Numerical Analysis of Supersonic Scramjet Combustion Engine with Double Cavity Configuration at Mach 2 Fuel Injection

Nithin .N

Present - Associate Engineer, IBM India Pvt Ltd, India
Past – Department of Aeronautical Engineering, Jeppiaar Engineering College Chennai, India

Abstract: ***One of the unique growing researches in the field of aerospace is an air-breathing propulsion system SCRAMJET. Scramjet has a wide range of application at present from ballistic missile to launching vehicle and inter-orbitary space transportation in future. Scramjet (supersonic ramjet engine), which operation is simple consists of an inlet, combustion chamber, injectors and a nozzle were the combustion process is taking place in a supersonic flow region. Hence the time required for combustion is less than 0.0001s and it is a huge task which develops interest for most researches to improve efficiency of combustion with different methods. This paper is a further continuation of a double cavity region with a back ramp angle from the best performance model in the previous paper which is to be tested in a hypersonic combustion process. The design is carried out in Ansys Design Modeler with 2-dimensional hypersonic vehicle design. The ICEM fine meshing is done near the walls and inside the cavity region. Here the analysis are done in Ansys Fluent 14.5 were liquid hydrogen is used as a major fuel injected at mach 2 with the hypersonic air flow in a non-premixed combustion process and the analysis are carried out with two different viscous models to determine the better performance in terms of combustion. Finally the results are compared by taking the contours of static temperature, turbulence kinetic energy, total pressure, mass fraction of h2, mass fraction of o2, mass fraction of n2 and a comparative graph is plotted which is used to predict the best combustion efficiency between the two turbulence models.***

Keywords: Scramjet, Hypersonic combustion, Cavity, Ramp angle, Ansys, Air-breathing engine.

1. Introduction

Scramjet engine the most developing air-breathing propulsion system for future hypersonic vehicle. The main process behind the scramjet engine, it consists of an inlet which is used to increase the pressure and temperature for combustion process. In the combustion region the injectors are used to inject the fuel and the combustion process still place in a supersonic flow regime which is used to produce more thrust. Initially the ramjet engine can produce a thrust upto mach 5 but the scramjet engine which mainly developed for hypersonic flow combustion process used to produce mach of above 5 and NASA x-43 achieved a mach 9.8 and recorded as a fastest plane using scramjet hypersonic vehicle. The systematic hypersonic scramjet engine in 2-dimensional is shown in fig 1.

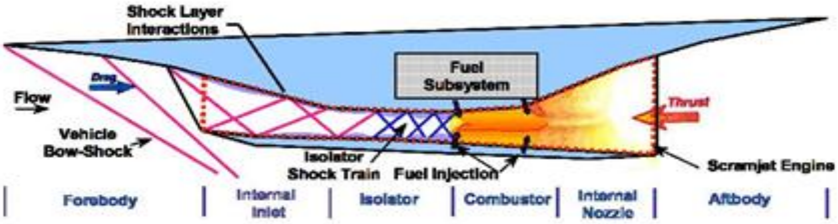

Figure 1: Hypersonic Scramjet Engine

The main drawback in the scramjet engine is the process of combustion taking place in a hypersonic flow condition. Hence the proper mixing of air-fuel should take place in a more quick time to produce thrust as required. Thus many researches used different methods to improve the combustion process the main task to improve combustion depends on the type of combustion chamber and the injection type used. In this we use normal injection techniques which provide a better flame holding capability due to the formation of detached shockwave at the downstream of the injection. As published in the previous paper the aerodynamic characteristic of a double cavity with back ramp angle of l/d ratio 10 proved to have a better performance than the other cavity models, hence it is used in this analysis with liquid hydrogen injected at the upstream of the cavity in a hypersonic flow condition. The fig 2 shows the cavity l/d 10 ratio with back ramp angle.

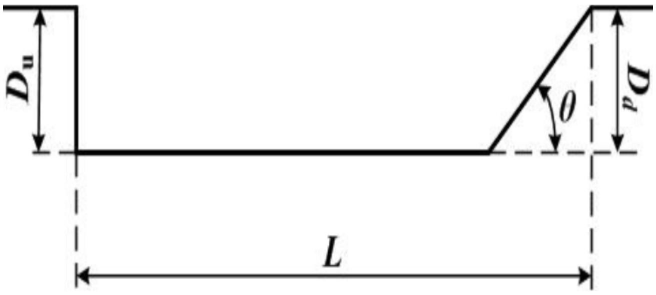

Figure 2: Cavity l/d 10 and back ramp angle 45°

2. Literature Review

A collection of detailed literature review is done on the basis of injection, cavity flame holder and hypersonic combustion process and they are discussed below. K.N.Jayachandran[1] and N.Nithin on Performance Analysis of Double Cavity Based Scramjet Combustion at Mach 2 using CFD undergone numerical analysis on different double cavity models with change in l/d ratio 5 and 10 and with and without back ramp angle using k-epsilon turbulence models with naviers-stroke energy equation in a two-dimensional density based energy equation and results shows that double cavity with l/d ratio 10 and back ramp angle showed better performance in-terms of mixing and flame-holding capabilities. K.M.Pandey[2] and T.Sivasakthivel paper on Recent Advances in Scramjet Fuel Injection has studied the details advantages of different injectors types and their disadvantages mainly like normal, parallel, transverse injectors, plasma injectors, ramp injectors, strut injectors, pylon injectors etc., and different cavity based design like a rectangular cavity, cavity pylon flame holder for better combustion process from this we infer to use a normal injection method because it provides a better flame holding capabilities at the downstream of the injection due to the separation of shockwave. Another paper by K.M.Pandey[3] and T.Sivasakthivel based on CFD Analysis of Mixing and Combustion of a Scramjet Combustor with a Planer Strut Injector has undergone numerical analysis of supersonic scramjet engine with struct type injectors were the undergone three dimensional naviers-stoke equation. They have used 3dimensional plane strut were hydrogen fuel is injected and the results shows the strong shock formation and reflection which used to increase the static pressure in the ignition process than in the cold flow process. Kyung Moo Kim[4] paper on Numerical study on supersonic combustion with cavity-based fuel injection has performed numerical analysis on a cavity with different back angle and compared each thing for better combustion efficiency and to reduce total pressure loss he concluded that with increase in back ramp angle will increase the combustion efficiency from that we have concluded to have a 45° ramp angle for better combustion efficiency and reduced total pressure losses.

3. Geometry

The hypersonic scramjet vehicle combustion chamber is designed from the prediction of x-51 NASA vehicle. The total length of the scramjet engine is of length 515 mm in which it comprises of an inlet, combustion chamber and the nozzle. The length of the inlet is 145 mm as to increase the pressure and temperature of the incoming air. The combustor is of length 275 mm which comprises of a double cavity with l/d ratio 10 with back ramp angle 45°. The fuel injector is placed of radius 2.5 mm at the upstream of the initially cavity. The geometry model is shown in fig 3.

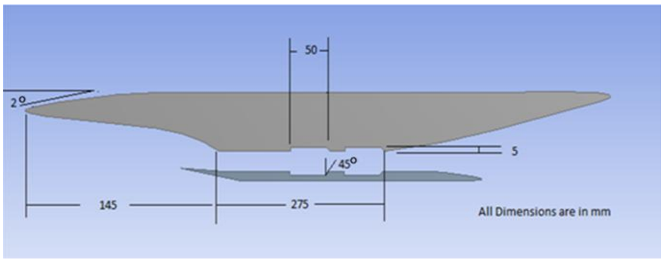

Figure 3: Geometry model

4. Meshing

The meshing plays an predominant role in determining the accuracy of the flow, the rectangular fine mesh is used because it is used to improve the accuracy in the combustion chamber cavity build region and a fine mesh of maximum nodes of 333286 nodes is presented in our model sizing is done in the cavity region using body of influence property to increase the nodes near the upstream and downstream of the combustion region. Fig 4 shows the meshing of our model

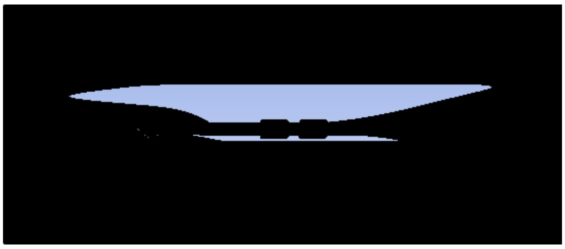

Figure 4: Meshing of our model

5. Analysis

The fine meshed model is undergone analysis in Ansys Fluent, the analysis is carried out using two-dimensional naviers stroke equation, here two models are taken to compare standard k-epsilon and k-omega sst models. The simple difference between them is k-epsilon is two-equation and k-omega is three-equation solving method. Here fuel such as liquid hydrogen is used for non-premixed combustion inlet diffusion process is applied were the required gas exchange are indicated and the reaction are listed in table 1.

Table 1: chemistry reaction of hydrogen with air

Reaction Process		
$H + O_2$	→	$O + OH$
$H + H$	→	$2H$
$2H + O$	→	$OH + H$
$2H + OH$	→	H_2O
$H_2O + O$	→	$OH + OH$
$H_2O + H$	→	$OH + H_2$

The boundary condition is applied were the incoming air flow at a mach 7 in which the injectors which is just placed at the upstream of the cavity region inject the fuel at a mach 2 condition as shown in table 2. The outlet is maintained at atmospheric condition and wall are maintained with no-slip condition were it will be stationary in condition. The steady state pressure based simple solver is used for analysis and the spatial discrimination is solved in second-order upwind for determination of accurate results. Then the analysis is carried out by more iteration until the equation of parameters like k-epsilon or k-omega sst parameters solved using continuity, momentum and energy equation by achieving a steady converged solution.

Table 2: Boundary condition

Parameters	*Air*	*Fuel*
Mach no	7	2
Pressure (Pa)	101325	1940.28
Temperature (k)	520.98	300
K (m^2/s^2)	10	2100
Y_{O2}	0.767	0.019
Y_{H2}	0	0.58
Y_{N2}	0.233	0.01
Yc	0	0.391

6. Results and Discussion

6.1 K-epsilon Model

Here are the results of contour of static temperature and turbulence kinetic energy as shown in fig 5&6 respectively. The value of static temperature is maximum of 2931k which is found near the cavity and the exhaust nozzle of the scramjet engine, this contour proves that a vital combustion process is occurring due to the air-fuel mixing in the region of cavity and hence the flame stabilization method can be achieved. The contour of turbulence kinetic energy shows a vortex region is formed inside our double cavity region and a maximum value of 9.92 j/kg is achieved in the cavity region were the proper mixing of air and fuel is applicable for proper combustion which can increase the combustion efficiency of the engine. The contour of total pressure is shown in fig 7, shows that the total pressure value is more at the upstream of the injection after that the total pressure obtain a minimum value of -2.9e7 Pa were the losses are minimum in the cavity region. The contour of mass fraction of H2 is shown in fig 8, the hydrogen combination if found more inside the cavity region due to the injection of liquid hydrogen through the injectors. Hence the incoming air flow will mix with the fuel present in the cavity region were a stable combustion process can be obtained for a long period of time and increase the performance of the scramjet engine. The fig 9 shows the mass fraction of O2 indicates the oxygen is found minimum in the region of cavity, this shows oxygen is consumed in the combustion process and a minimum of all oxygen molecule is consumed during this process. The contour of mass fraction of N2 is shown in fig 10 shows that a little nitrogen is also contribute to the combustion process were we can see a minimum value of nitrogen is obtained in the first cavity and after that it gradually increase.

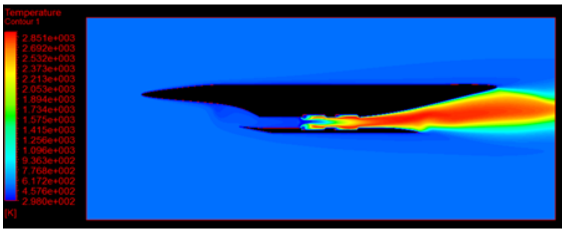

Figure 5: contour of static temperature

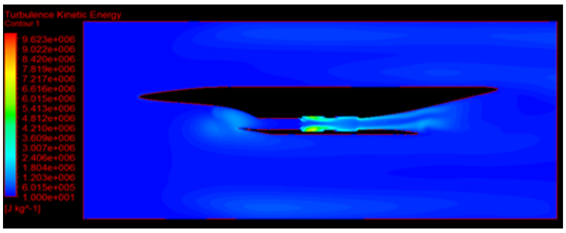

Figure 6: contour of turbulence kinetic energy

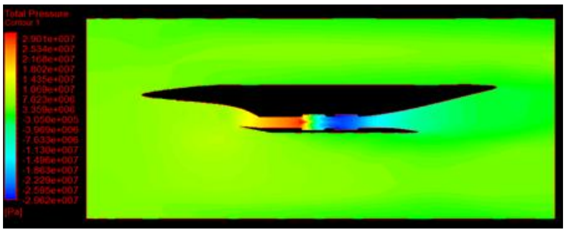

Figure 7: contour of total pressure

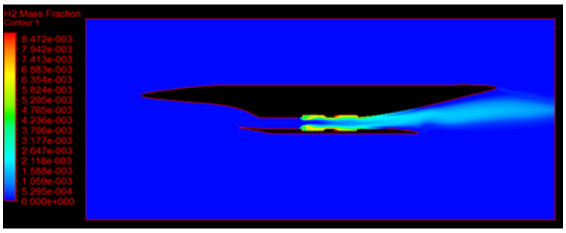

Figure 8: contour of mass fraction H_2

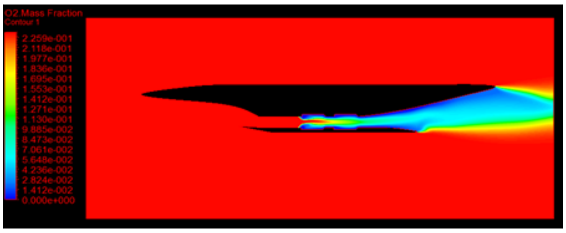

Figure 9: contour of mass fraction of O_2

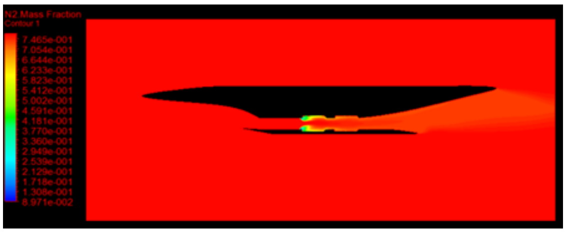

Figure 10: contour of mass fraction of N_2

6.2 K-omega Model

The contour of static temperature is shown in fig 11, here we can see that a combustion process is happening and a maximum value of 3347 k is obtained along the cavity region hence a strong flame stabilization can be obtained with the presence of the cavity region. The fig 12 shows the contour of turbulence kinetic energy, more turbulence region is found in the second cavity were a strong vortex is formed which enhance a proper air-fuel mixing. In fig 13 contour of total pressure, a low pressure region is formed in the combustion chamber due to the presence of the cavity and after the region the pressure value increases gradually a minimum value of -6.8e7 is found inside the cavity region. The fig 14 shws the contour of mass fraction of H2 were it is found maximum in the cavity region due to the injection of the liquid hydrogen and can obtain a stable combustion process for a long period of time. The fig 15 and fig 16 shows the contours of mass fraction of O2 and N2 respectively, here both the oxygen and nitrogen are consumed in the cavity region due to the process of combustion were oxygen plays a major role in the air-fuel burning process. On the other hand nitrogen is also consumed in smaller quantity a minimum value of 0.14 is found inside the cavity region.

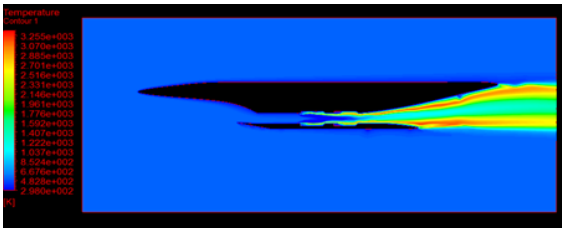

Figure 11: contour of static temperature

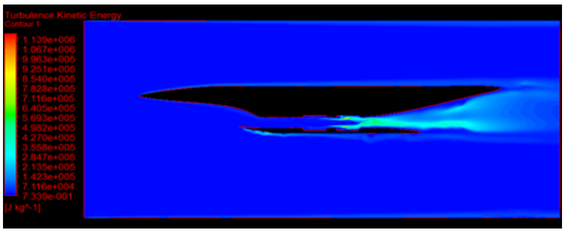

Figure 12: contour of turbulence kinetic energy

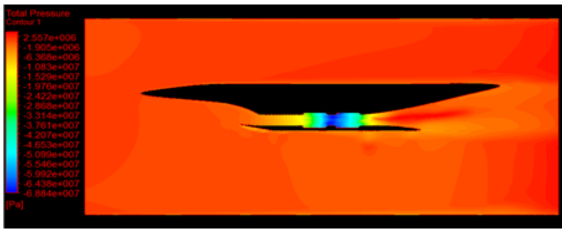

Figure 13: contour of total pressure

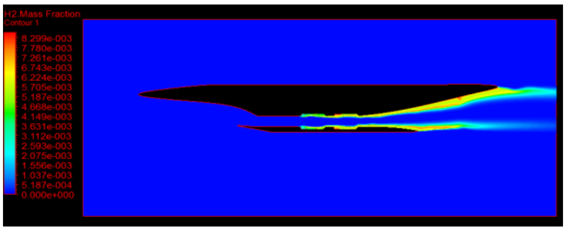

Figure 14: contour of mass fraction of H_2

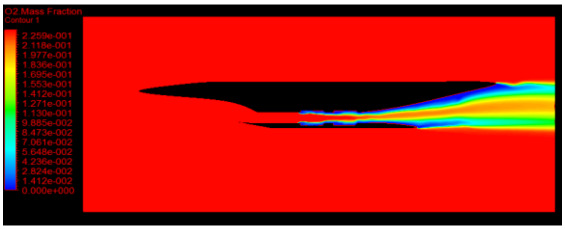

Figure 15: contour of mass fraction of O_2

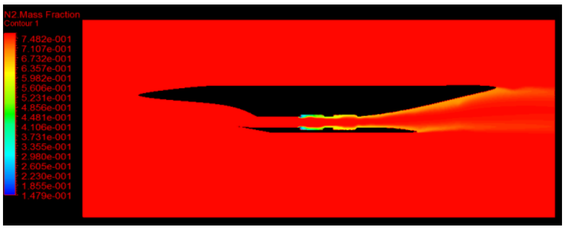

Figure 16: contour of mass fraction of N_2

7. Comparative Graph

Here the plots are compared between two models k-epsilon and k-omega sst to determine the best performing turbulence models. Fig 17 shows the plots of static temperature were a high temperature value is obtained in k-epsilon model were we can find the better flame stabilization process. The plots of turbulence kinetic energy as shown in fig 18 more turbulence value is achieved in k-epsilon turbulence model and hence more vortex region is formed. Total pressure plots are shown in fig19, its states that the total pressure losses are achieved minimum while using a k-omega sst turbulence model. finally the plots of heat gain loss shows that the wide range of heat loss is found more in k-omega sst models. Fig 21 shows the plots of mass fraction of H2 which shows the hydrogen is present more inside the cavity for longer combustion stability in k-epsilon model. As usual oxygen and nitrogen is consumed more in the cavity region for k-epsilon turbulence model as shown in fig 22 and fig 23 respectively.

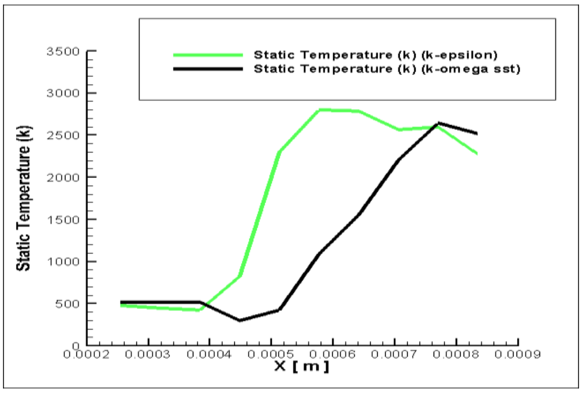

Figure 17: plots of static pressure

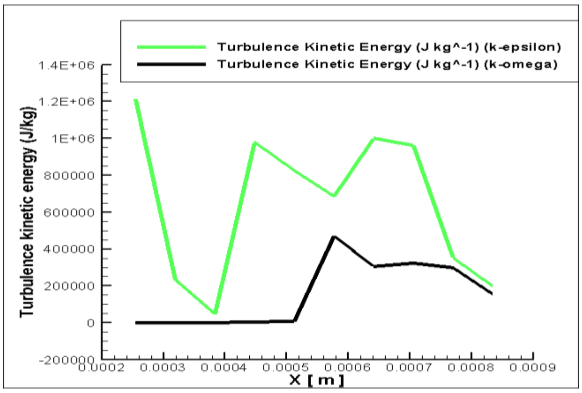

Figure 18: plots of static temperature

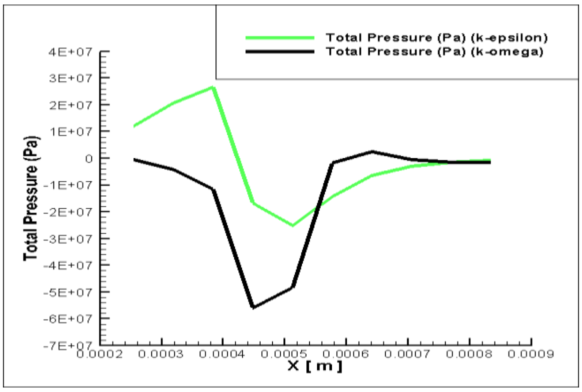

Figure 19: plots of total pressure

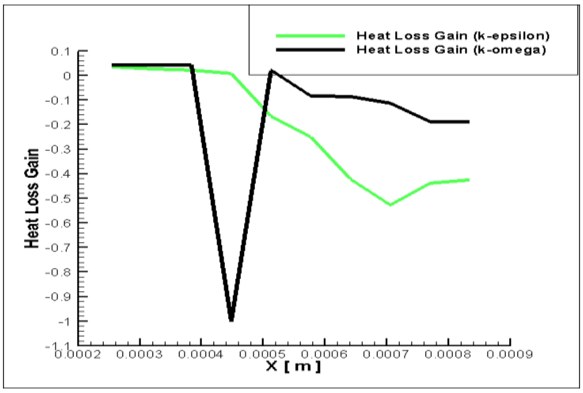

Figure 20: plots of heat loss gain

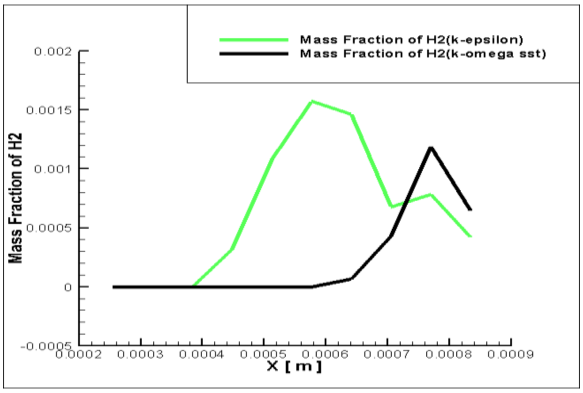

Figure 21: plots of mass fraction of H2

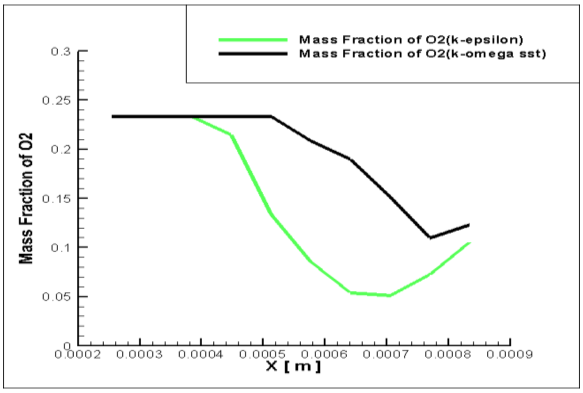

Figure 22: plots of mass fraction of O2

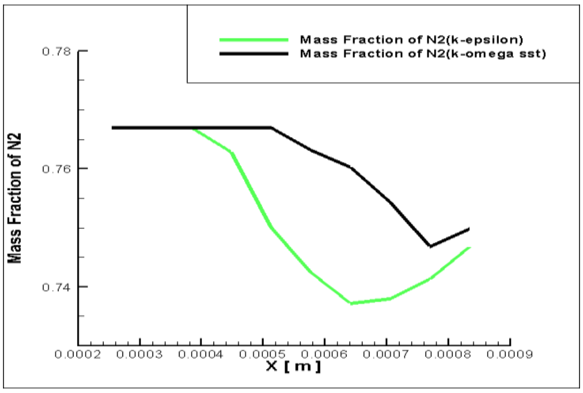

Figure 23: plots of mass fraction of N2

8. Conclusion

In order to determine the most efficient turbulence models in terms of combustion and mixing process, the two turbulence models undergone numerical analysis using steady state pressure based energy equation with similar boundary condition and finally infer that;

- k-epsilon turbulence models is more efficient in-terms of mixing and flame stabilization process, hence a more vortex region is found inside the cavity region more suitable for a supersonic combustion process in relatively a small amount of time and the static temperature value is more to provide more flame stabilization process for a comparatively prolonged time.
- From the comparative graph total pressure value is minimum for k-omega sst model hence the k-omega sst turbulence model produce a minimum losses.

On the whole depending on the combustion efficiency mixing process and heat loss gain task k-epsilon turbulence model is more suited for a hypersonic scramjet combustion

9. Acknowledgement

The author is very thankful to our Director, Principal and Mr.G.Prabhakaran, Professor and Head, Department of Aeronautical Engineering, Jeppiaar Engineering College, Chennai for their initiative and continuous support for this project. Also I extend our hearty thanks to Mr.Thanigaivel Murugan and my colleague P.Chitra Palaniswamy student of Nanyang Technology University, Singapore for their valuable suggestions towards the project. The author also thanks their friends and parents for their valuable encouraging words and support.

References

[1] K.N.Jayachandran, N.Nithin, S.Dhinesh, A.Mohamed Irfan and D.Thanikaivel Murugan," Performance Analysis of Double Cavity Based Scramjet Combustion at Mach 2 using CFD", International Journal of Emerging Technology and Advanced Engineering, ISSN 2250-2459, ISO 9001:2008 Certified Journal, Volume 4, Special Issue 3, February 2014.

[2] K.M.Pandey and T.Sivasakthivel," Recent Advances in Scramjet Fuel Injection", International Journal of Chemical Engineering and Applications, Vol. 1, ISSN: 2010-0221 No. 4, December 2010.

[3] K.M.Pandey and T.Sivasakthivel," CFD Analysis of Mixing and Combustion of a Scramjet Combustor with a Planer Strut Injector", International Journal of Enviromental Science and Development, Vol. 2, No. 2, April 2011.

[4] Kyung Moo Kim, Seung Wook Baek and Cho Young Han," Numerical study on supersonic combustion with cavity-based fuel injection", International Journal of Heat and Mass Transfer 47 (2004) 271–286, Received 1 November 2002; received in revised form 7 July 2003.

[5] Jeong-Yeol Choia,, Fuhua Mab and Vigor Yang," Combustion oscillations in a scramjet engine combustor with transverse fuel injection", J.-Y. Choi et al. /

Proceedings of the Combustion Institute 30 (2005) 2851–2858.

[6] Wei Huang, Shi-bin Luo, Mohamed Pourkashanian, Lin Ma, Derek B.Ingham, Jun Liu and Zhen-guo Wang," Numerical Simulations of a Typical Hydrogen Fueled Scramjet Combustor with a Cavity Flameholder", Proceedings of the World Congress on Engineering 2010 Vol II, ISBN: 978-988-18210-7-2 WCE 2010, June 30 - July 2, 2010, London, U.K.

[7] Fengquan Zhong, Lihong Chen, Fei Li, Xinyu Zhang and Chih-Jen Sung," Numerical Simulation of Ignition and Combustion of Ethylene in a Supersonic Model Combustor with a Reduced Kinetic Mechanism", Combust. Sci. Technol., 185: 548–563, Copyright # Taylor & Francis Group, LLC ISSN: 0010-2202, 2013.

[8] A.P. Singh, K.M.Pandey, Arun Burman, Mohit Sharma and Navneet Tyagi," Numerical Analysis of Hypersonic Combustion without Cavity Based Injection with Finite Rate Chemistry Model", International Journal of Advanced Trends in Computer Science and Engineering, Vol.2 ISSN 2278-3091 , No.1, Pages : 60-66 (2013) Special Issue of ICACSE 2013 - Held on 7-8 January, 2013.

[9] Tian Wan, Lihong Chen, Jing Wang, Xuejun Fan and Xinyu Chang," Computational Study of Supersonic Combustion Using Three Kerosene Reaction Mechanism Models", Proceedings of the 13th Asian Congress of Fluid Mechanics 17-21 December 2010.

[10] ZHANG Ruo-ling, JIANG Jin and LE Jia-ling," The simulation of endothermic fuel flow in cooling channels of Scramjet", International Conference on Methods of Aero physical Research, ICMAR 2008.

[11] Shiva Prasad U and Suresh Kumar R," Computational Analysis of Hypersonic Vehicle Intake Configuration", The International Conference of Engineering Sciences and Management (TICESM)-October 5-6, 2013.

Author Profile

Nithin N was born in Chennai in 1993. He graduated as a Bachelor of Engineering degree in Aeronautical Engineering from Jeppiaar Engineering College in 2014. He now with IBM India Pvt Ltd as an Associate Operation, India