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EMBEDDED LARGE EDDY SIMULATION OF PARTIALLY PREMIXED HYDROGEN FLAME: STUDY OF INJECTOR NOZZLE GEOMETRY

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1. ABSTRACT

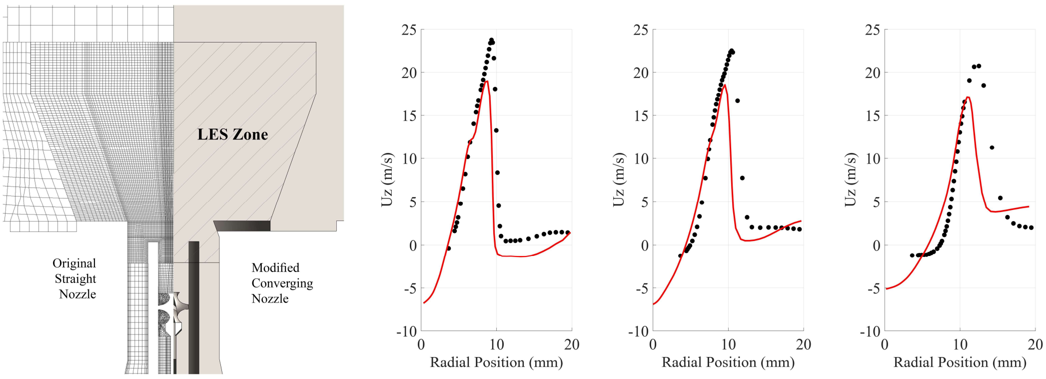
This study used Embedded Large Eddy Simulation (ELES) and steady diffusion flamelet to model partially premixed hydrogen flame under a modified converging injector nozzle design with the flame structure and NO_x emission analysed. The numerical results have revealed that adding a converging section at the injector outlet has minimal impacts on the mixture formation but despite a higher central flame temperature, results were evident that this modification improves the overall combustor's NO_x emission from the reduced flame length and accelerated H_2 consumption.

2. INTRODUCTION

Emerging as a zero-carbon fuel for the future, hydrogen has presented a promising route in driving the decarbonisation of the aviation sector. However, hydrogen's susceptibility to insufficient mixing poses inferior effects on its NO_x and new combustor designs. Many hydrogen injector designs based on premixed and non-premixed combustions were proposed and reviewed by studies [1], but mere designs have focused on partially premixed combustion (PPC). This study aims to encapsulate an understanding of the impacts of injector nozzle geometry on a partially premixed hydrogen flame and the findings will provide preliminary insight for designing future low NO_x partially premixed hydrogen combustors.

3. COMPUTATIONAL METHOD

The combustor model is a coaxial dual-swirl partially premixed hydrogen injector developed by IMFT, named HYLON [2]. The inner hydrogen swirl flow is formed by a helical swirler, and a radial swirler generates the outer swirling airflow. The modification to the geometry is done by adding a converging throat at the original straight nozzle that points inward at 20.56° (Figure 1(a)).



(a) (b) (c) (d)

Fig. 1 Combustor geometry and computational grid (a), and axial velocity at 2.1mm (b), 4.6mm (c), 8.1mm (d) from injector nozzle compared with experimental velocimetry data.

A zonal hybrid RANS-LES approach, embedded Large Eddy Simulation (ELES) has been utilised with global RANS zone's turbulence closure provided by $k - \omega$ SST model, LES zone sub-grid turbulent viscosity

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modelled using dynamic Smagorinsky model and at upstream RANS-LES interface, synthetic turbulence generation is achieved by vortex method. The steady diffusion flamelet model has been implemented as the PPC model with the hydrogen oxidation and NO_x emission chemistry captured using a detailed mechanism [3]. The time step has been selected to achieve a Courant number of ~1 within the LES zone, where time sampling is conducted after 19 flow-through-time through the whole computational domain.

4. VALIDATION

Fig. 1(a) presents the computational grid, which contains 644 thousand cells, and the shaded region on the right indicates the LES zone which contains structured hexagonal mesh. Further on the right, panels (b), (c) and (d) compare Vilespy et al.'s experimental data [2] on the radial distribution of axial velocity U_z to the numerical results from ELES. The general trend and the position of the maximum axial velocity prediction have presented a good agreement. However, for all three axial positions, the maximum velocity magnitudes are under-predicted with over-prediction of the negative axial velocity within the centreline position. This discrepancy might have originated from the under-resolution of the turbulent kinetic energy of the flow.

5. RESULTS

Fig. 2 below presents the temperature contour produced by the reactive ELES simulation of the original and the modified design. For both cases, an anchored triple-flame structure is seen, with the isolines indicating the lean and rich premixed branches. For the straight nozzle design, the isoline at $\phi = 1$ is directly positioned at the non-premixed flame anchor extending into the inlets, but in the case of the converging nozzle design, the flame anchor near the convergent nozzle section has presented a richer premixed behaviour.

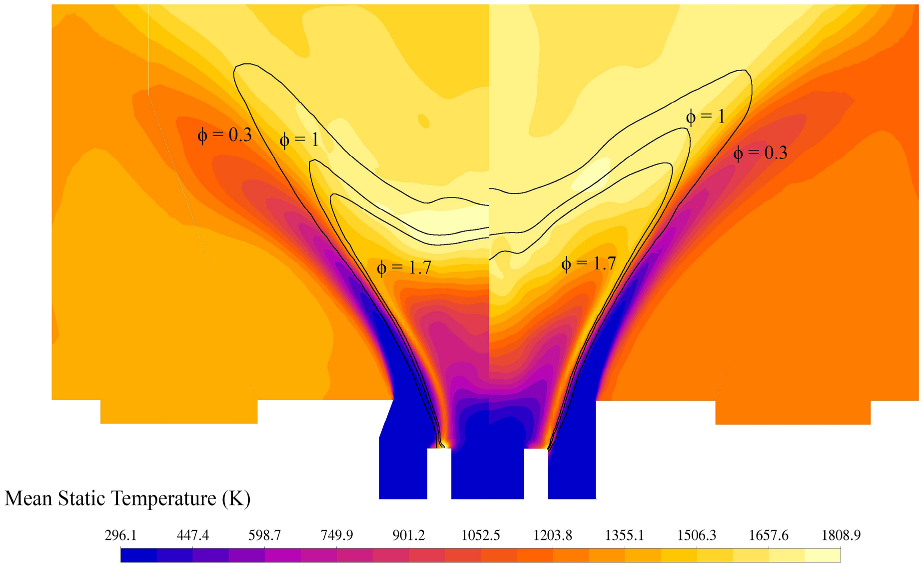
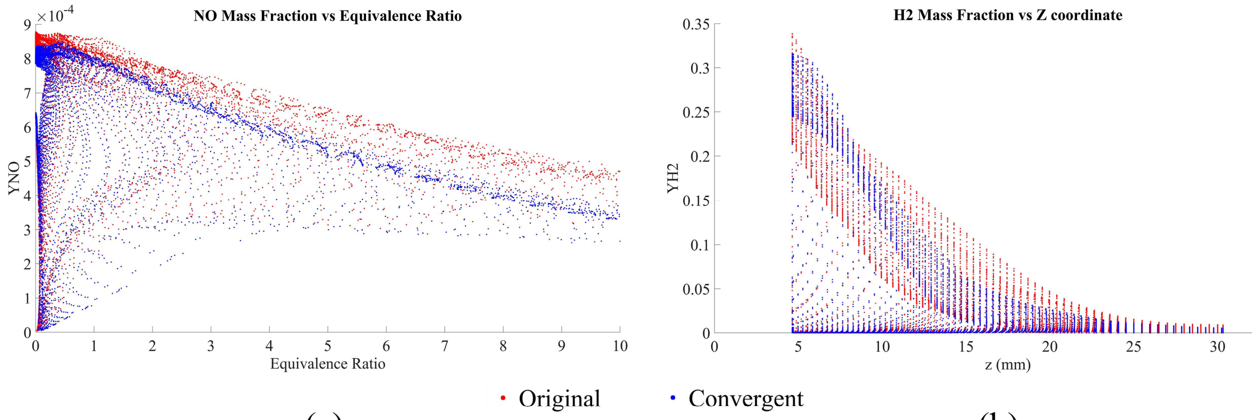


Fig. 2 Temperature contour of the convergent (left) and original (right) injector flame overlapped with isoline with equivalence ratio ϕ of 0.3, 1 and 1.7.

The presence of the converging throat causes the outer air swirl flow to flow radially inward which results in a more curved flame anchor, but interestingly, it does not have a significant impact on the shape and size of the isoline at $\phi = 0.3$. Both designs have presented the maximum temperature region near the centreline, but the convergent nozzle design has demonstrated a maximum temperature region that is flatter in a less inverted V-shape and of higher temperature. The higher temperature can be seen from the faster consumption of the H_2 illustrated by the smaller width between the $\phi = 1.7$ and 0.3 isoline and also in Fig. 3(b), where a more rapid decline in H_2 mass fraction is spotted between axial position of z = 10mm and 20mm. This faster consumption of fuel has resulted in a lower temperature region directly downstream of the maximum temperature region, indicating a potential decrease in the overall flame length and, hence, resulting in an observable reduction in NO production at all equivalence ratios for the convergent nozzle design and is presented below in Fig. 3(a).



(a) (b)

Fig. 3 Scatter plot of NO mass fraction vs. equivalence ratio (a) and H_2 mass fraction vs. z axial coordinate (b) between z = 5mm and 30mm.

6. CONCLUSIONS

Reactive ELES simulation has been conducted on a swirl stabilised partially premixed hydrogen flame produced by a straight and 20.56° converging injector nozzle on a dual swirl HYLON injector. Numerical results on the original injector have shown that despite a relatively low mesh number, the general trend in the radial axial velocity distribution has been captured with good agreement but still shows inaccuracies in the prediction of the magnitudes, which poses needs in future studies to reconduct ELES simulations with higher mesh number and Courant number well below unity. By comparing the ELES results between the original and modified injector, the overall flame structure and the H_2-air mixture have shown to be of minimal impact from the presence of the convergent throat, but the introduction of the converging section leads to a more intense mixing between fuel and air at the central flame region which resulted in an overall shorter flame length from prompted H_2 consumption, and eventually leading to a reduced NO emission level. This study also poses a direction for future studies to investigate the impacts of convergent nozzle angles on NO_x emission, further extending the understanding of how the flame shape and length can be optimised from geometric changes in addressing low NO_x partially premixed hydrogen combustion.

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