscosity, μ_T as seen in eq. (2). SST $k-\omega$ model was used to solve μ_T where two transport equations for the turbulence kinetic energy, k and the turbulent frequency, ω are deployed. SST $k-\omega$ model is selected for turbulence model as for this analysis, highly accurate resolution of boundary layers is crucial since the impingement of reactants with the wall of annular chamber plays a major role towards mixing quality due to the tight space within the chamber [9-10].

$$\rho\left(\frac{\partial \overline{u_\iota}}{\partial t}+\overline{\mu_k}\frac{\partial \overline{u_\iota}}{\partial x_k}\right)=-\frac{\partial \bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial \overline{u_\iota}}{\partial x_j}\right)+\frac{\partial R_{ij}}{\partial x_j} \tag{1}$$

$$R_{ij}=-\rho\overline{u_\iota' u_j'}=\mu_T\left(\frac{\partial \overline{u_\iota}}{\partial x_j}+\frac{\partial \overline{u_j}}{\partial x_i}\right)-\frac{2}{3}\mu_T\frac{\partial \overline{u_k}}{\partial x_k}\delta_{ij}-\frac{2}{3}\rho k\delta_{ij} \tag{2}$$

As the non-reacting data for the mixing of H_2 and O_2 in RDE is unavailable, the validation was made based on the reacting flow experiment thus, reacting flow simulation was executed for validation purposes. To resolve the reacting flows, Eddy-dissipation model is used and the reaction is describe using a single step Arrhenius reaction for H_2-O_2 [1]. Throughout the variation of parameter *R*, fixed mass flow rate with stoichiometric equivalence ratio is used. This is done to make certain the same mass flux of H_2 and $O_2$to enter the annular chamber of RDE seeing that the area of injection for H_2 and $O_2$are also fixed throughout the variation of *R*. Mass flow rate for H_2 and $O_2$are 39.96 g/s and 5.04 g/s respectively. As other variables were fixed, investigation on the mixing performance are solely focused on the influence of fuel injection scheme. In the current contribution, comprehensive analysis towards the fuel homogeneity in annular chamber was analyzed radially and axially. Throughout the annular chamber, six planes were created at constant intervals. Each plane was divided into 12 regions with 30° angle each as shown in figure 3.

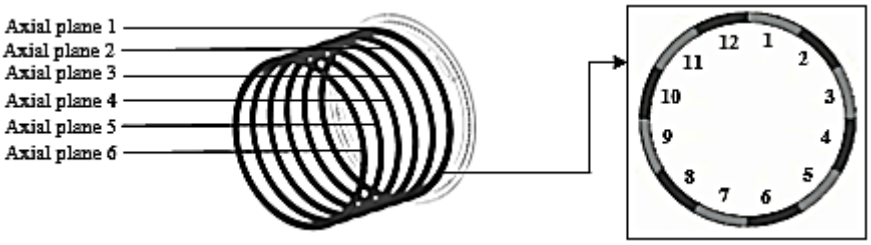


Figure 3. Configuration of axial planes throughout the annular chamberin which each axial plane is divided into 12 circumferential regions.

Using figure 3, new parameter is introduced to evaluate the inhomogeneity of fuel distribution in annular chamber which is the magnitude of maximum deviation from the mean mass fraction, $|S_{max}|$. To compute $|S_{max}|$, the deviation of average H_2 mass fraction in the circumferential region from the average H_2 mass fraction in the axial plane, $S_l$was first calculated. Next, the highest value of S_l from each interval axial planes, $|S_j|$ was determined. Since there are six axial planes, six values of $|S_j|$ were established and the highest value of $|S_j|$ is $|S_{max}|$.

4. Validation based on detonation simulation

Ahead of validation, mesh was accomplished at 0.5 million cells with average element size of 2 mm. As the non-reacting data on the mixing ofH_2 and O_2 is unavailable, the validation was executed using the reacting flow experiment as the basis, where the predicted detonation front displacement, r and thepredicted detonation velocity, v_D from CFD modeling were compared with the interpolated r and v_D recorded by Shanks experimental works [7]. Table 2 shows the validation results.

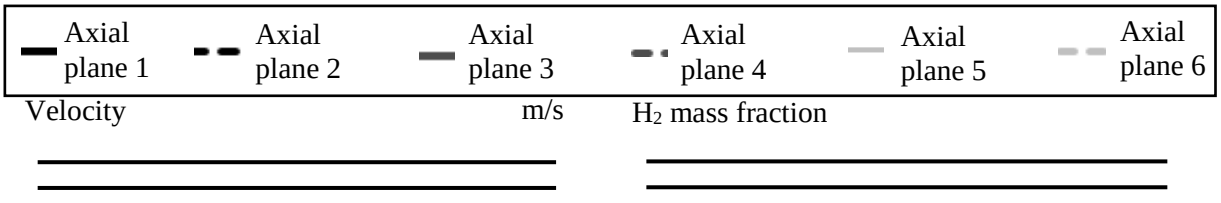
Table 2. Comparison in the results from experimental and numerical works.

Parameters	Results at t = 8.16 μs		Percentage difference (%)
	Experimental	Numerical	
r	0.0156	0.0141	9.6
v_D	1593.8000	1476.4220	7.4

From these comparisons, the reliability of the present CFD model is proven as the numerical results are in good agreements with the published experimental data. The percentage difference between predicted results and experimental values are only 9.6 % for$r$ and 7.4 % for v_D. Since detonation simulation is computationally expensive, simulation was run in a short period of time, where the simulation stop at □ = 8.16 μ□, just adequate for detonation front to manifest in the annular chamber.

5. Results and discussions

In the present study, to analyze the fuel homogeneity radially and axially within the RDE annular chamber, a set of numerical results showing the generated S_l from circumferential regions are shown in figure 4 along with the respective $|S_{max}|$ for each cases.



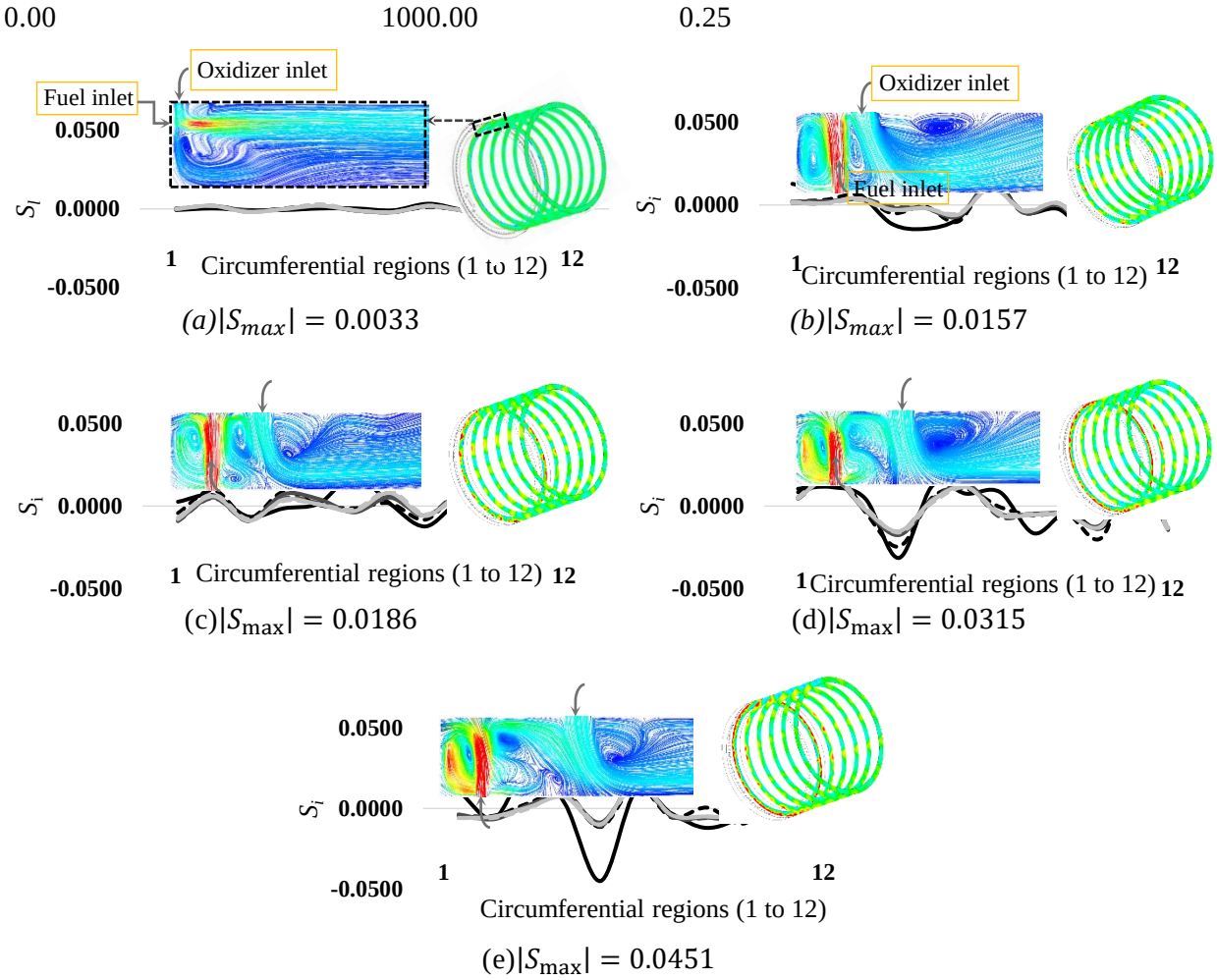


Figure 4. Cross-sectional view showing the implementation of REF injection in RDEGraph of S_i versus circumferential regions, velocity streamline in the upstream of annular chamber, contour of H_2 mass fraction and $|S_{max}|$ for (a) baseline, (b) R1, (c) R2, (d) R3, and (e) R4.

In figure 4, the fuel homogeneity within the annular chamber for each cases are quantitatively and qualitatively shown. The baseline case shows an excellent fuel homogeneity as $|\square_{max}|$ value is the lowest compared to that of the rest of the cases implying the capability of AEF injection to produce better fuel homogeneity within annular chamber than REF injection. The trend in cases R1 to R4 shows an increase in $|\square_{max}|$ with an increment in *R*. The results from velocity streamline show improper mixing in the upstream of annular chamber for cases R1 to R4. As the reactants stream experiencing high velocity asit entered the chamber, the static pressure in the central core of the upstream is reduced thus creating flow recirculation which formed vortex between the reactant streams. Formation of vortex separates most of the fuel and oxidizer streams thus, reduced the interaction between the reactants. In addition, the higher the value of *R*, the lower the interaction between the reactants as the distance between both streams is higher. In baseline case, the fuel stream which entered the annular chamber has a direct impingement with the oxidizer stream allowing proper mixing of the reactants.

6. Conclusion

A comprehensive numerical study investigating the fuel in homogeneity within the anular chamber of RDE has been executed to provide a systematic set of numerical results which represents the flow behavior at the split second before ignition. A comparison in the fuel homogeneity between AEF injection with REF injection was done. The $|\square_{max}|$ value from AEF injection is the lowest compared to that of the rest of the cases implying the capability of AEF injection to produce better fuel homogeneity within the annular chamber than REF injection. With AEF injection, the injected fuel stream has a direct impingement with the injected oxidizer stream allowing proper mixing of the reactants. In REF injection, the higher the value of *R*, the higher the value of $|\square_{max}|$. This phenonemon comes from the formation of vortex between the reactant streams and the increased in distance between both streams that reduced the reactants interaction. For the cases of R3 and R4, the homogeneity of fuel is severed in the upstream of annular chamber. This is a major issue since the ignition happened at the upstream region. Thus, it is essential for the reactants to mix properly within the upstream region. In the present contribution, the ability to produce information regarding fuel homogeneity and mixing behaviour has been shown using numerical approach and it is recommended that further analysis of RDE mixing schemes should be done. To relate the effect of reactant injection design towards the workability of RDE, the reacting flow simulations are much needed.

Acknowledgments

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