TEST Engineering & Management

January - February 2020
ISSN: 0193 - 4120 Page No. 7800 - 7806

Numerical Investigation of Variation of Combustion Efficiency of Scramjet Combustor with Change in Length of Wedge Shaped Strut Blunt End

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Article Info
Volume 82
Page Number: 7800 - 7806
Publication Issue:
January-February 2020

Article History
***Article Received**: 18 May 2019*
***Revised**: 14 July 2019*
***Accepted**: 22 December 2019*
***Publication**: 04 February 2020*

Abstract:

The numerical study has been carried out to investigate the combustion efficiency by changing the length of the strut blunt end. Four different length have been selected for the comparison. All the numerical simulation has been performed through Ansys 14.0 Fluent based solver. Hydrogen fueled supersonic combustor is selected to perform the analysis. Reynolds Averaged Navier-Stokes (RANS) equation withinite-rate/eddy-dissipation turbulence modeling are selected to complete the chemical reaction. The same modeling was chosen to complete the validation with the open excess experimental paper. Similar results was identified through the pressure plot and density contours. Grid independence test was also performed through three different size of mesh elements. The maximum combustion efficiency is found in the 3 mm extended length case. However except the 3 mm length case, similar trend can be seen in all rest of the cases.

Keywords: *Supersonic combustion, High Mach number, Blunt end length, Combustion Efficiency.*

I. INTRODUCTION

Scramjet is a type of air breathing engine. As the name suggest that the air as oxidizer enters in to the combustor to mix and react with the fuel at supersonic condition to complete the combustion process. The thermodynamic process is based on Brayton Cycle. Authors are also gaining more attention towards the high speed flow engine. Various reviews [1], [2] and analysis [3] has been performed to get the optimum performance. Experimental observation with extended version of numerical investigation have been performed to understand the combustor performance by Tanner B.Nielsen et al [4]. The sensitivity in the performance was identified by increasing the combustor wall temperature. Chenlin Zhang et al. [5] found that the equivalence ratio and the incoming Mach number have a noteworthy influence on the pressure rise. To understand the flame stabilization modes of parallel fuel injection through strut inside the combustor has been analyzed by changing temperature and overall equivalence ratio. Thus numerical investigation has been done to accomplish the behavior two types of flame stabilization by author Kun Wu et al. [6]. Junsu Shin et al. [7] analyzed the combustion performance with the help of hybrid RANS/LES numerical method by using hydrogen as a main fuel with using additional cracked kerosene. Flame stabilization of DLR scramjet combustor was numerically studied with the help of large eddy simulation code. Three stages of flame stabilization has been identified by Kun Wu et al. [8]. Flame stabilization mechanism of kerosene based parallel fuel injection with the help of strut has been identified and analyzed by Junlong Zhang et al. [9]. The strut was performed as a flame holder. During the experimental investigation, partial premixed flame characteristics was seen. Fei Qin et al. [10] also studied the flame stabilization mechanism by changing the operating condition of incoming air. Comparison between cavity based scramjet combustor and strut based scramjet combustor were also done to get the simplest location of flame stabilization, which was seen in strut based combustor. Parametric variation of strut design has been numerically analyzed by Gautam Choubey and K.M. Pandey [11]. Combustion and mixing efficiency were got improved by two strut based design in the place of single strut. The behavior of partial premixed combustion at supersonic level inside the combustor was explained by Jinshui Wu et al. [12] with the help of hybrid RANS/LES based numerical model. Reaction zone at low temperature was reproduced after the wedge shaped strut identified through G/Z flamelet model. Gautam Choubey and K.M. Pandey [13] investigated the overall performance of combustor by using multiple strut. To minimize the thermal chocking and the effect of this over performance of the combustor have also been pointed out. Due to addition of multiple strut, more number of shock wave was generated, this was found more helpful for mixing efficiency. To get the improved combustion performance with the help of better fuel injection. The numerical observation has been performed to get the optimum geometry for fuel injection system by P. Nithish Reddy and K. Venkatasubbaiah [14]. Performance of the combustor was dominated by the inlet condition in addition with the divergence angle. Malsur Dharavath et al. [15] explore the thermochemical behavior of hydrogen fueled supersonic combustor. The observation was performed with the help of commercial CFD software and found good agreement with the experimental data. The above literature review signifies that the boundary parameters can influence the performance nonetheless location and design of the strut can also affect the performance of the engine. It is also evident from the literature that the commercial CFD software are appropriate for capturing the behavior of the turbulent mixing and chemical reaction. By choosing this idea, present work will be carried out.

In this article the wedge shaped strut has been chosen for fuel injection. The slight modification is done by changing the length of the blunt end of the wedge shaped strut i.e. 0, 3, 6, 9 mm. The reference point of this length is set at the initial point of the blunt end. The detailed behavior of the combustion performance is explained with the help of contours and graph.

II. EXPERIMENTAL DETAIL OF DLR-SCRAMJET COMBUSTOR

The experimental test rig has been chosen by open excess research article of Waidmann et al. [16]. Author performed all the observation in German Aerospace Center. The test section was divided in to three major part i.e. isolator, combustor and exhaust nozzle. Laval nozzle was used to preheat the air before entering into the combustor. Cross section of the combustor is 40×50 mm2. 32 mm length of wedge shaped strut with 6 mm of blunt end face was selected for fuel injection. Same boundary condition was taken to complete the validation.

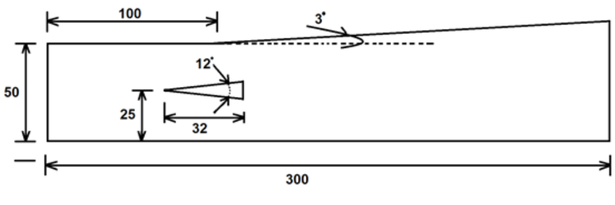

Figure 1 Schematic of Combustor (in mm)

In the present article the combustor geometry has been taken same as experiment with same fuel injector. Only slight modification has been performed to understand the effect of length of the blunt end. Figure 1 shows the schematic of the combustor. And Figure 2 shows the four types of strut with extended blunt end.

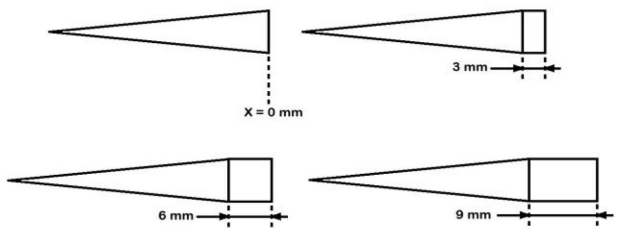

Figure 2 Schematic of Strut

III. GEOMETRY AND GRID GENERATION

Two dimensional model has been chosen to complete the all the observation. Ansys 14.0 is used to design a geometry and modeling part. Three different cases i.e. coarse, medium and fine model have been analyzed to get the suitable element size with better capture feasibility. Fine elements Case A give better capture results compared with others elements. The schematic of the different elements model comparison is shown in Figure

3.

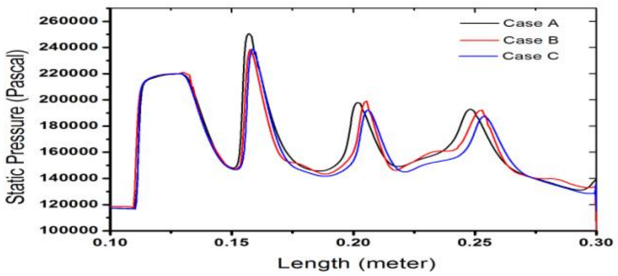

Figure 3 Grid Convergence Results

IV. SIMULATION DETAILS

Numerical simulation has been performed with the help of Ansys 14.0 based solver due to its availability and less computational cost.

A. Numerical Modeling

Supersonic combustion is still a very challenging task for the researchers. By analyzing different equation, Two equation of k-ε RANS (Reynolds-averaged Navier-Stokes equation) gives better results for turbulence model. To complete the chemical reaction, species transport based finite-rate/eddy-dissipation model has been elected. The ANSYS 14.0 Fluent solver [17] has been chosen to complete the numerical simulation.

B. Combustion Modeling

Single step chemical reaction has been opted to complete the combustion between Hydrogen as a fuel and air. Volumetric Reaction mode is selected for complete combustion modeling. As from the literature, it is evident that the single step chemical reaction also gives the correct result as in multistep moreover the steady state condition is also added to reduce the computational time.

V. BOUNDARY CONDITION

In the present computational model, different bounties has been specified to extract the results i.e. inlet, outlet, fuel inlet, upper and lower wall. The no slip condition is taken at the walls. All the solution has been extrapolated with respect to the inlet condition. The detailed boundary conditions is shown in Table 1. Detailed Mass fraction values of incoming air and fuel have been given in Table 2. For the consistent simulation, CFL (Courante Friedrichse Lewy) number is taken as 0.5.

Table 1 Boundary Conditions

Variables	Incoming Air	Fuel (Hydrogen)
Mach Number	2.0	1
Static Pressure	115299	115299
Static Temperature	833	310
Density	0.4716089	0.0901807
Velocity	1146.36	1339.69
Viscosity	1.72e-05	1.72e-05

Table 2 Species Concentration

Mass Fractions	O_2	H_2O	N_2	H_2
Air	0.232	0.032	0.736	0
Fuel	0	0	0	1

VI. ASSUMPTIONS FOR THE PRESENT WORK

All the computational simulation has been done through some pre assumptions, these are explained below:

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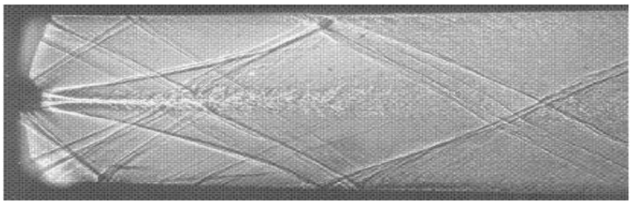
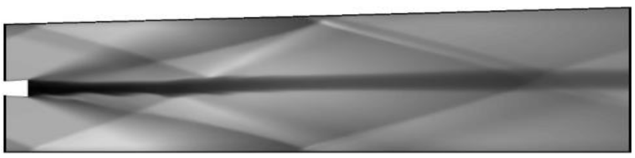
- Two dimensional model.
- Single step chemical reaction.
- Steady Sate condition.
- Dirichlet boundary conditions for incoming condition.
- Neumann boundary conditions are applied for outflow.

VII. VALIDATION OF THE MODEL

To check the feasibility and understanding of supersonic combustor with the help of numerical investigation is performed through Ansys 14.0 Fluent solver. The experimental combustor geometry [16] has been chosen to compare the obtained results from the software to the experimental results at the same boundary conditions. The density contour plot gives the similar shock wave trends as seen in the experimental Schlieren image. This can be easily identified in Figure 4 (a) and (b). Nonetheless the wall pressure graph also gives significant similarity. The graph shows the calculated wall pressure through software with experimental data in Figure 5.



(a)



(b)

Figure 4 (a) Schlieren image, (b) Contour of density

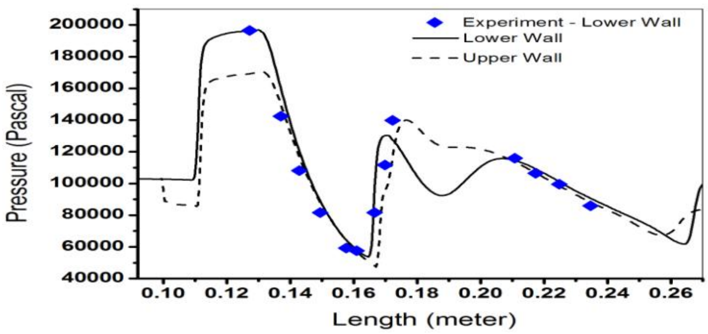


Figure 5 Wall Pressure (Experimental and Numerical)

VIII. RESULTS AND DISCUSSION

In this article the wedge shaped strut has been chosen for fuel injection. The slight modification is done by changing the length of the blunt end of the wedge shaped strut i.e. 0, 3, 6, 9 mm. The reference point of this length is set at the initial point of the blunt end shown in Figure 2. The detailed behavior of the combustion performance is explained with the help of contours and graph.

A. Wall Pressure (Lower and Upper)

Shock wave incidence at the wall creates a high values of pressure. This can be identified by visualizing Figure 6, Figure 7 and Figure 11. In 3 mm extended length case, wall pressure is much higher at lower and upper wall. The maximum value reaches up to 4.5 bar.

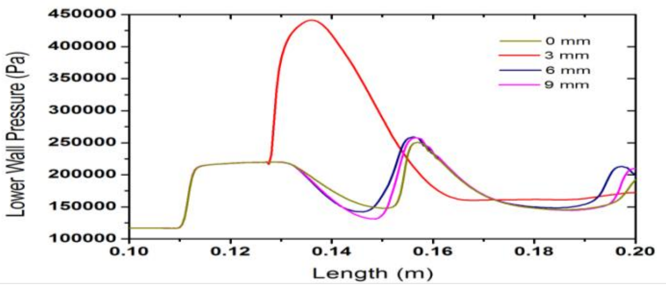


Figure 6 Lower Wall PressureThe sudden change after 140 mm length of the combustor can be realized from the wall pressure graph. This sudden effect can be also seen in combustion performance. Wall pressure at the lower and upper wall of all four cases are plotted for the comparison shown in Figure 6 and Figure 7.

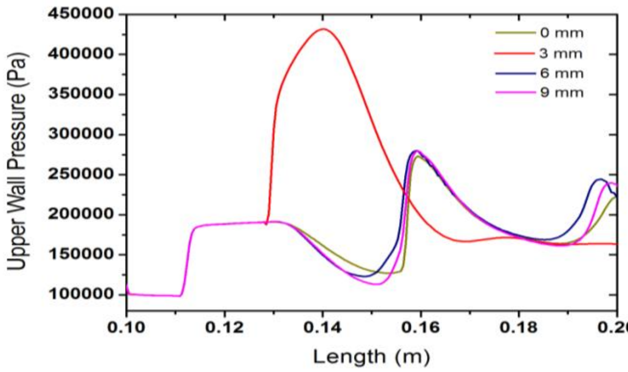


Figure 7 Upper Wall Pressure

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B. Mach Number (Contour and graph)

Mach number at the lower wall has been analyzed to get the comprehensive understanding of supersonic flow characteristics. Figure 8 and Figure 9 show that in all cases Mach number is approaching to 1 (sonic speed) before interacting with fuels. The sudden drop can be seen after 100 mm combustor length in all four cases but the maximum drop can be observed in 3 mm extended length case. Near to this zone mixing of fuel with incoming air is quite easy, this phenomena can be realized through Figure 11.

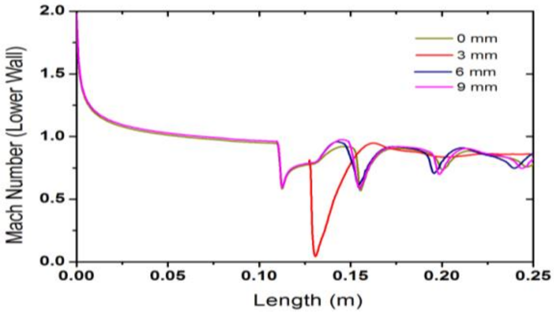

Figure 8 Mach Number at Lower Wall

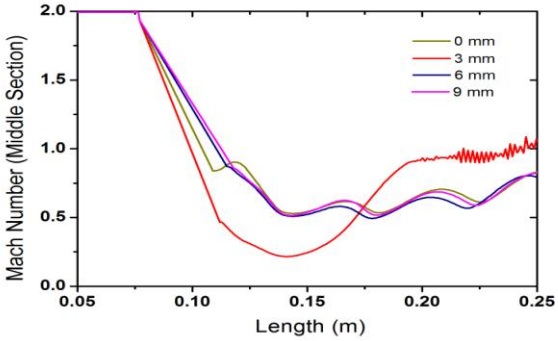

Figure 9 Mach Number at Middle Section

C. Combustion Efficiency

The different size of the strut blunt end signifies the similar trend while considering combustion efficiency except the 3 mm extended length of the strut.

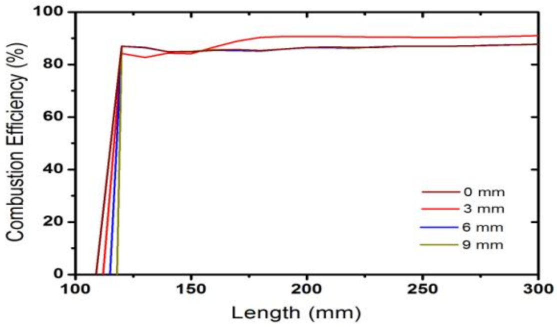

Figure 10 Combustion Efficiency

As the performance of the combustion efficiency near to the length of 125 mm combustor has follow the same trend in all four cases. However as the length going ahead of the 125 mm length, the enhanced performance can be observed in Figure 10. The maximum combustion efficiency is observed 91% in 3 mm extended length of the blunt end of the strut.

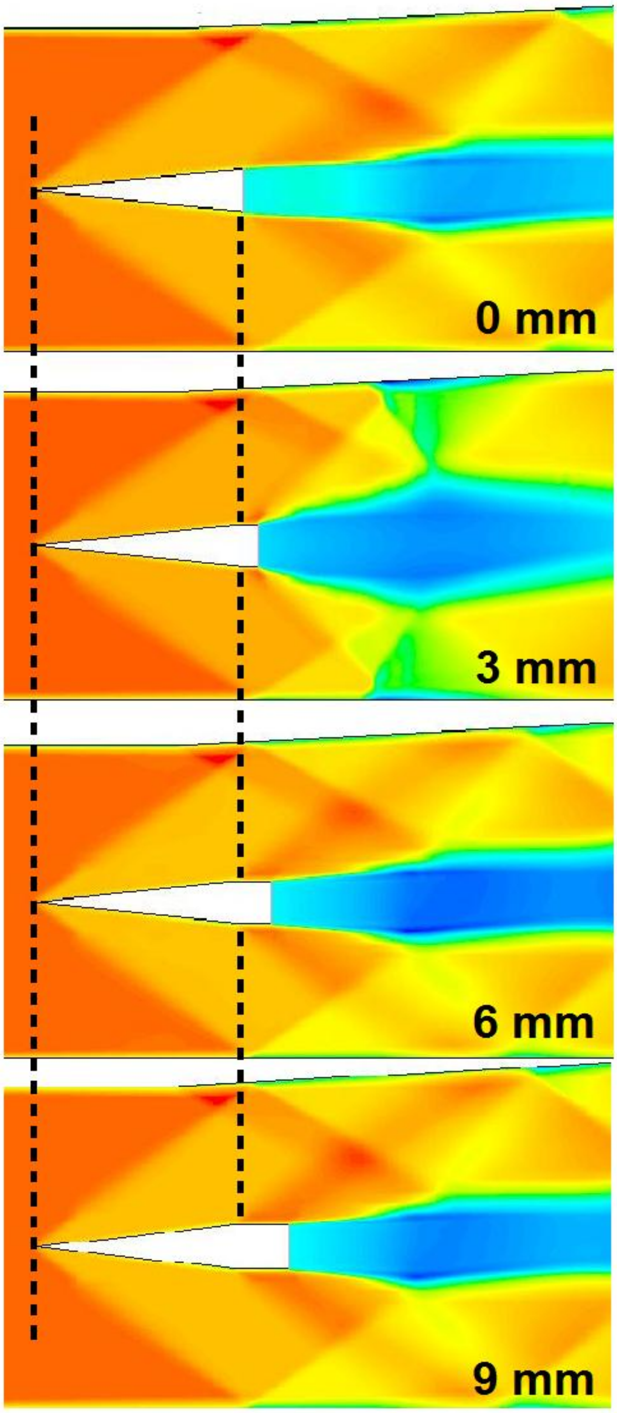

Figure 11 Mach Number Contour plots in all cases

IX. CONCLUSION

The numerical study has been carried out to investigate the combustion efficiency by changing the length of the strut blunt end. Four different length have been selected for the comparison i.e. 0, 3, 6, 9 mm. All the numerical simulation has been performed through Ansys 14.0 Fluent based solver. Hydrogen fueled supersonic combustor is selected to perform the analysis. Reynolds Averaged Navier-Stokes (RANS) equation with finite-rate/eddy-dissipation turbulence modeling are selected to complete the chemical reaction.

From the detailed analysis of all four cases have been summarized below:

- Extended length of the strut blunt end gives additional shock waves effect due to extra corner of the strut. Which creates the favorable domain near the fuel injector to complete the chemical reaction.
- The maximum combustion efficiency is found in the 3 mm extended length case. However except the 3 mm length case, similar trend can be seen in all rest of the cases.
- Based on the all above observation, the optimum extended length of the blunt end is 3 mm, which is considered as applicable length in accordance to the combustor performance.
- Mixing efficiency is also a major problem, however this objective has not explored in this article.

X. ACKNOWLEDGEMENTS

All the authors are grateful towards the facilities provided by the TEQIP III and Department of Mechanical Engineering, National Institute of Technology Silchar, Assam, India to carry out the research work.

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