

**NUMERICAL STUDY OF THE REGION BEHIND REARWARD STEP
IN SUPERSONIC COMBUSTION**

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ABSTRACT:

In an advance design of the combustor for supersonic combustion studies a rearward-facing step is required for suitable condition for the fuel injection. A numerical code is developed to study the role of the step for the mixing phenomena in the supersonic combustor. A two dimensional Navier stokes solver is developed and validated with the experimental data. Cold flows of sonic injection in free stream of Mach Number 2.0 are considered for the investigation.

Two separate cases are compared for the transverse fuel injection with and without rearward facing step in the combustor. The data analysis is carried out in terms of pressure variation and pressure distribution across and along the length of the combustor respectively. An empirical relation is used to evaluate the mixing efficiency for both cases. In this numerical study it is observed that rearward-facing step is suitable for the fuel injection and to enhance the mixing phenomena.

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INTRODUCTION:

Recent advances in the technology of air breathing propulsion addresses the development of a unique high performance scramjet engine. Scramjet is a variation of a ramjet, where combustion of the fuel air mixture occurs at supersonic speed. In an earlier paper, we have studied and analysed the effect of pre injection in supersonic stream to enhance the mixing efficiency. As a continuous effort, in this paper we are going to analyse the effect of rearward facing step in the combustor and explain its importance to improve the mixing phenomena. A rearward step is provided to create a low Mach number region or re-circulation zone so that fuel can be injected and mixed in the air stream. In an advanced design of the combustor for supersonic combustion studies the step with transverse or angular injection of fuel at the downstream of the step are used for the following:

1. To create local separation zone for effective mixing of fuel with air
2. To limit the interaction between reacting flow and inflow
3. To serve as a flame stabilizer

Fuel mixing with air, ignition and then flame stabilization are the crucial issues in supersonic combustor and critical for the development of Hypersonic Air breathing Propulsion systems. It is essentially required to mix the fuel with air at the molecular level in the near field of the fuel injection, to enhance the efficient performance of this type of very high-speed combustor system. One of approaches is the transverse and angular injection of the fuel from the wall of the combustor through a hole. When fuel jet at sonic velocity interacts with the supersonic air stream, a bow shock is produced. The cross interaction of two high speed flows the upstream wall boundary layer separates and fuel jet mixes subsonically at upstream of the exit. This region is important in transverse injection flow fields owing to its flame holding capability in combustion situations.

THEORETICAL INVESTIGATIONS:

It is very difficult to investigate the detailed structures of fuel jet and mixing mechanism analytically and experimentally due to the complicated structure of various shock waves, re-circulation and their interactions. Numerical investigations by using computational fluid dynamics techniques have become a strong tool to analyse the problems. A numerical code is developed to study fuel air mixing and to investigate the effect of step in the mixing phenomena. The importance of step in the combustor is discussed. The primary objective of this study is to investigate the mixing phenomena in various configurations by using the numerical code to design and analyze the advanced propulsion system. This paper presents an overview of the validation requirements of code applicable to advance propulsion system and it identifies the enabling technology requirements in the development of the next generation of code. This paper is divided into two sections; the first section introduces the concept of validation with the experimental values. The second section provides analysis of the mixing phenomena. A rearward-facing step of size 4mm is chosen for the theoretical study. This model basically divided into two major portions:

1. 100 mm length isolator and
2. 112 mm length constant area combustor

Same size section without step is chosen for the comparative study.

A schematic layout of the 2-D model scramjet combustor is shown in Fig.01A and

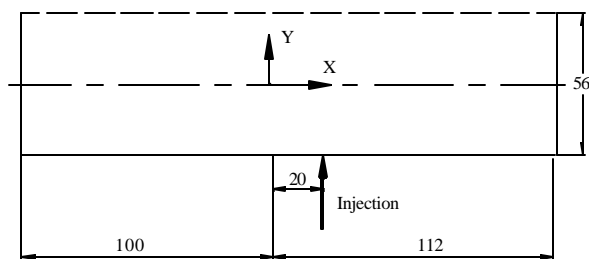


Fig. 01A: COMBUSTOR WITHOUT STEP

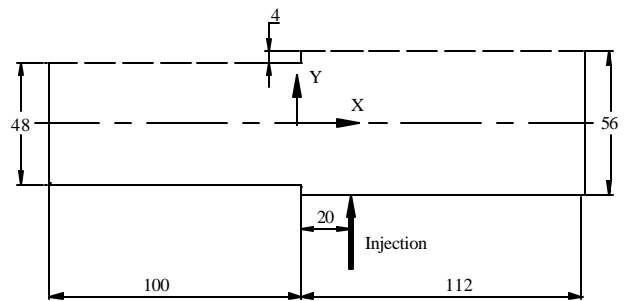


Fig. 01B: COMBUSTOR WITH STEP

Two fuel jets are injected at sonic speed ($M=1$) at upstream and downstream of the step. The injector distance from the step is kept same as 20mm. The injector diameter for pre injection is 1.0mm and the main injection is 2.5mm. Combustor entry Mach number for this study is taken as 2.0. The analysis considers two-dimensional and laminar flow. The governing equation considered is Navier Stokes equations, containing transport equations are expressed in non-dimensional form. A 2-D compressible cell centered finite volume Navier-Stokes solver has been developed. Reconstruction on primitive variables is used to obtain second order accuracy in space and the derivatives of primitive variables required for reconstruction and the viscous stress terms are obtained. The Navier-Stokes solver has been applied to the present case and confirmed its validity and robustness.

The full 2-D Navier-Stokes equations can be written in conservative form as

$$\frac{\partial U}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = 0$$

Where U is the state vector and the Flux vectors are F and G . The numerical algorithm used in this study is validated with a number of numerical simulations for the cases where experimental data exist. However, there is a minor difference between numerical results and experimental data due to the numerical study being carried out for two dimensional geometry, while, the experiment was performed in a three dimensional combustor¹.

RESULTS AND DISCUSSIONS:

Before using any numerical code for analysis purpose, it is necessary to build confidence in the result obtain from the model. This is accomplished by performing a series of validation exercise where the results of the calculations are compared with well-characterized experimental data. Therefore, in this theoretical investigation, firstly, the code is tested for a simple problem. The

definition of the problem is chosen from the work carried out by Chen Jianqiang et. al². for the correctness of the code. The test results are compared with their experimental data. The conditions are - a simple parallel supersonic flow over a rearward-facing step, laminar flow of $M=3.5$ passed through a 19 mm step height. The pressure variation at three different locations and distribution across (in y - direction) and along (in x - direction) combustor are plotted and compared with the experimental data as shown in Figs. 02A and B respectively.

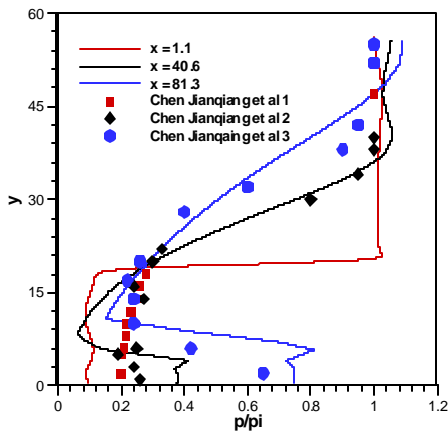


Fig. 02 A: PRESSURE VARIATION

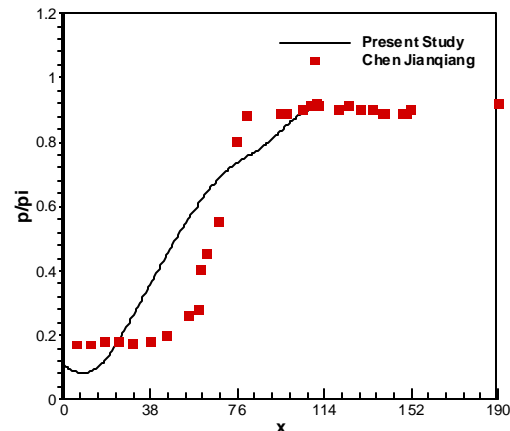


Fig.02 B: PRESSURE DISTRIBUTION

It shows comparison of numerical results with an experimental study carried out by Chen Jianqiang et. al. by using the initial conditions of the experiments. After, the performance was found satisfactory, the code was validated for the investigation. The theoretical studies are carried out on the combustor without and with rearward facing step. Initially the performance of without step is evaluated in terms of pressure and Mach contours for the transverse injection as shown in Fig.03A and B respectively.

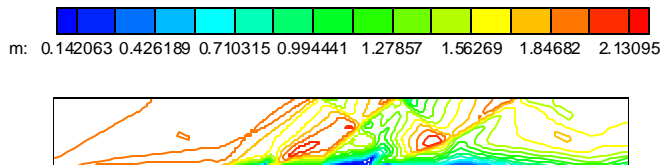


Fig.03A: MACH CONTOUR
(WITHOUT STEP)

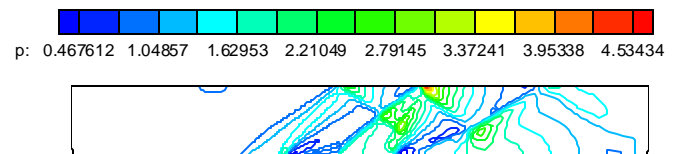


Fig. 03B: PRESSURE CONTOUR
(WITHOUT STEP)

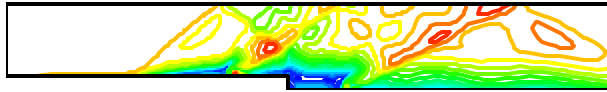
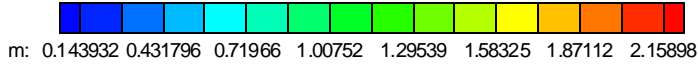


Fig. 05A: MACH CONTOUR (WITH STEP)

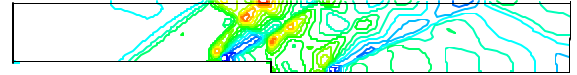
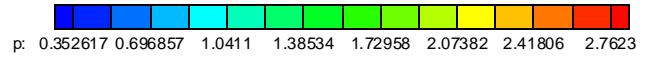


Fig.05B: PRESSURE CONTOUR (WITH STEP)

It is clearly observed that re-circulation regions near step is found more, which is essentially required for fuel injection into supersonic stream. The pressure and Mach number values are found of the order of 1.72–1.38 and 0.14 – 0.43 respectively as shown Fig.06A&B. On comparison, these values are found suitable for the fuel injection as compared to the previous case.

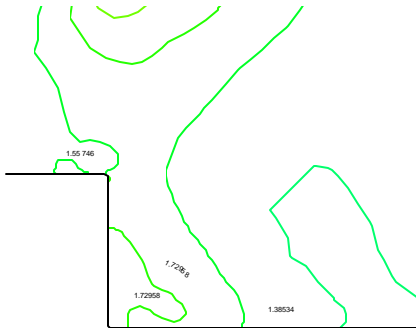


Fig.06A: PRESSURE (NOMINAL) VALUES NEAR STEP



Fig. 06B: MACH NO NEAR STEP

Due to large re-circulation zone (sub sonic zone) the penetration of fuel is found more suitable. The role of step can be highlighted by evaluating the mixing efficiency in both cases. The mixing efficiency (η_m) is calculated and plotted along the length of the combustor by using an empirical relation⁴ as given below:

$$\eta_m = \left\{ \frac{x}{L_m} + \frac{1}{50 + 1000 \alpha} \right\}^\alpha$$

Where, L_m is the total distance required for mixing layer boundary to reach the wall, which is estimated from various measured parameters from the code and ? is a

parameter, which varies from 0.17 to 1.00 based on different configurations. The mixing efficiency is evaluated at two different planes across the combustor (in y-direction) i.e. $y=5$ & $y=10$. It confirms again that due to the large re-circulation zone, mixing efficiency is found to be more in case of stepped combustor. The mixing efficiency of both cases are plotted as shown in Fig 07.

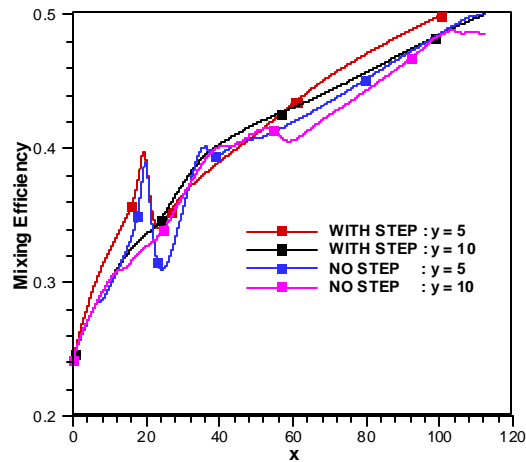


Fig.07: MIXING EFFICIENCY

It is clearly observed from Fig.07 that near injection zone the efficiency at plane $y=5$ is found to be better in the case of step combustor in comparison with the case of without step combustor.

Conclusions:

The numerical method employed in this paper is found suitable for supersonic combustion studies. The effect of rearward facing step in the combustor is studied and the following conclusions are made from the theoretical studies.

- The comparison indicates good agreement between code and experimental studies and it is found that the code predicts accurately laminar supersonic flow fields over a rearward-facing step.
- Sonic injections into the high temperature supersonic Air Stream are studied for two configurations i.e. with and without rearward facing step.
- The performance of both cases is compared by using various parameters / contours.
- Rearward facing step in the combustor creates large re-circulation (sub sonic) zone, which is favorable for transverse injection in supersonic combustor studies.
- The mixing efficiency due to the step in the combustor for transverse injection is improved by approximately 5-8% near injection area.

References:

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3. R C Rogers, Mixing of Hydrogen injected from multiple injectors normal to a Supersonic Air stream', NASA Technical Note, 1971
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