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Combustion & Mixing Analysis of a Scramjet Combustor using Different Fuel Injection Strategies

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ABSTRACT

Numerical simulations are performed for scramjet combustor with different fuel scheme using Fluent tool Ansys 17.2. For fuel injection spilt part is done at the inlet wall of the combustor. This research work shows the internal flow behaviour of fuel with air for scramjet combustor. Temperature, pressure and velocity profile shows the turbulence mixing effects at various sections of cross-stream flow. Two dimensional Reynolds-Averaged Navier-Stokes equation and k-ε model has been considered for modelling chemical reacting flows for hydrogen-air and methane-air fuel. The finite rate/eddy dissipation chemistry turbulence model is considered for combustion modelling.

***Keywords:* CFD, combustion, scramjet, injection and efficiency.**

I. INTRODUCTION

There are so many applications of hypersonic propulsion that include space access, national defence systems and high-speed transport, etc. and scramjet engine is the most preferred choice for such kind of application. Effective propulsion systems are capable of generating large thrust which is the main base for the progress of the hypersonic vehicle development programs. For the reasonable combustion efficiency, it is necessary to maintain the temperature and pressure within the permissible limits in the scramjet combustor for the flight Mach No. above 6. Inside a combustion chamber, the flow field is highly complex. In the combustion chamber for supersonic speed, complete combustion of fuel plays an important role as well as the mixing of reactants, flame holding and stability of flame. Fuel injection schemes like cavity, pylon, and strut having different geometrical configurations have been used for the enhancement of the mixing process. In past studies, the fuel injection techniques greatly improve the performance of scramjet [1,2]. However, the strut injection technique also increases the tendency of higher pressure losses. The goal of the researchers is to sustain the residence time of air for a long duration in scramjet combustor so that a high amount of energy released thus producing large thrust. Wei Huang et al. [3] overview the scramjet combustor along with cavity flame holders for different fuel injection techniques like strut injection, cantilever ramp injection and normal injection. In the last few decades, so many researches are carried out by various countries in the field of Scramjet Engine from the last few decades has been reviewed by Curran [4].

There are so many processes for enhancing the mixing of fuel and air in Scramjet are reported [5]. Some of the mixing devices are tabs, port, vanes, cavity, pulse jet, vibrating splitter, etc. Yu[6] et al., with the help of experiments, invested eight different types of integrated wall injector with cavity to study the characteristics of flame holding using Hydrogen fuel and also observed the performance of scramjet combustor. Zhang et al. [7] carried out an experimental investigation of a strut based hydrocarbon fuelled scramjet combustor and studied three different combustion mode scramjet mode, weak ramjet mode, and strong ramjet mode) transitions concerning for fuel equivalence ratio. A good number of Numerical and experimental studies are mentioned in literature review [8, 9, 10–11,12,13,20,21]. Wei Huang et al. [22] investigated the effect of H2O species mass fraction and also studied the H2 - O2 combustion phenomenon in supersonic flows. The combustion phenomenon is affected by the no. of mole fraction of species. So pre-defined species mole fraction will improve the combustion.

II. MODELLING

Numerical Modelling

Internal flow phenomenon in combustor is greatly affected by the governing equations of fluid flow. So while selecting governing equations for fluid flow, we have to give more importance. In the case of Reacting flow, governing variables for fluid flow plays a major role in the combustion flow phenomenon. In this problem, the incompressible and turbulent case is considered. Using the Reynolds Averaged Navier- Stokes (RANS) we observed the different flow behaviour of scramjet combustor for different geometries and input conditions. The

Pressure based solver with k-ε (2D) turbulent model has been used. The fuel used is Methane- Air and Hydrogen-Air and density is taken as an ideal gas. Eddy dissipation (volumetric reaction) combustion model is used. The governing equations for fluid flow and species transport equations are considered below as (14, 15-17). For observing the nature of the turbulent flow field and mixing characteristics of hydrogen-air and methane-air, steady 2D computations are performed by using Ansys 17.2 commercial code

The continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_i} = 0 \qquad (1)$$

Momentum equation

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_i} = -\frac{\partial \rho}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} \qquad (2)$$

Energy Equation

$$\frac{\partial (\rho e_t)}{\partial t} + \frac{\partial (\rho h_t u_j)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\tau_{ij} u_i - q_i\right) \qquad (3)$$

Species Transport Equation

$$\frac{\partial (\rho Y_i)}{\partial t} + \frac{\partial (\rho u_j Y_i)}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\rho \breve{u}_i Y_i\right) + w_i \qquad (4)$$

Where τ_{ij} is the stress tensor and Y_i is the mass fraction of chemical species. w_i is the chemical source term of species *i*.

q_i is the heat flux vector because of convection and conduction mode of heat transfer.

$$q_i = -\lambda \frac{\partial T}{\partial x_j} + \rho \sum_{k=1} h_k Y_k \breve{u}_{j,k} \qquad (5)$$

Combustion Modelling

In modelling scramjet combustor, the combustion process is the main key feature, and the turbulence mixing of fuel with combustion air influences it. The present computational work combustion model used are species transport along with the eddy dissipation reaction model (18, 19). Combustion depends on the rapid chemical reaction between the combustible elements of fuel and oxidizer. As chemical reaction occurs a large amount of energy released because of high-intensity turbulence. For this research paper global one-step reaction mechanism has been considered and defined as follows:

$$2H_2 + O_2 \rightarrow 2H_2O$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2$$

Geometrical Modelling

The combustion geometries are developed using design modular Ansys- Fluent 17.2. The length of the intake is about 225 mm. The total length of the combustor is 1800 mm. For fuel injection split, part is considered at a height of 5 mm and 50 mm in the horizontal part. Here we have prepared 2 models using two different fuels hydrogen-air and methane-air. The geometry of the combustor is shown in Fig.1 and Fig.2.

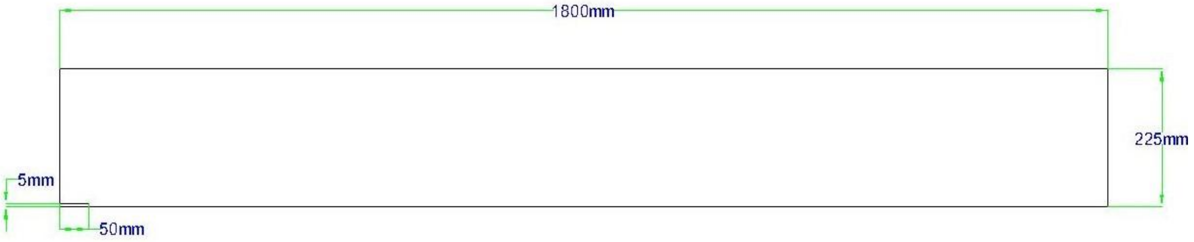

Fig. 1. Systematic diagram of the 2D computational domain

Fig. 2. Fuel Injection through the split part

Boundary conditions

Solving the model numerically boundary layer plays a very significant role. The entry of air takes place through the combustor at a stagnation point. The air and fuel conditions are defined at specified variables given in below table as

Table. 1. Input conditions for Air and Fuel inlets

Variable	Air	Fuel
M_a	2	1
U	0.5	80
T	300	300
ρ	0.25	0.25

III. RESULTS AND DISCUSSION

The present work using numerical techniques shows the effect of different fuel schemes and fuel injection methods. In the analysis, X-axis represents the length of the combustor and the Y-axis represents its height. The origin for the co-ordinate is considered at X, Y (0, 0). Numerical Analysis of different fuel strategies in scramjet combustor has been carried out. The mixing phenomenon and stability of combustion are observed. Shear layer development and recirculation zones are visualized using streamline flow field. The Static pressure variation along the length of the combustor flow field is calculated. Pressure distribution has been compared for the Hydrogen-air and methane-air at mid-plane (Fig.3) of the combustor and also at the wall surface (fig.4). The combustion phenomenon with different fuel strategies has been compared by studying temperature variation at the wall surface (Fig. 5). The velocity of the flow stream at different cross-sections (x=0.6, 0.8, 1.2, 1.4) of the combustor has been evaluated along the length (fig.5-Fig.8). Also, the temperature variation at different cross-sections (x=0.6, 0.8, 1.2, 1.4) has been observed along the combustor length (Fig. 9-12).

The combustion phenomenon has been visualized for different fuel configurations by studying the temperature profile and species mass fraction at different cross-stream sections for Hydrogen-Air (Fig.13) and Methane-Air (Fig.14).

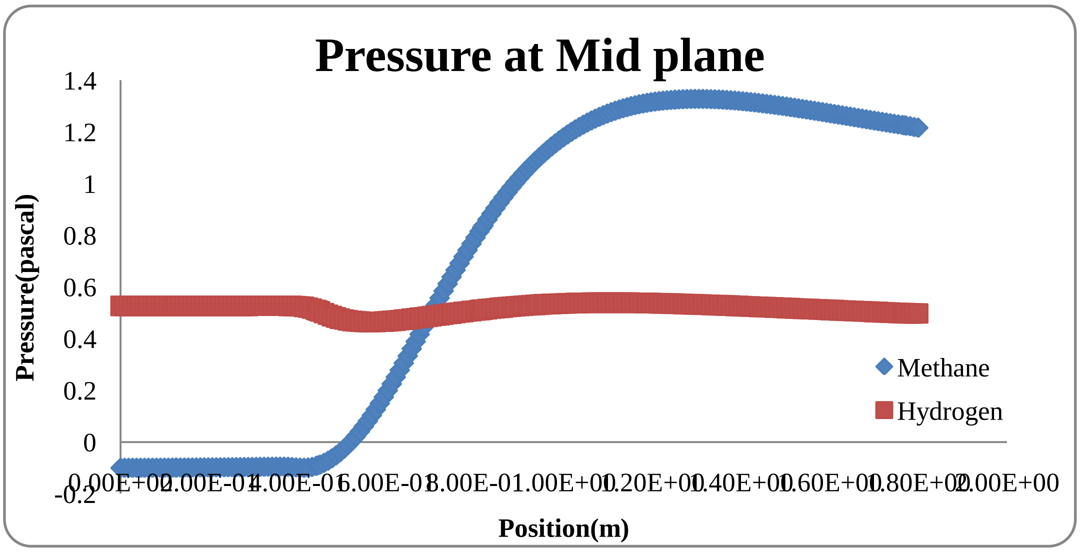

Fig. 3. Pressure distribution at the mid-plane of the wall

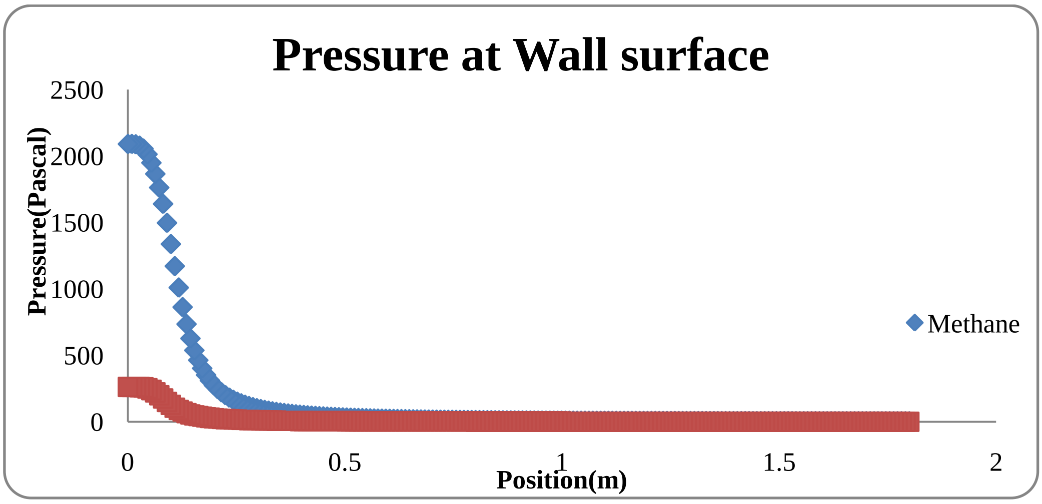

Fig. 4. Pressure distribution at the wall surface

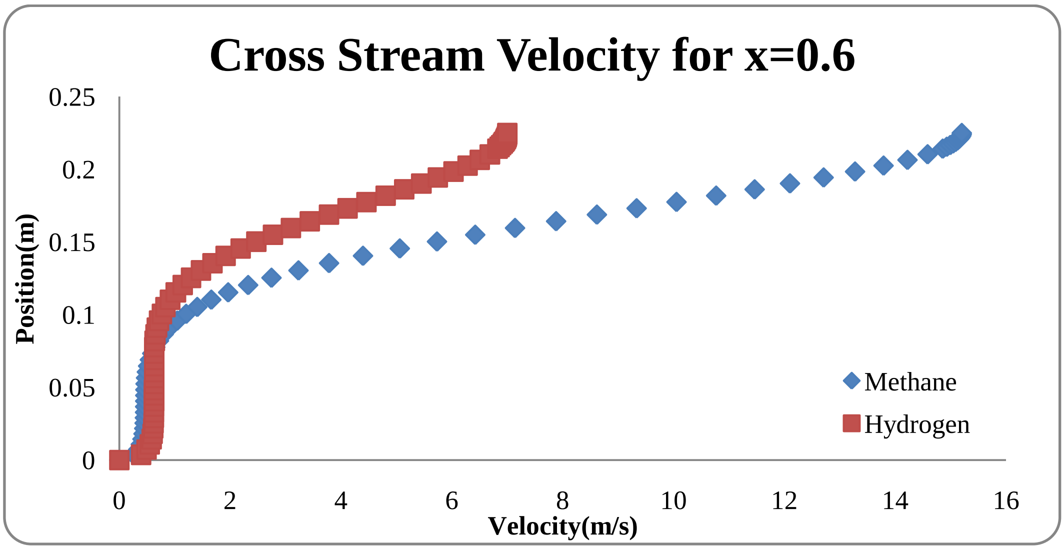

Fig. 5. Velocity distribution along combustor at the cross-section x=0.6

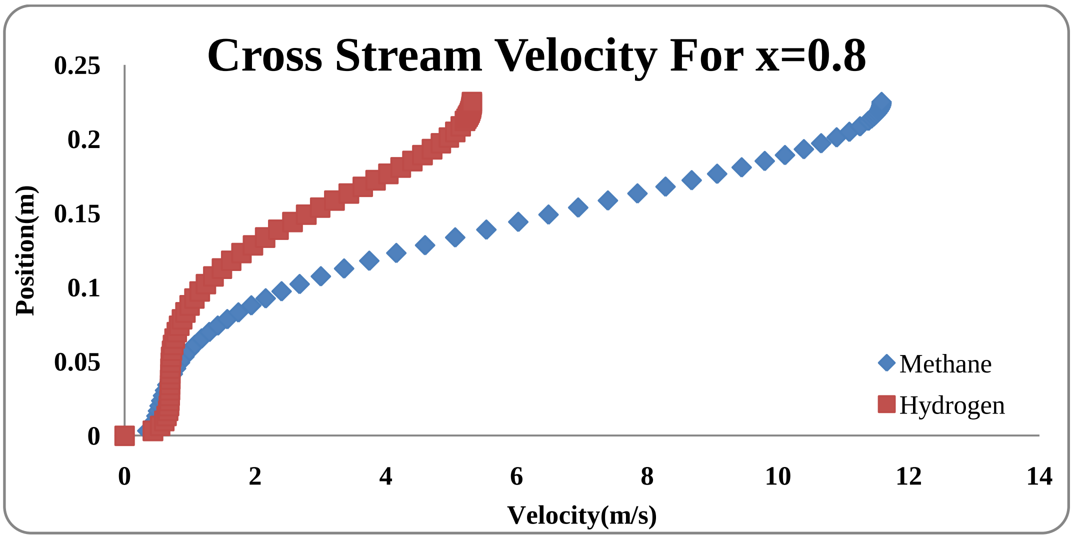

Fig. 6. Velocity distribution along combustor at the cross-section x=0.8

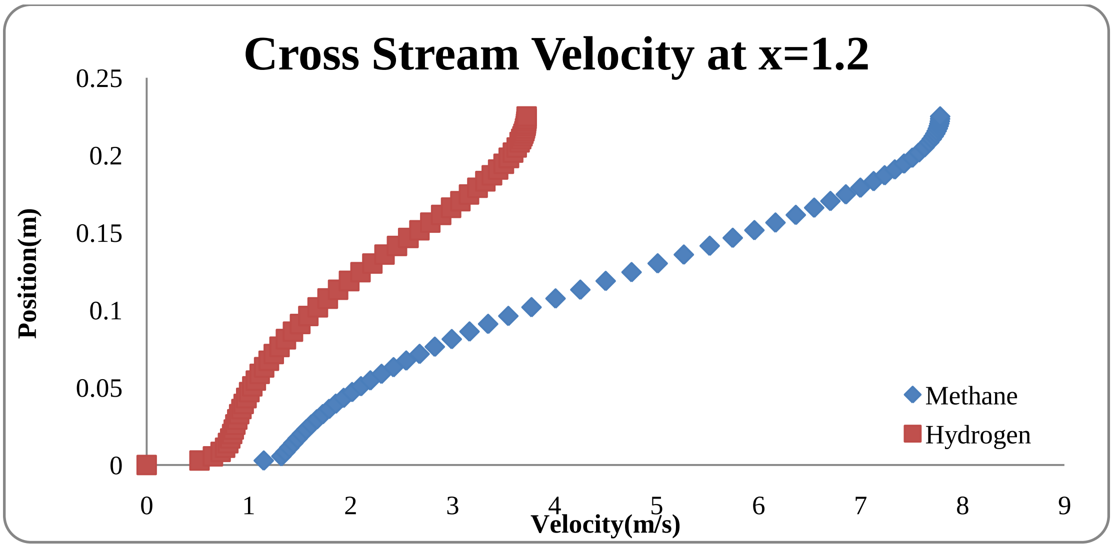

Fig. 7. Velocity distribution along combustor at the cross-section x=1.2

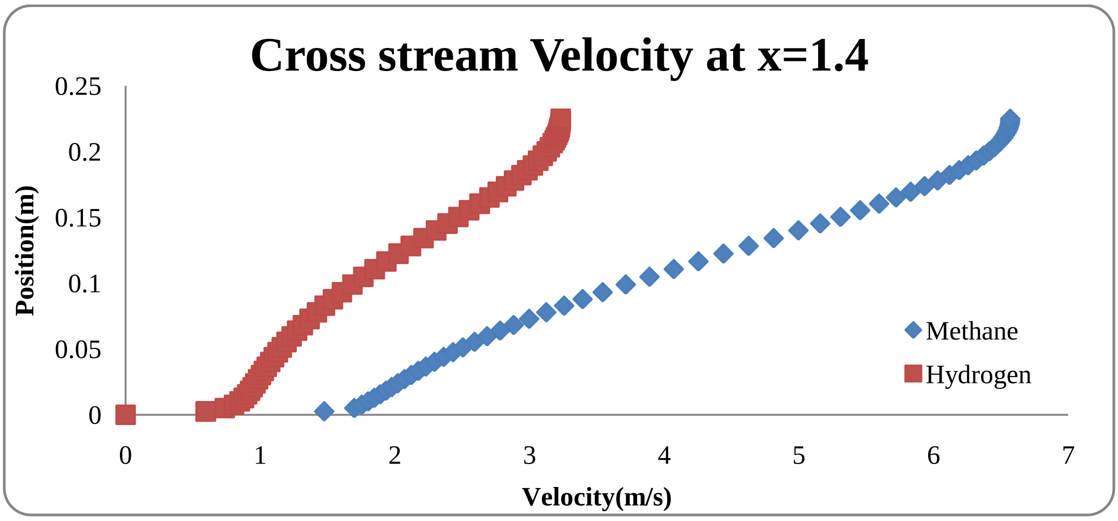

Fig. 8. Velocity distribution along combustor at the cross-section x=1.4

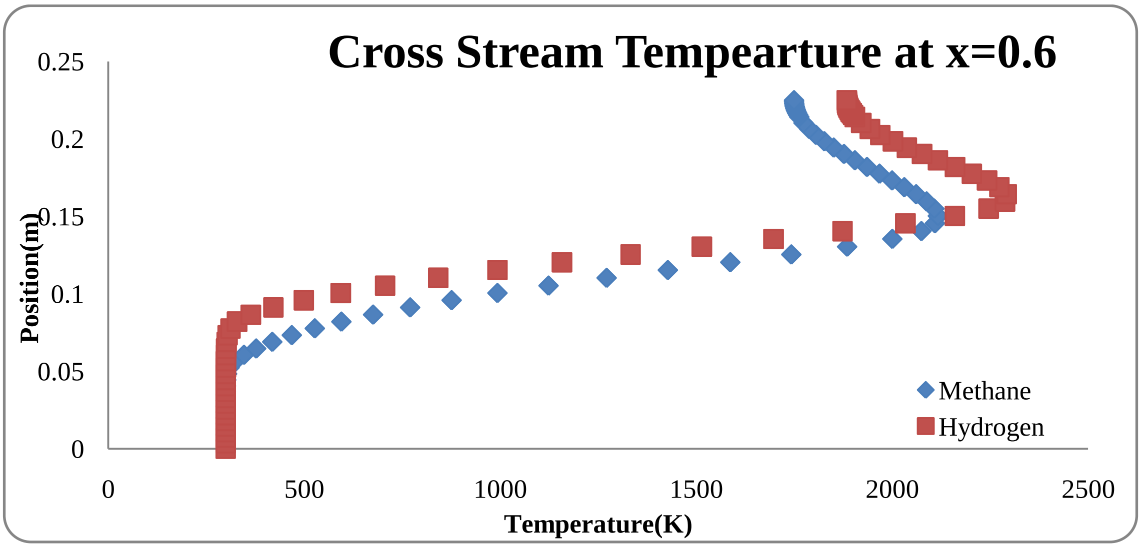

Fig. 9. Temperature distribution along the length of combustor at the cross-section x=0.6

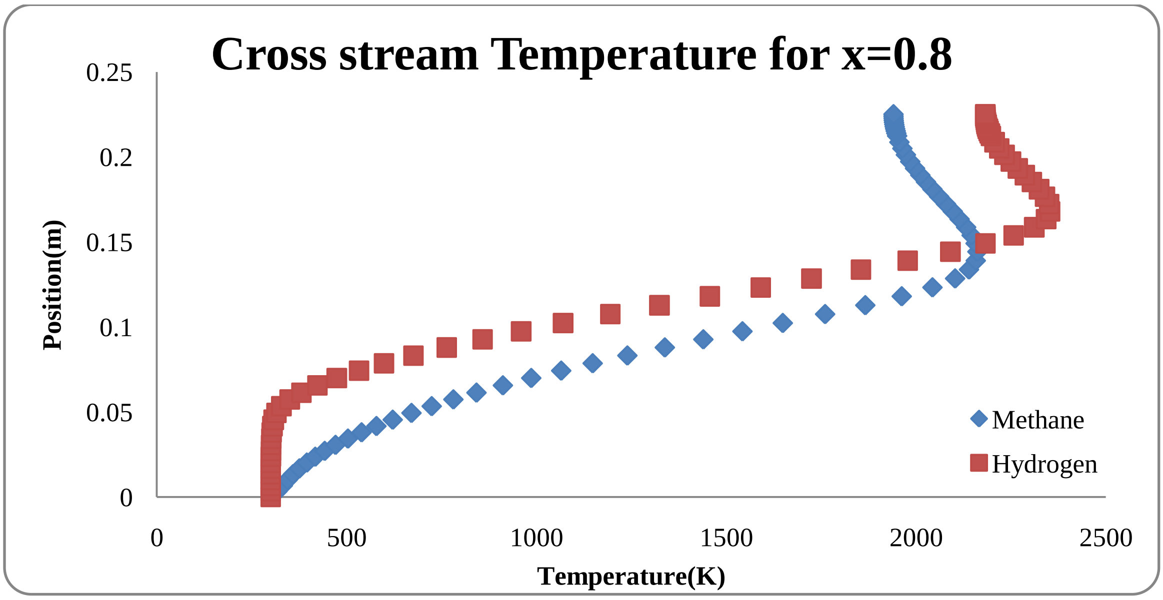

Fig. 10. Temperature distribution along the length of combustor at the cross-section x=0.8

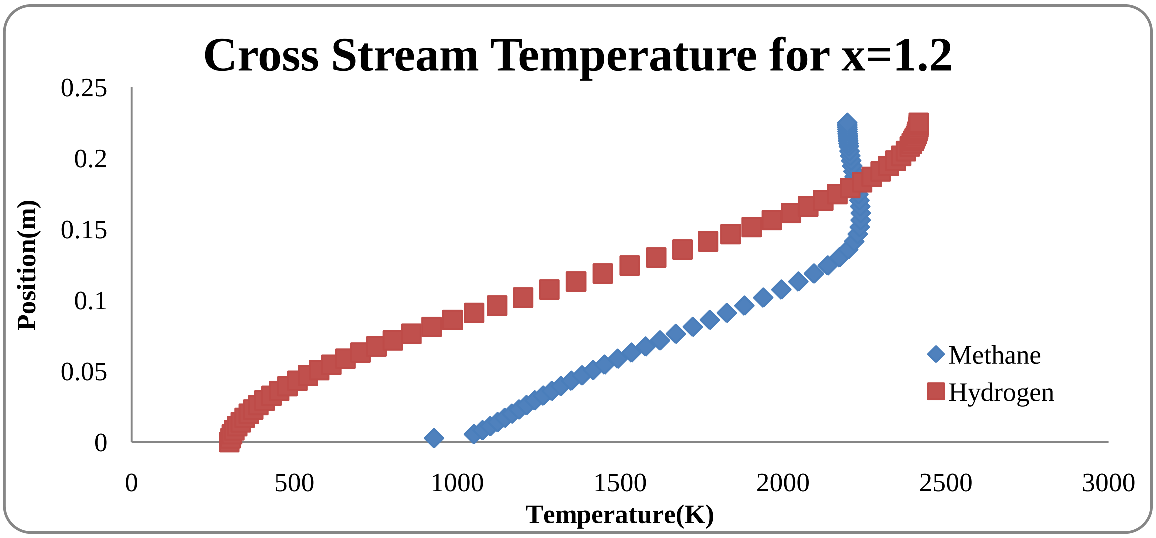

Fig. 11. Temperature distribution along the length of combustor at the cross-section x=1.2

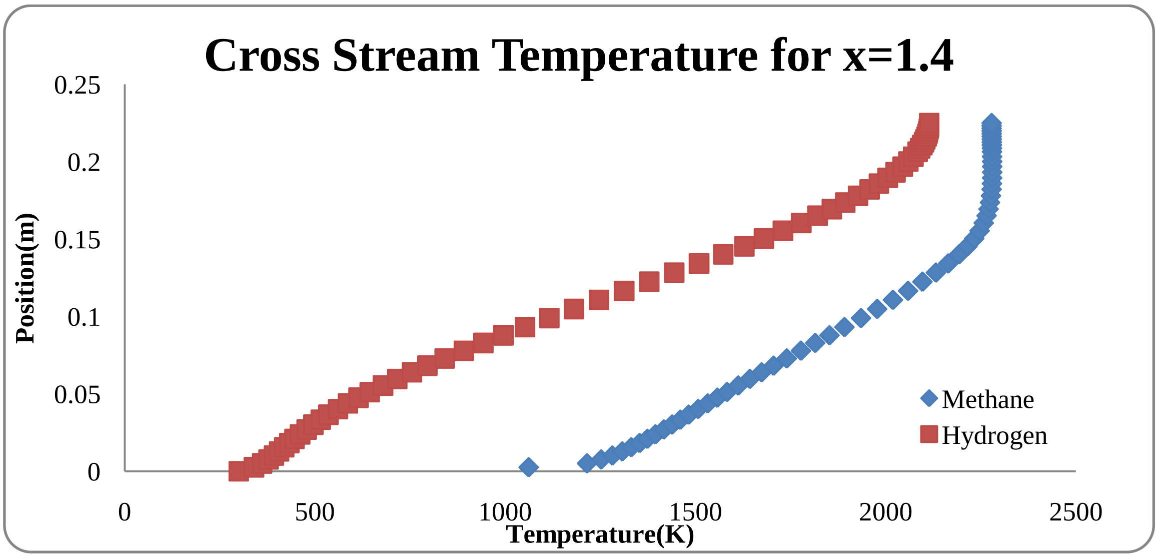

Fig. 12. Temperature distribution along the length of combustor at the cross-section x=1.4

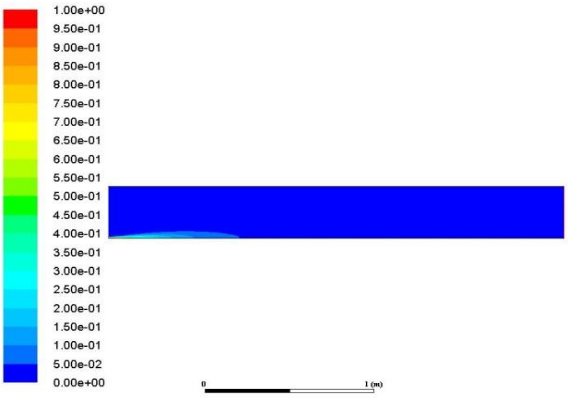

Fig. 13. H_2 mass fraction for hydrogen-air

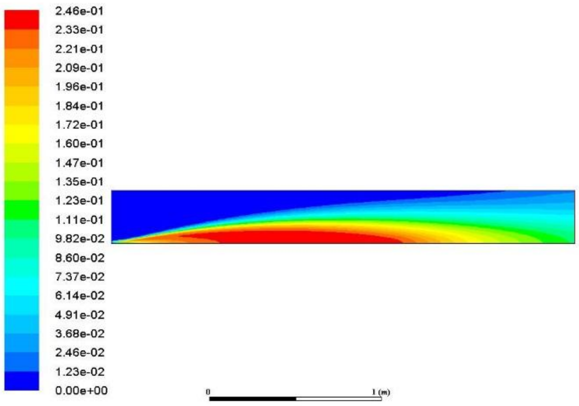

Fig. 14. H_2Omass fraction for hydrogen-air

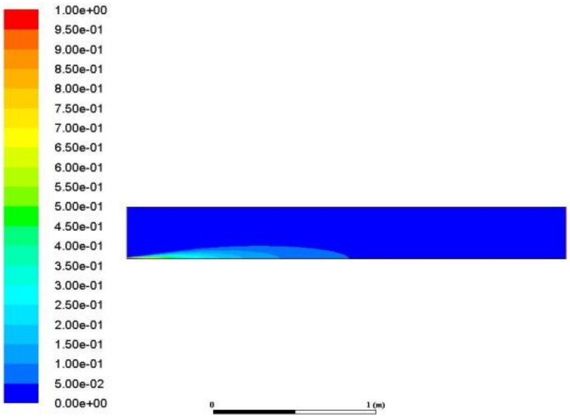

Fig. 15. CH_4 mass fraction for methane-air

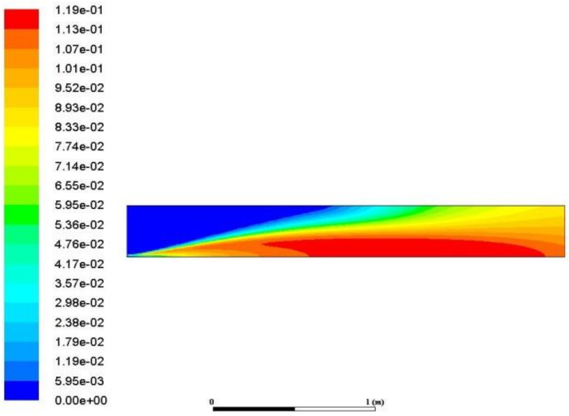

Fig. 16. H_2O mass fraction for methane-air

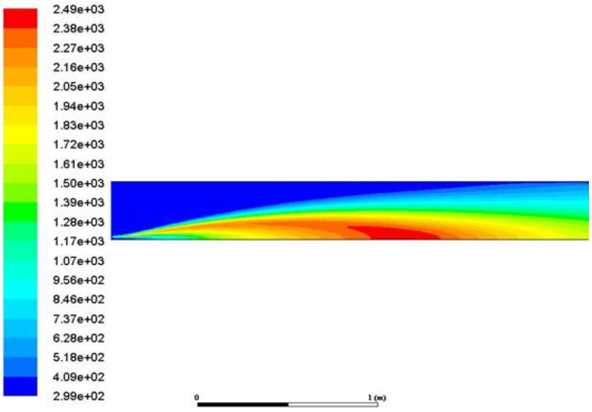

Fig. 17. Temperature contours for Hydrogen-Air Fuel

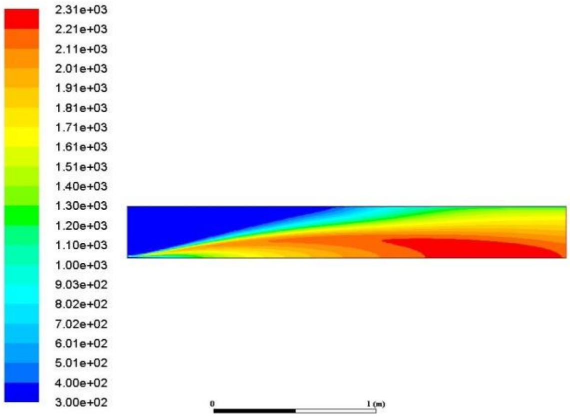

Fig. 18. Temperature contours Methane-Air Fuel

IV. CONCLUSION

For the numerical analysis, we have use RANS governing equations (2D), k-ε turbulent model and Finite Rate eddy-dissipation model to investigate the internal flow characteristics for the different fuel schemes for the combustor. From the results, we concluded the following: (1) fuel injection is taking place from split part to combustor. (2) When we observe pressure at the mid-plane of the combustor, by comparison, it is concluded that Change in pressure for hydrogen-air almost negligible. However, for methane-air for the particular length of combustor pressure, change is abrupt and then it becomes almost constant and then a slight pressure drop takes place. (3) At the wall, surface pressure for methane-air is high as compare to hydrogen-air fuel. (4) The velocity of the combustible mixture changes abruptly along the length of the combustor for methane-air. But for hydrogen-air, changes are comparatively less. (5) Fig.9 – Fig.12 shows the temperature profile at various positions of cross-stream along the length of the combustor.

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