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IMPLICATION OF DIFFERENT FUEL INJECTOR CONFIGURATIONS FOR HYDROGEN FUELLED MICROMIX COMBUSTORS

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ABSTRACT

A design of a hydrogen fuelled micromix concept based combustor is proposed in this paper. The proposed micromix concept based combustor yields improved mixing, which leads to wider flammability range of the hydrogen-air flames compared to conventional kerosene and micromix concept based combustors. This improved mixing allows the combustion zone to operate at a much lower equivalence ratio than the conventional kerosene based and micromix concept based combustors considered in this study. Furthermore, when burning hydrogen the thermal energy radiated to the surroundings is lower (as the result of using lower equivalence ratio) than that of kerosene, consequently resulting in an increased liner life and lower cooling requirement. The aim of this paper is to highlight the impact of using hydrogen as a fuel in gas turbine combustors. It is perceived that this new micromix concept based combustor would also help in achieving low emissions and better performance. Possibilities for lowering NO_x emissions when using hydrogen as a fuel in new designs of micromix combustor are also discussed.

NOMENCLATURE

CO_2	Carbon dioxide
H_2	Hydrogen
H_2O	Water
NO_x	Nitrogen oxides (NO and NO_2)

INTRODUCTION

Discharging green house gases and particulates into the atmosphere has an impact on global climate. Environmental concerns and depletion of fossil fuel resources have become the driving forces for research and development for introducing hydrogen as a fuel for air transport. Additionally, emissions of carbon dioxide, water vapour and oxides of nitrogen (as a consequence of fossil fuel combustion) contribute to global warming. However, combustion of hydrogen yields only H_2O and NO_x emissions (carbon and sulphur emissions are not produced [1]). One fundamental difference between kerosene and liquid hydrogen is the fuel energy density. For a given mission, the mass of the fuel required will be 2.8 times less for liquid hydrogen than kerosene (Fig 1). This high energy content per mass characteristic of hydrogen will lower the total fuel weight and allow for a higher payload or longer range compared with an equivalent kerosene fuelled aircraft. But this is counteracted by the fact that high volume of hydrogen will require heavy structure cryoplanes to carry the bulky fuel. (Density of liquid hydrogen=4.419 lb/cf at 20 K and 14.7 psi)

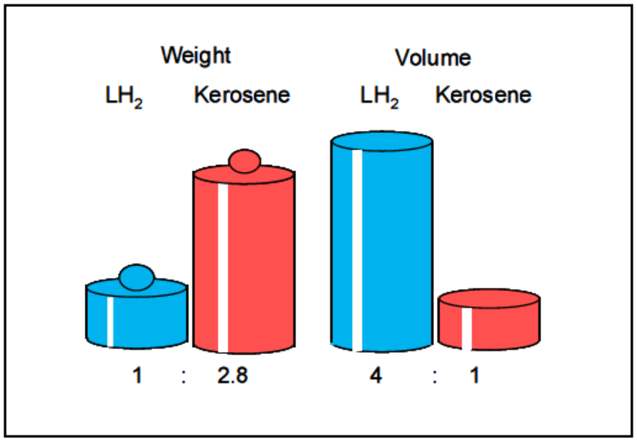


Figure 1: The weight and volume of kerosene and liquid hydrogen, respectively, containing the same energy content. (Illustration idea from Heinz-Günter Klug, retired from Airbus Germany.)

A subsonic hydrogen fuelled passenger aircraft will on average burn 16% less fuel then a similar conventional aircraft and the advantage is 28% in case of supersonic aircraft [2]. Using hydrogen has an additional advantage of being safer as compared to presently used jet fuel [2]. This is due to the fact that, hydrogen is lighter gas and in case of emergency hydrogen escapes into the atmosphere, whereas, kerosene remains there and poses a potential fire hazard. Liquid hydrogen is stored in cryogenic tanks which are at substantially low temperatures. This liquid hydrogen can also be used as a heat sink (coolant) for combustor and other parts before introducing it in the combustion chamber as a fuel.

Pohl et al. [3] have carried out studies on hydrogen as a fuel for future aviation. After analysis of performance, operating costs, handling and safety aspects they deduced that the fuselage-top mounted tank configuration is the most favourable solution to modify an existing airplane for hydrogen operation. Their study also suggests that the greenhouse effect of water vapour depends on altitude; at an altitude of above 6 km it exceeds the effect of carbon dioxide for an equal number of molecules. However, the situation looks quite different if the residence time of H_2O vapour and CO_2 is taken into consideration. CO_2 has a residence time of more than 100 years (independent of altitude), whereas residence time of H_2O vapour is 3-4 days at ground level and up to 6~12 months in stratosphere. Studies suggest that for minimising the global warming potential due to water vapour and reducing the formation of contrails, optimisation of cruise altitude is necessary [4]. The results suggest that cryoplanes should cruise at an altitude of 2-3 km below the conventional aircraft cruise altitude [4].

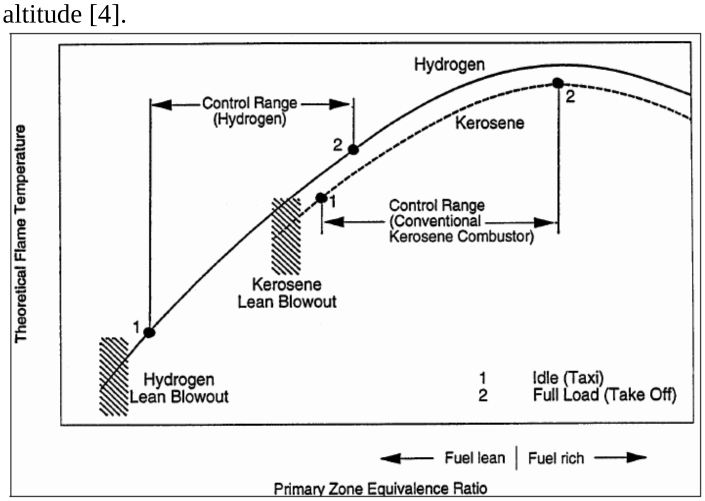


Figure 2: Temperature characteristics of the combustion chamber primary zone [5].

Theoretical and experimental work done by researchers suggest that there is a potential to design a combustion system that produces lower NO_x emissions than burning kerosene, and NO_x emissions could be reduced by 42% or more [1]. As shown in Figure 2, control range of hydrogen is at leaner equivalence ratios, this suggests that hydrogen could be burned at much lower equivalence ratios as compared to kerosene. This would help in reducing the flame temperature thereby lowering the NO_x emissions.

Due to risk of auto-ignition for premixed systems and the problems of large scale hydrogen diffusion flames, the lean non-premixing concept of micromix combustion, which is based on miniaturised diffusive combustion, is suggested as a promising hydrogen combustor configuration [5-8]. The concept of miniaturised diffusive combustion is shown in Figure 3. As illustrated in Figure 3(a), hydrogen is being injected radially through the holes into the main air flow, which then burns as a diffusive combustion. An array of such miniaturised diffusive combustor, in a ring shaped structure of the micromix hydrogen combustor is shown in Figure 3(b). The proposed injector configurations in this paper are aimed to improve these combustor designs for better performance.

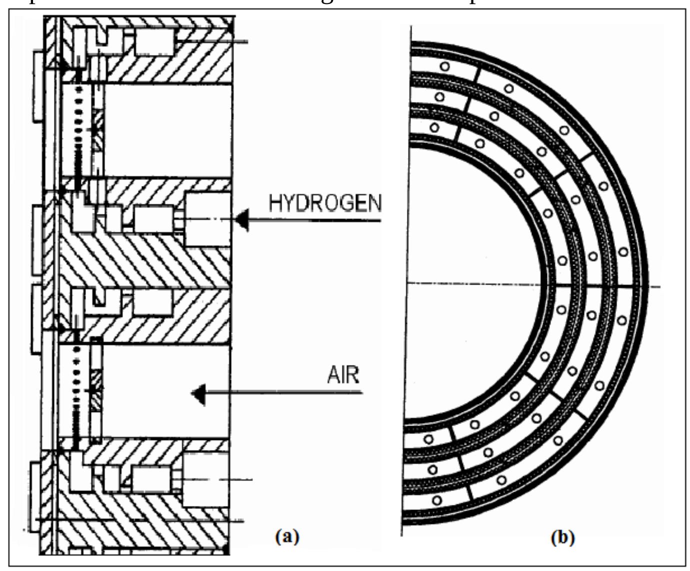


Figure 3: Ring-shaped structure of the micromix hydrogen combustor (Air and hydrogen admission for diffusive combustion in the micromix hydrogen combustor of third generation for the APU GTCP 36-300 engine [8]).

Ziemann et al. [9] have carried out experimental studies on low NO_x combustors for hydrogen fuelled aero engines. After analysis, they inferred that a very low level of NO_x emission was demonstrated with hydrogen fuelled lean premixed perforated plate combustion. The test results from their program suggest that the development of practical low-NO_x hydrogen combustors for gas turbines can be feasible.

NO_x emissions could be reduced by more than half of the existing levels. Limited amount of work has been done on micromix concept based combustors, and there is clearly a need for further investigations. In combustors, recirculation and mixing play vital roles in stabilising and increasing the flame stability limits [10].

A design concept of micromix concept based combustor with high mixing has been proposed in this study and its comparison with low mixing micromix concept based combustor has been performed using computational fluid dynamics. The improved mixing allows the combustion zone to operate at a much lower equivalence ratio than the conventional kerosene based and micromix concept based combustors considered in this study. Comparison of temperature profiles, NO_x emissions and mixing intensity are also reported here.

METHODOLOGY

A micromix concept based combustor with four radial injection holes for hydrogen/air is considered for this study. Figure 4 shows the schematic diagram of an injection tube. A micromix combustor may comprise hundreds to thousands of such injection tubes which will be in the form of an array. Hydrogen/air is radially injected from all four radial injector holes into the main air flow (which is introduced axially through air inlet, in a positive z direction). A rectangular prism shape combustion zone has been considered at the downstream of the injector.

Numerical simulations were carried out using CFD code ANSYS FLUENT 12.1 [11] and the results obtained were analyzed. The velocity inlet condition was employed at the inlet and outflow boundary condition at the exit of the combustor. Boundaries of the combustion zone have been considered as periodic for obtaining the computational results equivalent to an array of such injectors. As the air and hydrogen have separate inlets and type of combustion is diffusive combustion, the models used for computation are:

- non-premixed combustion (PDF)
- thermal NO_x model (no fuel NO_x)
- A Realizable k-ε viscosity model was used for the computation.

The solution was considered converged when scaled residuals had dropped by three orders of magnitude and the monitored parameters such as pressure, velocity and temperature fluctuated around a specified value within an acceptably small range.

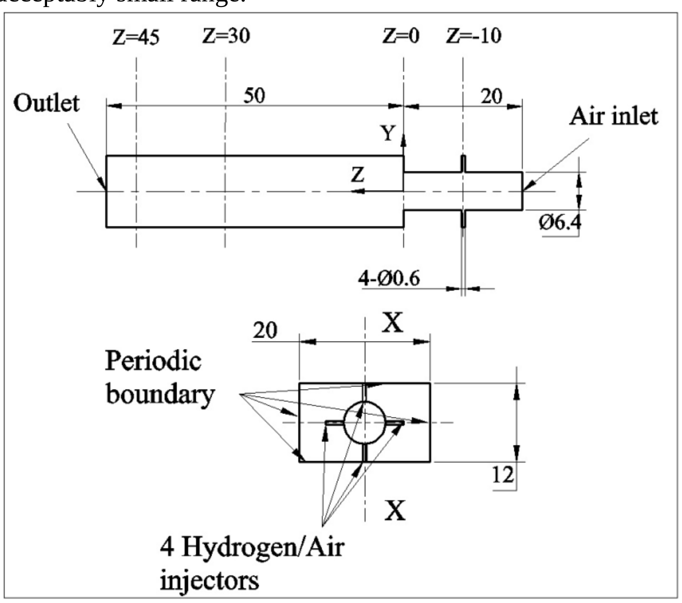


Figure 4: Schematic diagram of micromix combustor with rectangular prism combustion zone.

NO_x emission at the outlet and temperature profiles for different sections of injector and combustion zone, as well as mixing intensity were calculated numerically. Different temperature profiles and mixing profiles were also plotted for various cross sections along the z axis. A Realizable k-ε turbulent model was selected for the computation.

Two different cases have been considered in this study. In case 1, hydrogen was introduced by all four radial injectors into the main air flow, whereas in case 2, hydrogen was introduced by only two holes while the air was supplied by the other two. In case 2, hydrogen and air holes were kept directly opposite to each other for better mixing. The mass flow of hydrogen and air was varied in such a way, so as to get the overall equivalence ratio same for both the cases. The inlet temperature of hydrogen and air has been kept as 750K (a representative compressor delivery temperature of a high bypass ratio turbofan engine). Operating pressure was kept as 1.79 MPa.

Grid Sensitivity Study: This study was carried out by increasing the number of cells of the original model by 10 times (approximately) from 83307 cells to 900110 cells. The results show that the variation in the outlet temperature between these two grids is below 1.5%. Thus the original model is non-grid-sensitive and the results shown in this paper are accurate.

VALIDATION

The model validation study is carried out based on the Lean Direct Injection (LDI) hydrogen combustors, in which the data from the “N1 injector with 2.5in liner” are selected [12]. The test NO_x variation with the equivalence ratios under a certain operation condition is selected as the reference data for the validation. All the numerical models and the corresponding settings for the validation study are kept coincident with those for the two combustors intended to be investigated.

The operating conditions for the validation, corresponding to the selected test conditions, are listed in Table 1.

Parameters	**Settings**
Air inlet velocity (m/s)	30.5
Equivalence ratio	0.266, 0.319, 0.372
Operation pressure (MPa)	0.690
Inlet temperature (K)	600

Table 1: Operating conditions for the validation

The domain geometries for the validation investigation are shown in Figure 5.

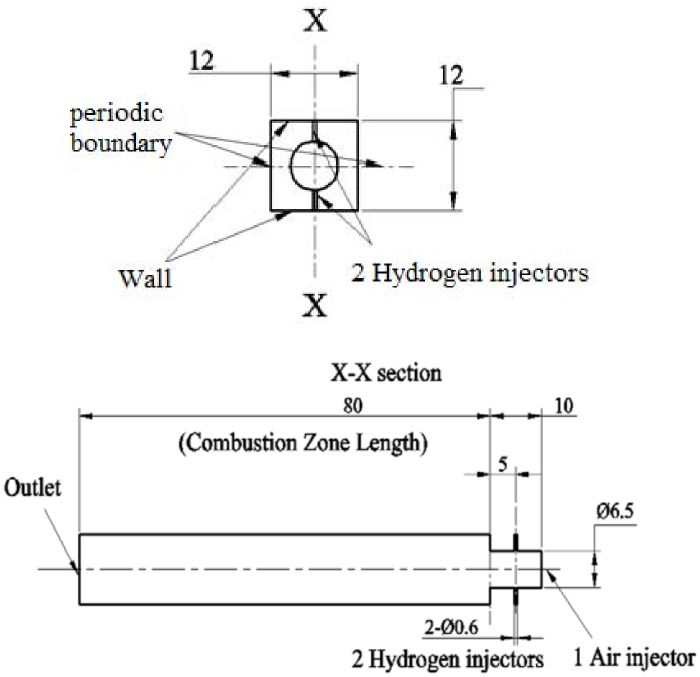


Figure 5: Domain geometries for the validation (mm)

The comparison of the outlet temperature against the equivalence ratio between the validation data and the test data is illustrated in Figure 6. The outlet temperatures, T_{out}, both in the test data and the validation are presented in the unit of ℉. From this figure, small discrepancies can be found between the outlet temperatures obtained from the validation and from the test under the same equivalence ratio. In addition, the test data also have 10% variation on the equivalence ratio. Therefore, the found small discrepancies between the test data and the validation data are acceptable.

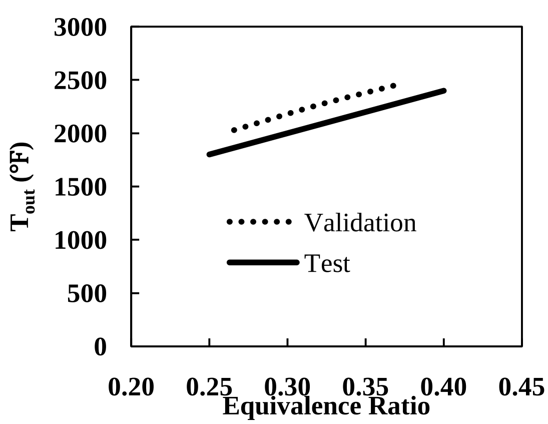


Figure 6: Comparison of the outlet temperature against the equivalence ratio between the validation data and the test data.

To sum up, the above validation study indicates that the numerical models used in this case have a reasonable accuracy.

RESULTS AND DISCUSSION

Figure 7 (a) shows temperature distribution across x-x plane with four hydrogen injectors and Figure 7 (b) shows the temperature distribution with two hydrogen injectors and two air injectors along the x-x plane. It is observed from the temperature distribution that area in which temperature is higher than 1900 K has reduced significantly in case 2 as compared to case 1. In case 1, the volume where the temperature is higher than 2500 K is quite substantial as compared to case 2. This shows that increased mixing by introducing air by two injection holes reduces high temperature regions thereby resulting in reductions of NO_x emissions. In this case more mixing has been achieved by injecting air by two holes and hydrogen by two holes into main air flow (evident by the early starting of combustion at the end of the injector zone).

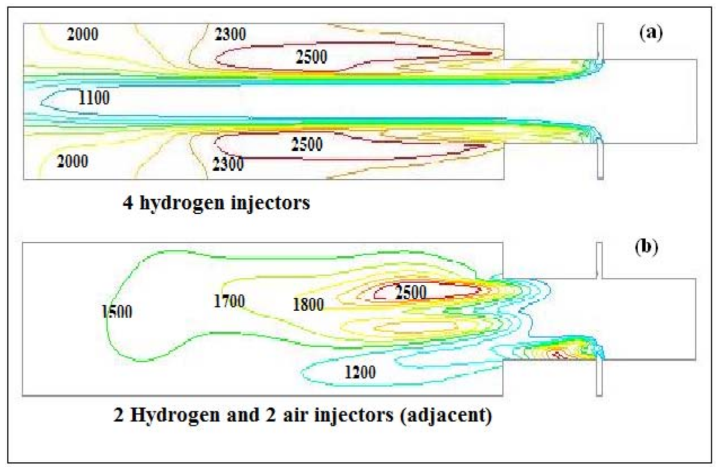


Figure 7: Temperature distribution along x-x axis (a) for four hydrogen injection holes (b) for two hydrogen and two air injection holes.

The temperature at the outlet of the combustion zone in case 2 is 1440 K. This suggests a relatively improved life for nozzle guide vanes and turbine blades.

It is perceived that if the micromix combustor comprises an array of combustors (as discussed in case 2), it will reduce the amount of dilution air and cooling air (in combustor liner) required due to smaller high temperature zone. This will also lead to significant reduction in length and subsequently weight of the combustion chamber.

Figure 8 (a) illustrates the temperature traverse along different cross sections (Z = -10, 0, 30) of the micromix combustor in which hydrogen is introduced by 4 holes. And figure 8 (b) illustrates the temperature traverse along different cross sections (Z = -10, 0, 30) of the micromix combustor in which hydrogen is introduced by two holes and air by two holes into the main air flow. Z = -10 represents the injection point of hydrogen/air into the main air flow, Z = 0 and Z = 30 represent downstream section of the combustion zone.

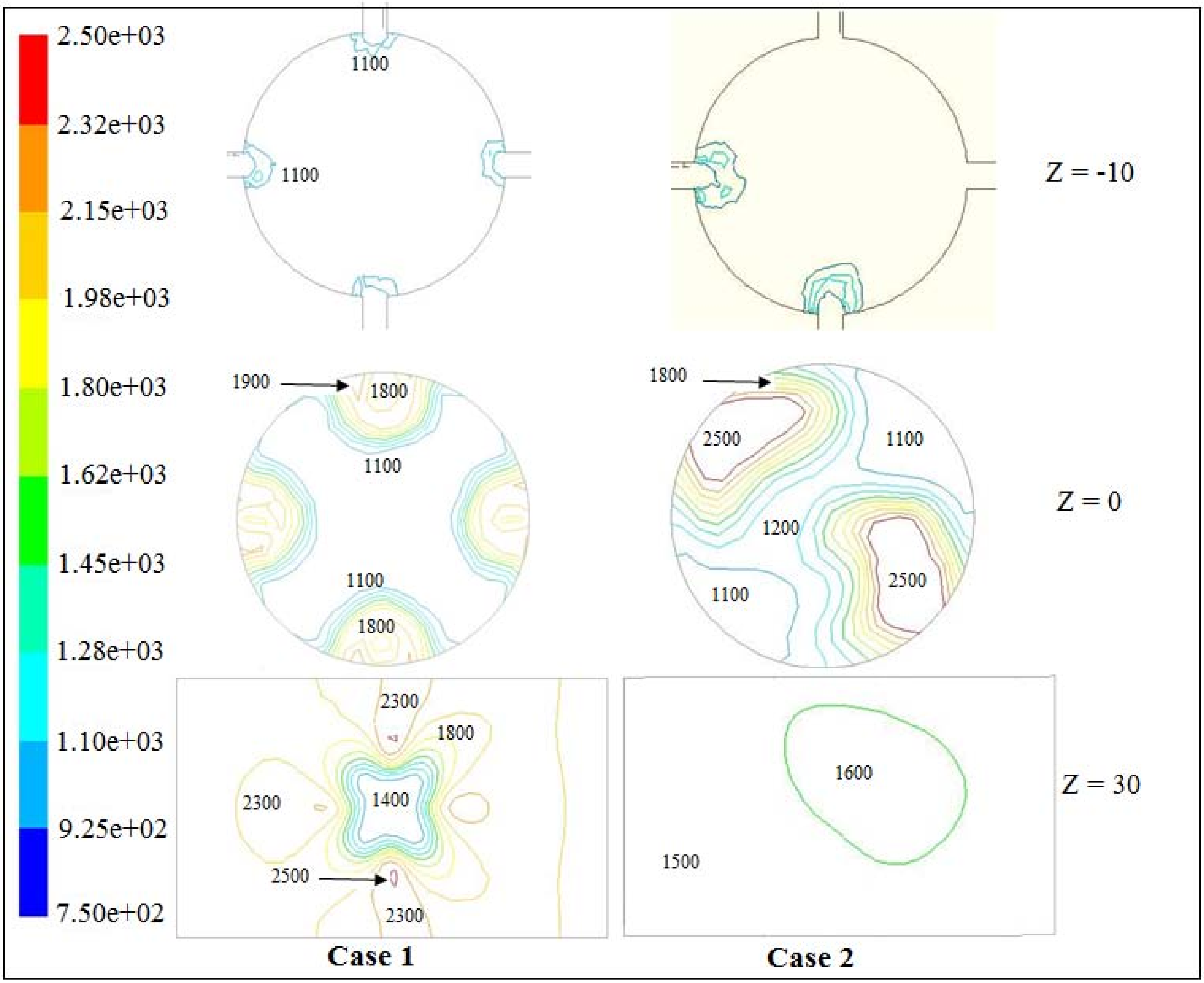
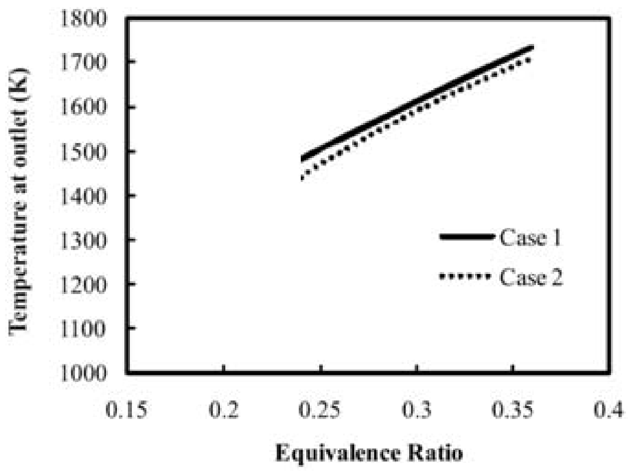


Figure 8: Temperature distribution at different cross sections along the z axis (a) for four hydrogen injection holes (b) for two hydrogen and two air injection holes.

1. At inlet section, i.e., at Z = -10, the contour plot shows the effect of hydrogen velocity on temperature distribution. For case 2 which has the higher H_2 velocity as compared to case1, a greater depth of temperature curves can be seen, in-turn suggesting rapid mixing of hydrogen with air.
2. At section Z=0, it can be clearly seen from Figure 8 that the high temperature contours in case 2 represent efficient combustion, occurring due to better mixing as a consequence of hydrogen and air being injected opposite to each other in the main air flow. But in case 1, the temperature traverse shows that the combustion is not substantial at this cross section which is probably due to less effective mixing of fuel and air.
3. At section Z = 30, the temperature is of the range 1800K-2400K in the four H_2 injectors indicating that combustion is taking place at this section, whereas in the other case, it is observed that combustion process is almost complete and the temperature has fallen down to the outlet temperature of combustion zone. This implies that the length of the combustion zone required has been reduced to half the original length.

Figure 9 shows variation of average temperature at the outlet of the combustion zone at different equivalence ratios for both cases. It is seen that the curves are similar which implies that the combustion efficiency is same. Thus it can be



said that case 2 has less combustion efficiency penalty.

Figure 9: Variation of outlet temperature at different equivalence ratios.

Since this is the hydrogen fuelled combustor, the fuel NO_x is absent. The major factor that is required for the formation of thermal NO_x is very high temperature which triggers the disassociation of molecular oxygen and nitrogen leading to a series of reactions producing nitrogen oxides (as given by Zeldovich mechanism). In the primary zone of the cases considered, the maximum temperature exceeds 2400K (NO_x formation begins at around 1700-1900 K.) because of the high flame temperature of hydrogen. But the thermal NO_x reaction is also influenced by the residence time of nitrogen at this temperature. In case 2, the region of high temperature is reduced and the above results have shown that the length of the combustor can be halved-both of these factors have helped to reduce the NO_x emissions by 40% compared to case 1. The proposed micromix combustor configurations could lead to lower NO_x emissions. This would eventually help in overcoming the effect of depletion of ozone layer caused due to NO_x produced by aircraft engines in stratosphere.

CONCLUSIONS

- A new design for a hydrogen fuelled micromix concept based combustor has been proposed in this paper by comparing two different injection models.
- High temperature zone can be fairly reduced by introducing air by two injection holes and hydrogen by the other two injection holes to the main flow. The improved mixing seen in this new case, allows the combustion zone to operate at a much lower equivalence ratio than the conventional kerosene based and micromix concept based combustors considered in this study.
- The renewed model (case 2), not only reduces NO_x emissions, but also helps in decreasing the combustion chamber length by almost half of the normal length.
- An array of combustor design proposed in the study could be used in big gas turbine combustors for low NO_x emissions which can be highly controlled by varying equivalence ratio.
- This modified combustor model would need less cooling air as compared to other case considered in the study.
- Temperature at the end of combustion zone in case 2 is substantially less as seen from the results. Thus by reducing the thermal energy radiated to the surroundings, the life of liner, nozzle guide vanes and turbine blades can be increased.

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