Studies in hydrogen micromix combustor technologies for aircraft applications

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Abstract. Within the context of future aircraft turbine engine development technology, hydrogen has fast become one of the most favored candidates as an alternative fuel due to the possibility of producing extremely low levels of pollutants in particular NOx. The principal component of such an engine technology is the hydrogen micro-mix combustor which provides a solution to safe hydrogen combustion avoiding auto-ignition and flashbacks by addressing novel methods of hydrogen-air mixing. The current design concepts include a typical injection manifold composed of multiple concentric arrays of micro-mix combustors which produce hundreds of miniature low temperature diffusion flames having very low NOx levels.

Introduction

Air transport requires much energy and therefore it is necessary to have a fuel with a high energy density. Conventionally, jet kerosene produced from fossil fuels has been the main propellant used in aviation. The main problem with using kerosene as an aviation fuel is the environmental impact due to the production of the greenhouse gas, CO_2, which accounts for about 2,5% of global emissions as well as CO, SO_x.

A switch to hydrogen propelled aircraft would produce zero CO_2, CO, SO_x emissions and, when combined with a suitable technology may substantially reduce the levels of NO_x emitted into the atmosphere and potentially eliminate other pollutants. Additionally, hydrogen has an energy density almost three times that of kerosene but requires heavier storage facilities to kerosene. The main disadvantage of hydrogen is that it requires about five times the volume of conventional fuel to carry the same amount of energy and consequently new concepts for aircraft design need to be addressed to enable safe, light storage of liquid hydrogen.

Currently two lines of research are being pursued towards the application of combusted hydrogen as a propellant both of which aim to reduce the levels of NO_x produced: Lean Direct Injection (LDI), which tends to limit the levels of NOx emissions to those of current kerosene fuelled engines and the Micromix combustor technology which aims to lower the levels of NOx produced compared to kerosene. This latter technology is investigated in this paper.

Preliminary investigations and experiments using hydrogen were first conducted by Funke-et-al [1] using a hydrogen air mixture using an experimental test rig constructed for the GTCP 36-300 APU which was modified to incorporate a hydrogen combustor mechanism consisting of concentric arrays of numerous miniature micro-mix combustors as shown in Fig. 1.

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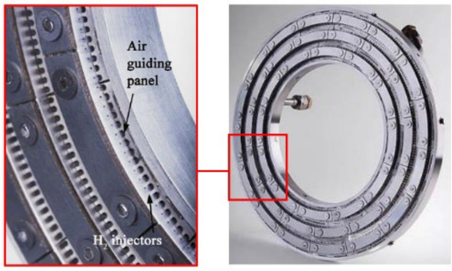


Fig. 1 Prototype micro-mix combustor for gas turbine Honeywell/Garrett APU GTCP 36-300 [2]

Numerical method

The commercial program ANSYS-FLUENT [3] was used as the main software used to obtain flow solutions for all test cases. Calculations using the FGM method with partially premixed combustion were conducted and compared with results from simulations using the eddy dissipation method also performed for a baseline test case hypothetical APU micromixer design at a relatively low pressure described by Ghali [4]. The chemical kinetic mechanism for the first series of FGM simulations used the Naik model [5] consisting of 9 species and 21 reactions. Turbulence was modelled using the k-ω SST turbulence model by Menter [6].

This turbulence model is particularly suited to these kinds of simulations where the recirculation and mixing of hydrogen is of primary importance. The model is capable of accurately capturing the detail of the turbulent flow both through the viscous sublayer down to the solid wall as well the large-scale eddies in the recirculation region and the small-scale eddies in the vicinity of the hydrogen jet.

To calculate the concentration of NO in ANSYS-FLUENT the extended Zeldovich chemical kinetic scheme was used, the details of which are given in [3] and where the calculation is restricted to thermal NOx formation.

Computational domain and numerical results

A structured grid having almost 580,000 cells was created using the ANSYS-ICEMCFD grid generator which satisfied the grid quality requirements where the air inlet is over the left vertical face and the hydrogen inlet is the cylindrical vertical tube shown in Fig. 2.

Mass flow rate boundary conditions are set with an air inlet temperature of 422K at a pressure of 2.5 atm., a hydrogen inlet temperature of 300K and the mass flow rates listed in Table 1 at a pressure of 1 atm. and pressure outlet boundary conditions of 2.4 atm. Adiabatic no slip boundary conditions were applied at the walls.

Table 1: Equivalence ratios and hydrogen mass flow rates for combustor

Equivalence ratio ϕ	H_2 mass flow rate ($kg \cdot s^{-1}$)
0.3	4.335×10^{-6}
0.4	5.75×10^{-6}
0.5	7.225×10^{-6}
0.6	8.67×10^{-6}

The results are presented from Fig. 3 to Fig. 9. Fig. 3 shows the flame anchored between two relatively large recirculation regions on the symmetry plane, the upper region being slightly larger than the lower one. The upper inner vortex originates from the main air jet whilst the lower vortex originates from the recirculated combusted gas downstream of the hydrogen jet. The velocity at the air channel exit is approximately 100 $m \cdot s^{-1}$ which is also consistent with that associated with the low pressure drop of a typical combustor. The velocity at the downstream edge of the H_2 channel at the entrance to the chamber is about 250 m·s^{-1}.

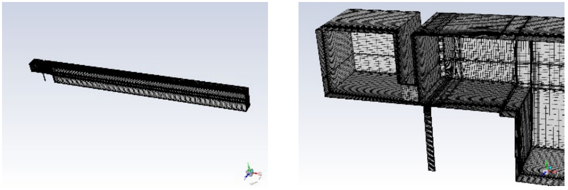


Fig. 2: Computational domain used in calculations

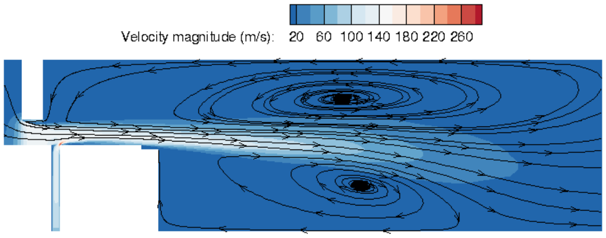
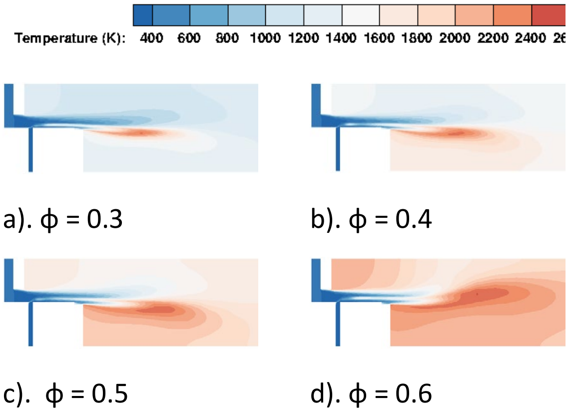


Fig. 3 Calculated flow field and stabilising vortices with EDM model for ϕ = 0.4

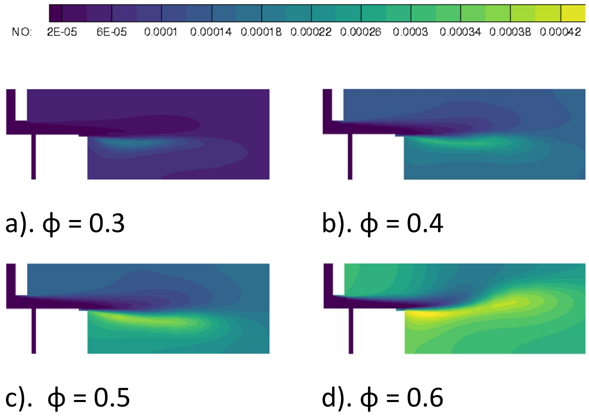
Fig. *4* and Fig. 5 show the temperature and NO distributions for different equivalence ratios on the symmetry plane obtained with the EDM model. The temperatures are consistent with those in [4], where a maximum flame temperature of about 2600 K is predicted for the highest equivalence ratio of ϕ = 0.6 associated with a larger more extended flame.



a). ϕ = 0.3 b). ϕ = 0.4

c). ϕ = 0.5 d). ϕ = 0.6

Fig. 4: Flame temperature for different equivalence ratios with EDM

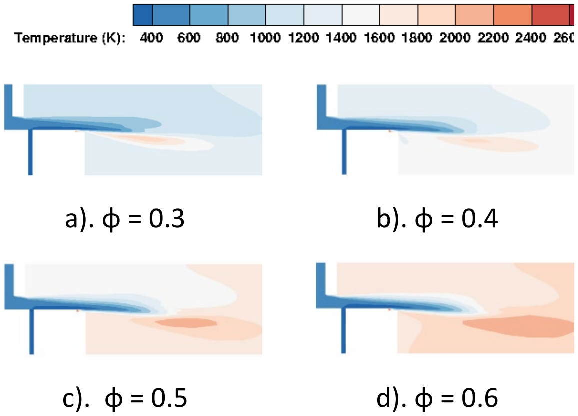


a). ϕ = 0.3 b). ϕ = 0.4

c). ϕ = 0.5 d). ϕ = 0.6

Fig. 5: Mass fraction of pollutant for different equivalence ratios with EDM

Similar distributions using the FGM method are shown in Fig. 6 and Fig. 7.



a). ϕ = 0.3 b). ϕ = 0.4

c). ϕ = 0.5 d). ϕ = 0.6

Fig. 6: Flame temperature for different equivalence ratios with FGM - Naik

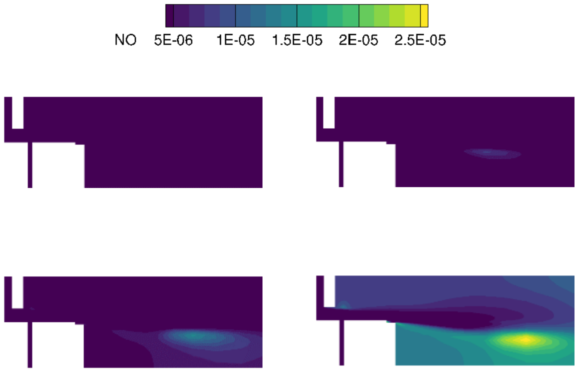


Fig. 7: Mass fraction of pollutant for different equivalence ratios with FGM - Naik

The flame temperature is about 200K lower than with the EDM due to the energy consumed in the chemical reactions in the FGM model compared to the single step reaction in EDM calculation with a corresponding reduction in NO concentrations.

The results for mass-averaged temperature and NO emissions corrected to 15% O_2 are shown in Fig. 8 and Fig. 9. The flame temperature and NO emissions are a direct consequence of equivalence ratio, the lower the equivalence ratio, the shorter and cooler the flames with the associated reductions in NO emissions.

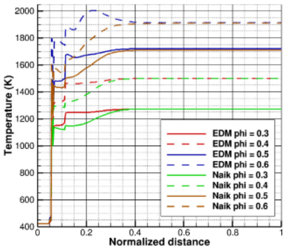


Fig. 8: Mass weighted average temperature along combustor length for EDM and FGM -Naik for different equivalence ratios

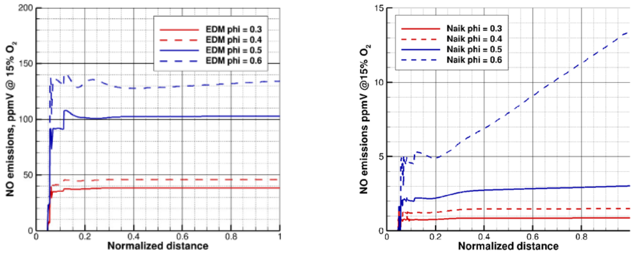


Fig. 9: NO distributions along combustor length for EDM and FGM-Naik models for different equivalence ratios

Summary

Comparison of results between the EDM and the FGM-Naik model demonstrated that the temperature distributions were in good agreement but much lower NO levels, of about three orders of magnitude were obtained with the latter model. Qualitative comparison of the temperature and NO emission levels indicated satisfactory agreement with the trends expected in the physics where higher temperatures and higher NO concentrations were obtained for increasing equivalence ratios which were also in broad agreement with similar results available in the literature [4].

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