DOI: 10.13009/EUCASS2023-369
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

Experimental and Numerical Study of Supersonic Flow in a Scramjet Combustor in Expansion Tube

GÜMRÜK TOKGÖZ Semra†, SÜMER Bülent* and USLU Sıtkı***
** TÜBİTAK SAGE*
*** TOBB University of Economics and Technology*
Ankara,Turkey
semra.gumruk@tubitak.gov.tr – bulent.sumer@tubitak.gov.tr – suslu@etu.edu.tr
† Corresponding Author

Abstract

Scramjet testing for design is quite unique due to demanding operation conditions that are the natural outcome of the hypersonic flight. The ground testing of scramjet engines is widely performed in scramjet test facilities, that have the capabilities to simulate both total enthalpy and total pressure of the incoming air flow. The construction of high mass flow rate blow down, scramjet test facilities need careful planning and respectable amount of investment. Expansion tube facilities, on the other hand, can be constructed with a relatively small investment cost and they can used to simulate these wide range of operating conditions by only changing filling pressures of test sections. In this study TUBITAK SAGE Expansion Tube Facility (TS-ETF) was modified for investigation of supersonic flow in scramjet combustors and used to investigate the flow inside a scramjet combustor. The main drawback of the expansion tube testing is the effective test time, which is in the order of microseconds, within which the measurements should be taken.

Computational Fluid Dynamics tools has been used for the prediction of high-speed flows for about half a century now. Yet the flow physics inside a scramjet combustor is highly demanding because of thin boundary layers, shock formations, turbulent mixing, real gas effects, combustion and their interactions. In this study a commercially available CFD solver is used to numerically investigate the flow inside the scramjet combustor. Two dimensional and three dimensional, steady Compressible viscous analyses are performed. Effects of different turbulent models on the flow characteristics are investigated A grid sensitivity study is performed for the 2D analyses, the result of which is used for the 3D analyses. The results of the numerical analyses are compared and validated against experimental data.

In conjunction with the numerical studies experimental studies are performed for same operating conditions in TS-ETF. Combustor model is fabricated with optical accesses, which utilizes quartz windows, on three sides to visualize the flow with imaging techniques. Experimental studies are performed for different operating conditions in TS-ETF to investigate shock train and shock/boundary layer interaction in combustor. Static pressure measurements on the top wall of combustor model and Schlieren imaging are used to characterize the flow in combustor model.

1. Introduction

Operational envelopes of scramjet engines are quite wide. Therefore, the flow within the combustion chamber exhibits a broad range of aerothermodynamic variations. To fully test these conditions on the ground, a test facility capable of operating over a wide range of temperatures, pressures, and Mach numbers are required.

In order to determine the turbulence model to be used in the analysis of the scramjet combustion chamber, a literature review was conducted, and it was generally observed that the SST k-ω turbulence model is commonly used.

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Gao and Le [1] used the SST turbulence model for the three-dimensional simulation of flow fields in a combustion chamber of a scramjet engine and they showed that good agreements of the numerical results with experimental data validated the turbulence model.

Lu et al. [2] studied combustion field in dual cavity combustor and they performed RANS simulations with the SST k-ω turbulence model and compared results CARDC experiments. Chemical reactions were modeled by the Eddy-Dissipation-Concept (EDC) model, which is an extension of the Eddy-Dissipation Model to include detailed chemical mechanisms in turbulent flows. They showed that position of pressure peak and oscillation consistent with the available experimental data both with and without combustion.

Choi et al. [3] carried out a two-dimensional computer code with RANS turbulence model to investigate the transient process of the combustion and the shock-train developments in an ethylene-fueled direct connect dual-mode scramjet combustor. They used in-house computational code and it was extended up to a fifth-order accurate scheme. Menter's shear stress transport (SST) model was used together with the SST DES (detached eddy simulation) extension to enhance the description for the separated flow while the characteristics of the boundary layer were compared with the RANS code.

Theory and working principle of the expansion tube shared in literature by Trimpi [4]. This study is currently used as a reference for calculating the filling pressures of expansion tubes. Within the scope of the studies conducted at the Langley Research Center by NASA's Langley Pilot Model Expansion Tube, a technical note has been published. In the shared study, experimental and theoretical studies conducted with the expansion tube were compared. The calculations shared by Trimpi were used in the theoretical studies. As a result of the conducted studies, it was observed that the flow velocity, test duration, and thermodynamic properties obtained in the test chamber yielded close results with Trimpi's theory.

Miller et al. [5] conducted a study using the Langley Expansion Tube, examining the effect of filling pressures on flow characteristics by using different test gases. It was observed that when helium was used as the expansion gas, it had the least decelerating effect on the incident shock speed.

Gamba et al. [6] conducted reactive and non-reactive tests for the Scramjet Combustion Chamber Model using the Stanford Expansion Tube at Stanford University. The designed scramjet combustion chamber model was used as a reference in the present study. The test model for the combustion chamber consists of an entrance modelled with a 10° angle to generate a shock train within the model. A constant-area combustion chamber is used after the angled entrance. The test conditions were determined as Mach 2.8, T=1200 K, and P=40 kPa at the entrance of the Expansion Tube test section to simulate a Mach 8 flow at an altitude of 30 km. Hydrogen was used as the fuel for the tests. Pressure measurements were taken over the upper wall of the combustion chamber for both reactive and non-reactive flows, and the flow inside the combustion chamber was visualized using Schlieren technique.

Gamba et al. [7] investigated the effect of fuel injection on the flow field using the Scramjet Combustion Chamber Model previously designed for the Stanford Expansion Tube. This combustion chamber model was used to study mixing, ignition, and combustion under supersonic conditions. The combustion chamber model, made of fused-silica glass on three sides, allows optical visualization of the flow inside the combustion chamber. The regions where combustion occurs were examined using OH* chemiluminescence, and the instantaneous reaction zones were visualized using OH planar laser-induced fluorescence (PLIF). In this study, the influence of heat release using air and nitrogen in free stream on the flow field was investigated and compared with pressure measurements taken over the upper wall of the combustion chamber.

Schranner et al. [8] analysed the Supersonic Combustion Chamber Model to be tested in the Stanford Expansion Tube using 2D numerical simulations. Shock generators with angles of 10° and 20° were used in the test models. The designed test models were tested in the expansion tube, and the results were compared with numerical simulations.

Gamba et al. [9] conducted tests for the scramjet combustion chamber model in the Stanford Expansion Tube using different fuel-air ratios and compared the measured pressure values over the upper wall of the combustion chamber with test results. Additionally, the shock structures inside the combustion chamber for fuel-injected and non-fuel-injected conditions were visualized using the Schlieren technique.

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Heltsley et al. [10] worked on the design and characterization of the "Stanford 6-inch Expansion Tube." This test facility was designed for conducting scramjet combustion tests between Mach 4-9. The characterization of the facility was carried out using a 22° wedge and Schlieren imaging technique.

Dufrene et al. conducted studies for Mach 3-7.1 flow conditions using a 152 mm Expansion Tube at the University of Illinois. Flow visualization on the wedge using the Schlieren method and a pitot tube were used for the characterization of the expansion tube. A uniform flow with a diameter of 60 mm was obtained in the expansion tube under Mach 7.1 conditions [11].

Abul-Huda et al. conducted studies on the design and characterization of the Michigan Hypersonic Expansion Tube Facility. The test setup can operate between Mach 4 and 11. Measurements can be taken using piezoelectric sensors, static pressure measurements, and pitot tubes. Calibration of the test setup was achieved using a 20° wedge and Schlieren imaging technique [12]

2. Numerical investigation

2.1 Introduction

The numerical investigation of the scramjet combustor model was performed using the commercially available ANYSY-Fluent software. The scramjet combustor model was designed and investigated by [6,7,8 and 9].
The Scramjet Combustor Model (SCM) has a rectangular inlet with 23 mm height and 75 mm width. After the inlet the flow are decreases with 10° angle at the upper part up to the constant area combustion chamber with 15 mm height and 75 mm width. Total length of the SCM is 315 mm. The main dimensions of the SCM are also given in Figure 1a. The combustion chamber model allows the testing of reactive flows with the help of a fuel injector located at the center of the bottom wall, whose main dimensions are given in Figure 1b. The SCM is also illustrated in Figure 2.

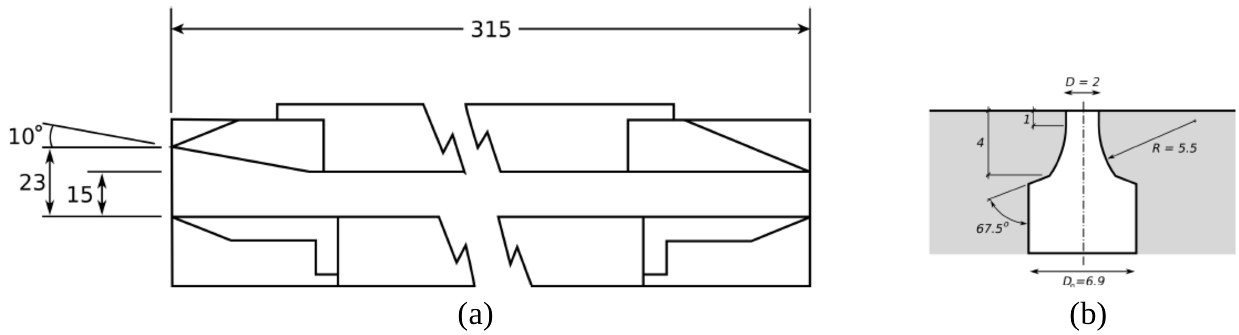

Figure 1: Schematic diagram of inlet/combustor model showing the dimension of the main components, all indicated dimensions are in mm [7].

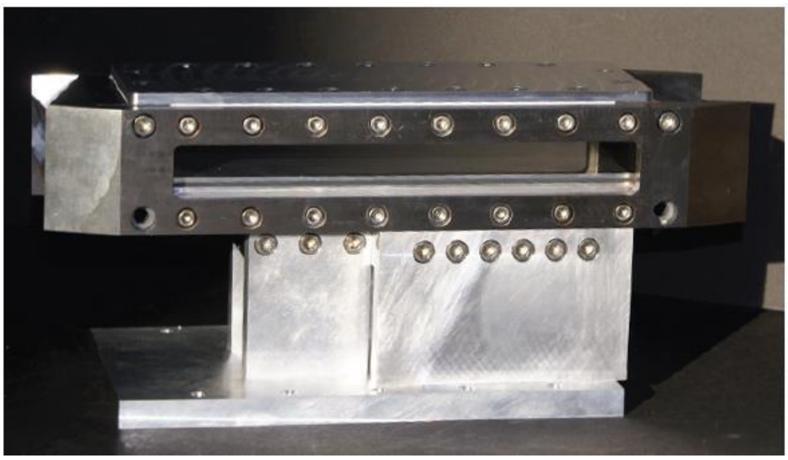

Figure 2: Model scramjet combustor [13].

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2.2. Numerical methodology

In the present study, CFD analysis were performed to create a validated numerical model for scramjet combustion process. The density based steady solver of the ANSYS-Fluent was used to perform both two dimensional and three dimensional compressible, viscous flow through the SCM. A fully implicit second-order finite volume method is used to discretize and solve the steady fluid-flow equations on structured grid in the study. NASA polynomials model was used for the definition of specific heat [14] and Sutherland model was used for the definition of viscosity [15]. All the gases in the simulations are assumed to be ideal gas. The parallel computations were performed on the 28 cores for 2D analysis and 500 cores for 3D analysis.

The results of the experiments performed by Gamba [7] were used for comparison of all numerical results in this study.

2.3 Two-dimensional simulation model

A two-dimensional simulation model was prepared for the initial investigation to save time and computational power. The two-dimensional simulation model is shown in Figure 3 along with the boundary conditions. The boundary conditions are also tabulated in Table 1.

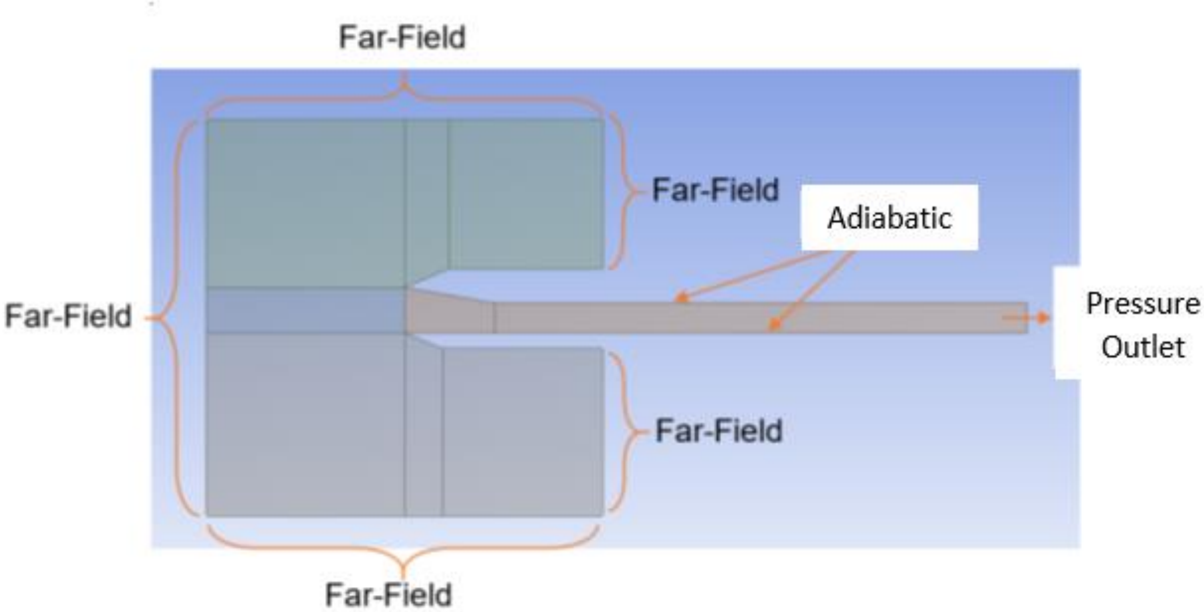

Figure 3: Two-Dimensional Simulation Model and Boundary Conditions.

Table 1: Boundary Conditions

Far Field	Air, M = 2.8, T=1200 K, P=40 kPa
Pressure Outlet	P=40 kPa, Backflow total temperature: 2724 K
Wall	Adiabatic

In the analysis, the initial focus was on the grid sensitivity study. Based on a literature review [1,2,3], the SST k-ω turbulence model, commonly used for supersonic flows, was employed.

2.3.1 Grid sensitivity study

Grid sensitivity study was performed using Grid 1, Grid 2, Grid 3, and Grid 4, which consists of 125 000, 500 000, 2 million, and 5 million elements, respectively. The grid structures are shown in Figure 4. In the construction of the grid structures, the boundary layer was considered by ensuring $y^+<1$ constraint for the SST k-ω turbulence model.

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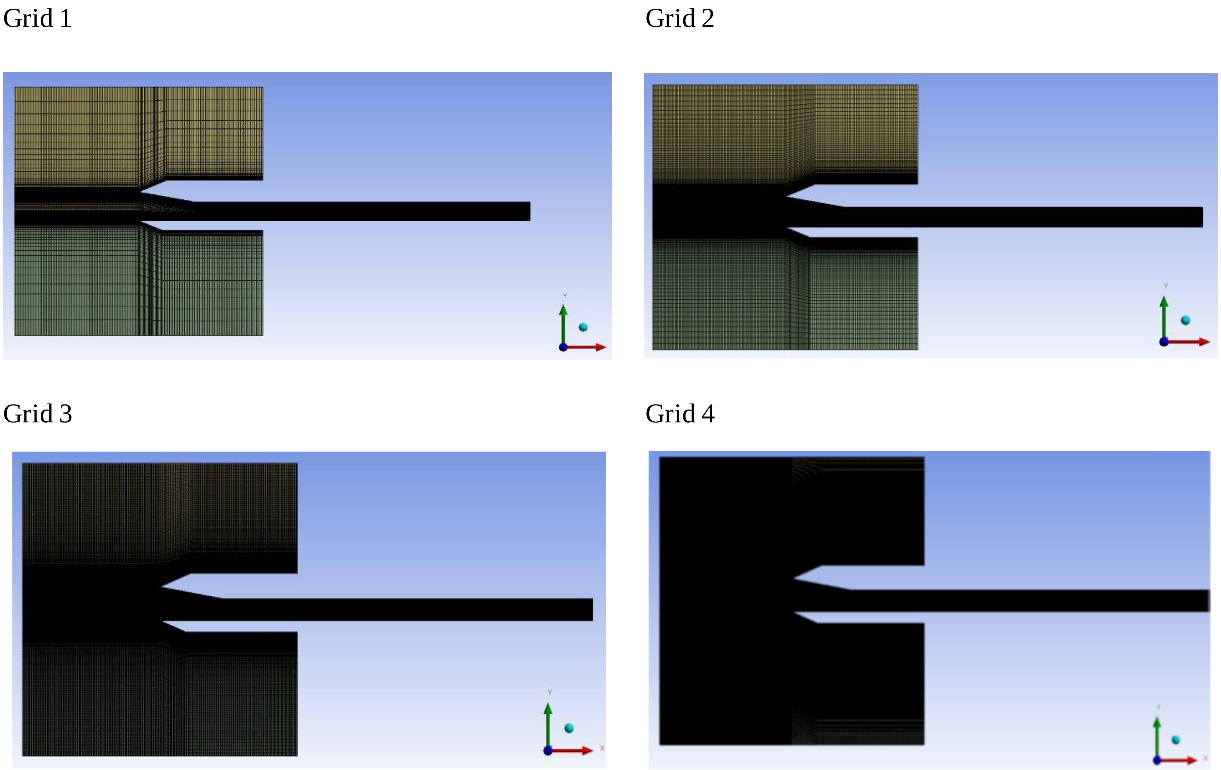

Figure 4: Grid sensitivity study

The pressure values obtained at the upper wall of the combustion chamber using different grid configurations are illustrated in Figure 5. When first pressure pick point is analysed in detail it is seen that pressure difference is not changing significantly after the Grid 3. As seen in Table 2, error value between Grid 3-Grid 4 is less than % 1, it was decided to use Grid 4 due to no more refinement in grid will not give any significant effect on pressure values.

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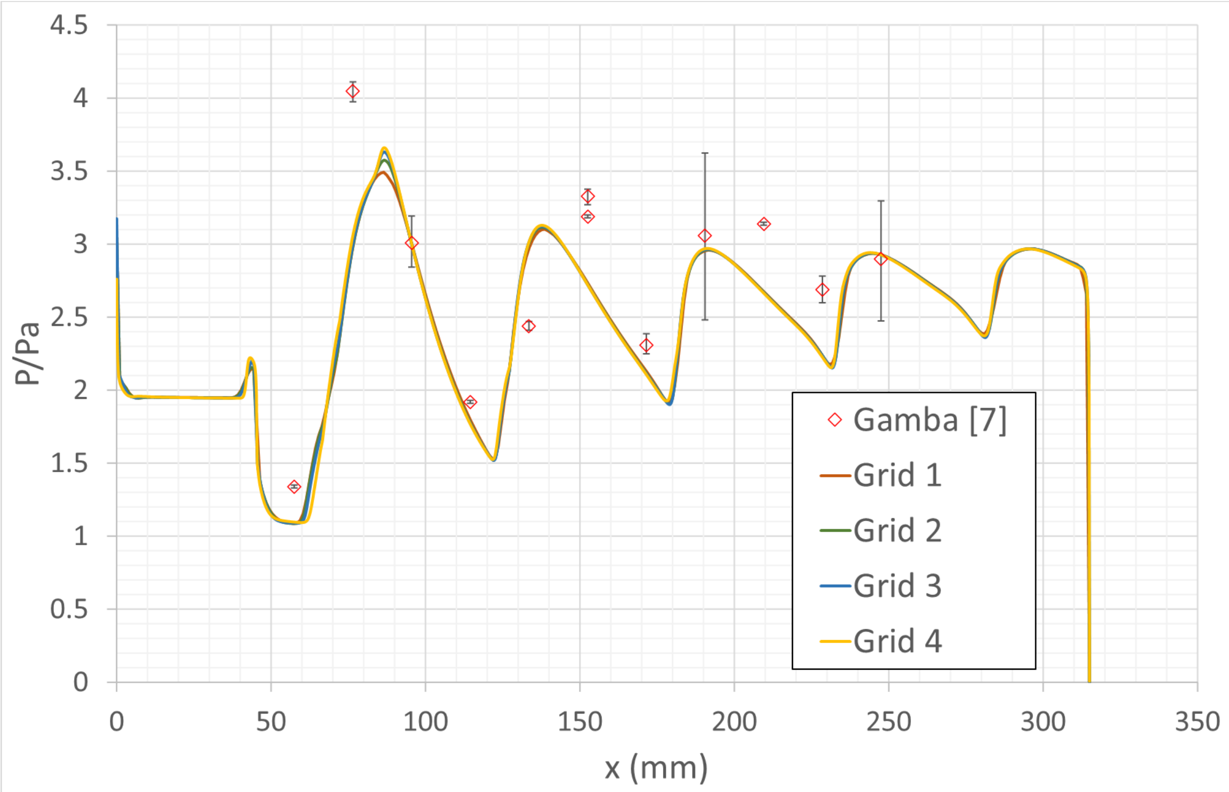
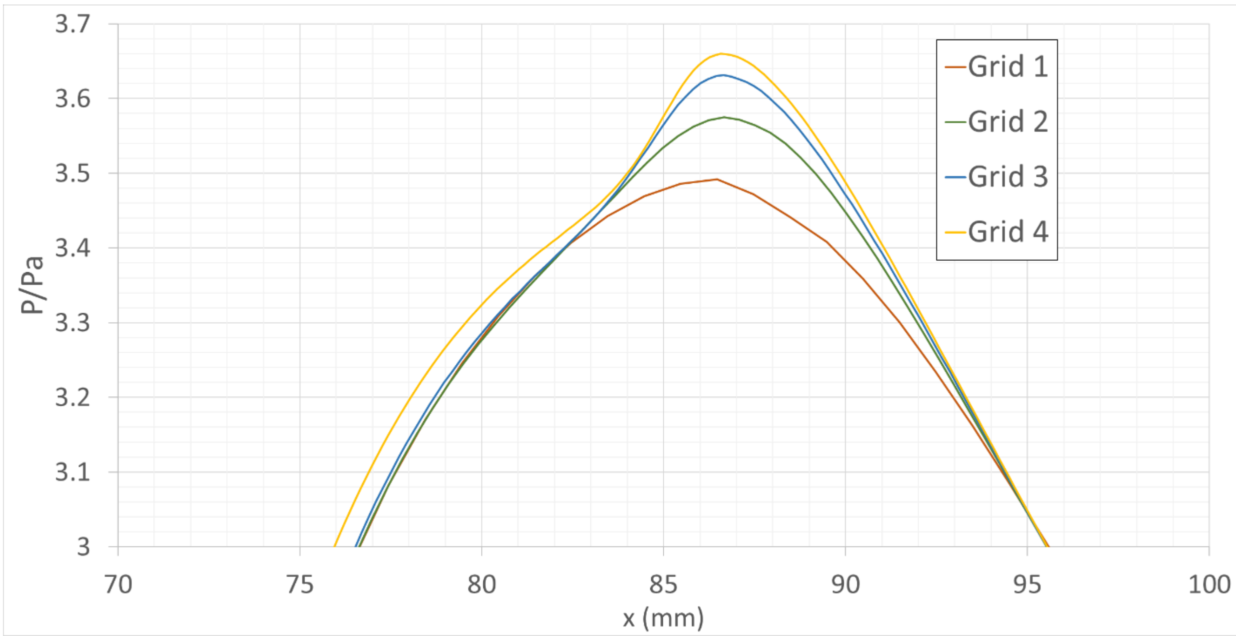


(a)



(b)

Figure 5: Dimensionless pressure values on the upper wall of the combustion chamber.
(a) All pressure points (b) First pressure point (Detailed view)

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Table 2: Error values between Grid 1, Grid 2, Grid 3, and Grid 4

	Error (%)
Grid 1-Grid 2	2.23
Grid 2-Grid 3	1.68
Grid 3-Grid 4	0.83

To visualize the oblique shock structures within the combustion chamber, a numerical schlieren study was conducted using the analysis results, and the results were compared with the test data, as shown in Figure 6 and cell size of all grids are written in figure.

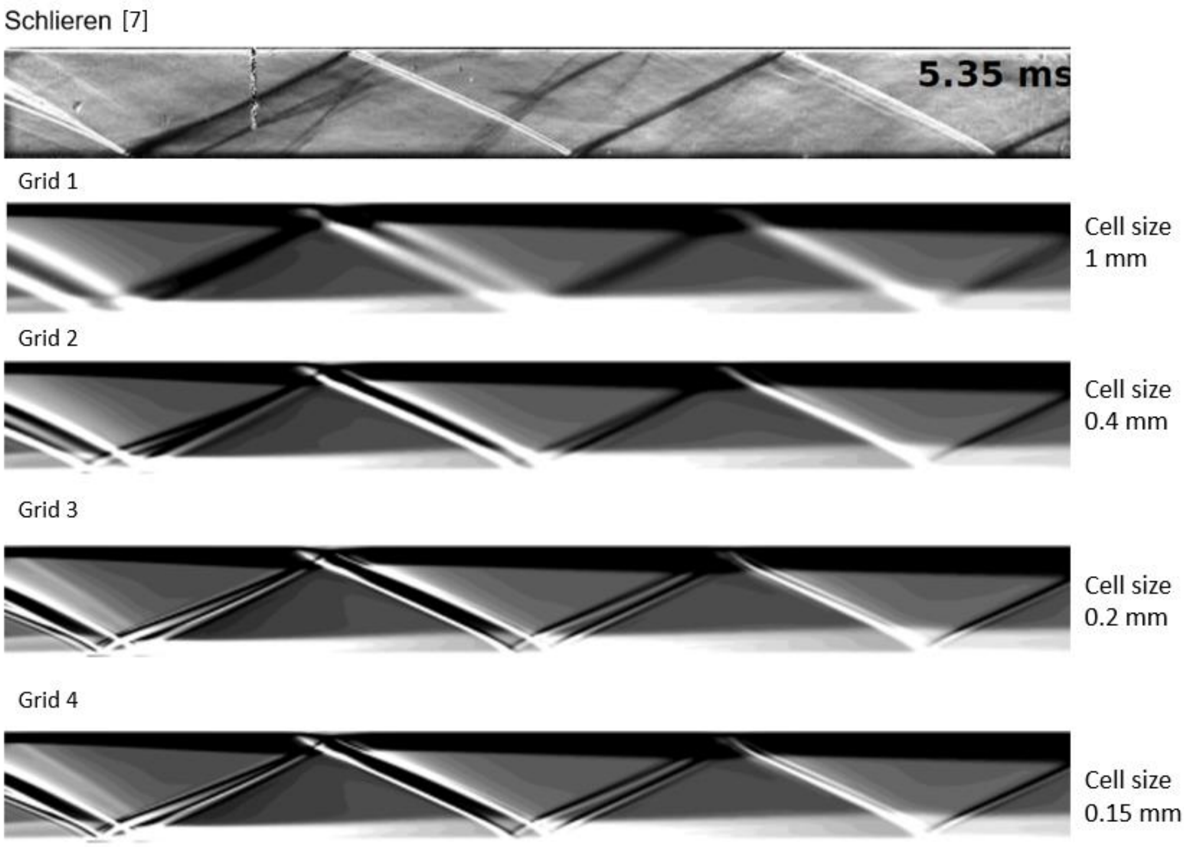

Figure 6: Comparison of numerical schlieren image with test results

2.3.2 Turbulence model study

To investigate the effect of different turbulence models on the analyses, simulations were performed, and the pressure values obtained on the upper wall of the combustion chamber are shown in Figure 7, while the numerical schlieren images are shown in Figure 8. When all the results were examined, it was seen that the SST k-ω model gave more consistent results with test results.

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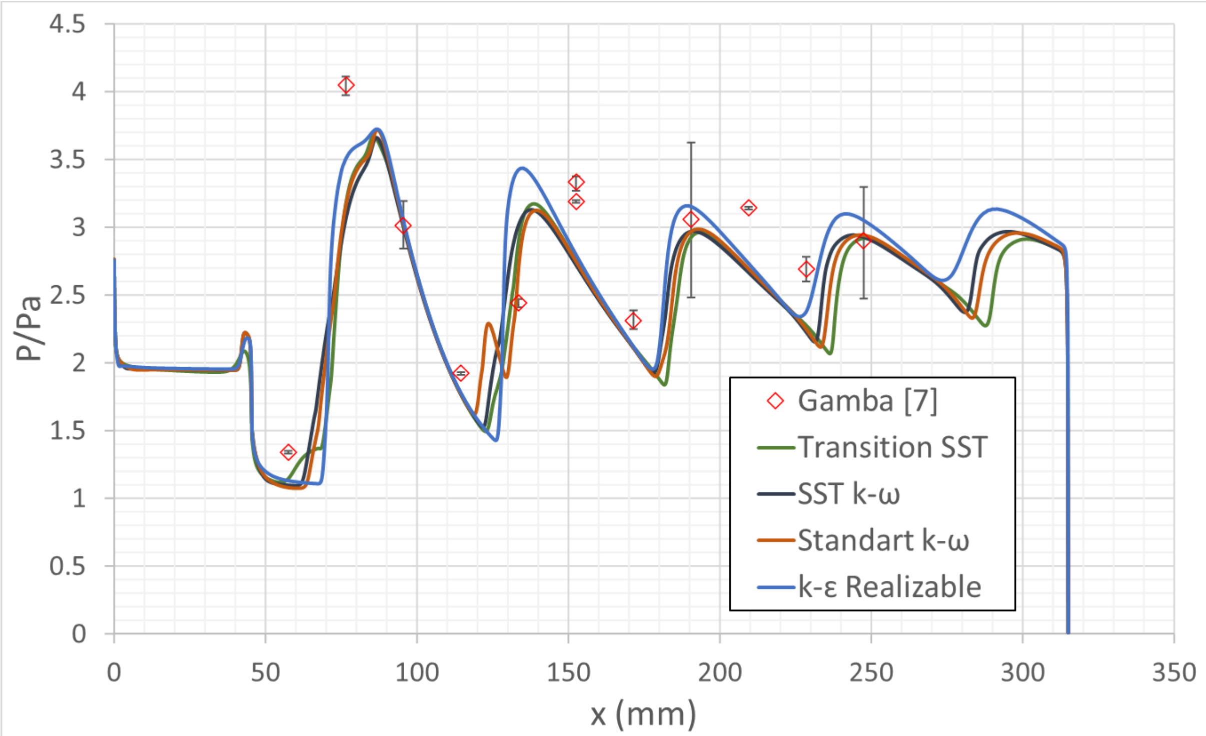

Figure 7: Dimensionless pressure values on the upper wall of the combustion chamber

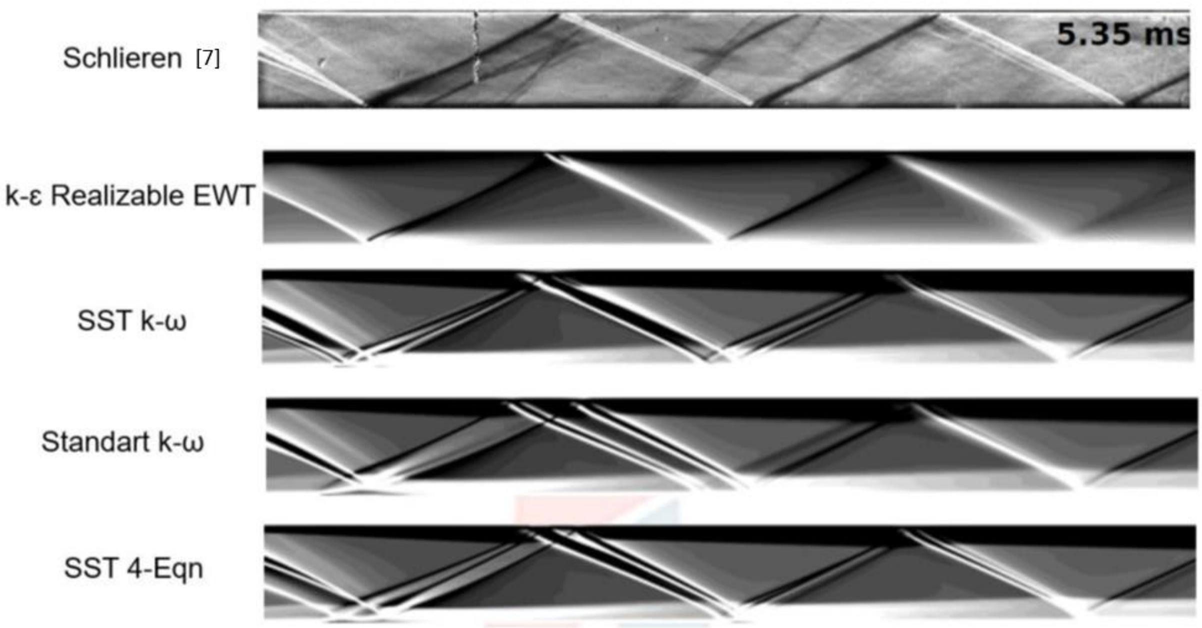

Figure 8: Comparison of numerical schlieren image with test results (EWT: Enhanced Wall Treatment)

2.4 Three-dimensional simulations

Three-dimensional compressible viscous flow through the SCM was solved using the density-based solver of ANSYS-Fluent with and without cross jet.

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The three-dimensional model was discretized using hexahedral elements and cell size was kept with the same as 2D cold flow analyses with Grid 4 and grid is given in Figure 9. In the initial stage, a grid structure consisting of poly-hex elements was used. However, due to the diffusive appearance in the analysis results, the grid structure was modified to consist only of hexahedral elements. The boundary layer was prepared considering the requirement of the turbulence model with the limit $y^+<1$.

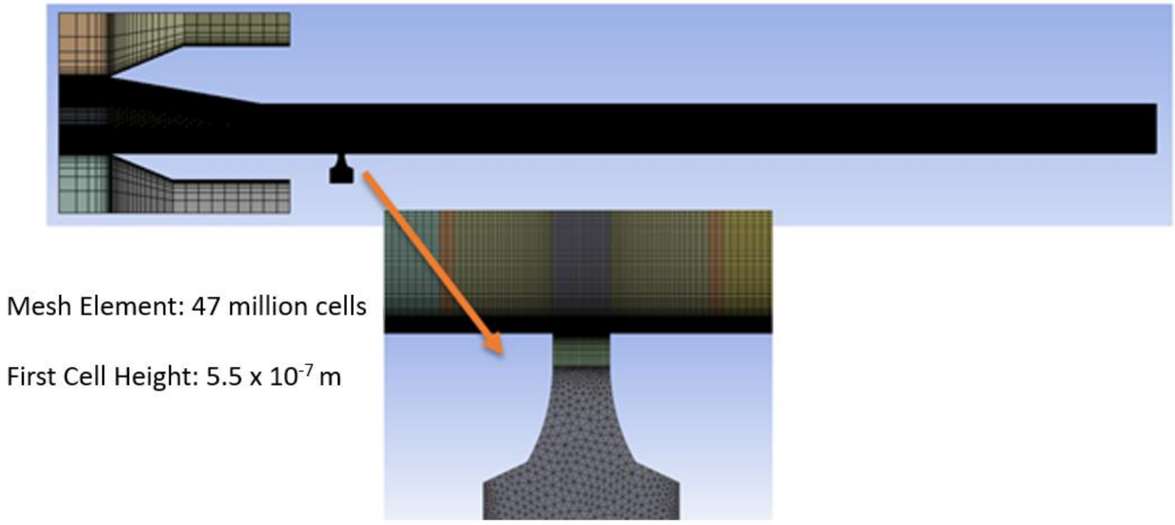

Figure 9: 3D Scramjet combustor model grid structure (FSH: Cell height closest to the wall)

The reference paper used for comparison of analysis results includes test data where fuel injection takes place, but no combustion occurs due to the use of nitrogen in the free stream [7]. Analyses were conducted to examine the mixing of fuel (hydrogen) with nitrogen through crossflow. The species transport model was used in non-reacting case analysis.

The boundary conditions used in the analyses are shown in Table 3 and Table 4. Pressure Far Field was used as the air inlet condition, Pressure Inlet was used as the injector inlet boundary condition, and Pressure Outlet was used as the combustion chamber outlet condition. Initially, an adiabatic wall boundary condition was used as the wall condition. However, due to flow separation at the region where the jet impacts in the injection analyses, the wall boundary condition was modified to "Twall = 298 K" to account for the flow separation.

Table 3: Boundary Conditions

Free Stream	Pressure, Temperature, Mach
Fuel	Pressure
Wall	Temperature, 298 K
Outlet	Pressure

Table 4: Boundary Conditions

	Air	Hydrogen
Static Pressure	40 kPa	668 kPa
Total Pressure	1140 kPa	1265 kPa
Mach Number	2.8	1
Static Temperature	1200 K	300 K
X_{H2} (Mass Fraction)		1
X_{O2} (Mass Fraction)	0.232	
X_{N2} (Mass Fraction)	0.768	

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2.6.1 Numerical results-Cross flow

Comparison of numerical schlieren images with the test results is shown in Figure 10. In the 3D analyses conducted with 47 million elements, the numerical schlieren images were found to be in good agreement with the test data, particularly regarding the locations of the shock waves.

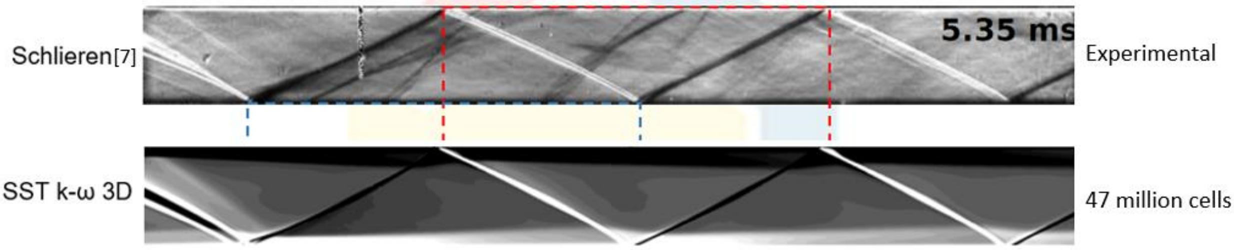

Figure 10: Comparison of numerical schlieren image with test results.

2.6.2 Numerical results-Jet in cross flow

The comparison between the numerical schlieren and test data obtained from the analysis is shown in Figure 11. By examining the test and analysis result images, shock angles have been calculated and presented in Figure 12. Due to the significant thickness of the shocks observed in the test data, exact shock angles could not be determined. Therefore, a certain deviation range was given, and the shock angles obtained from the analysis were compared with the test data, and the results are presented in Table 5. Upon evaluation, it is observed that the shock angles obtained from the analysis fall within the error range.

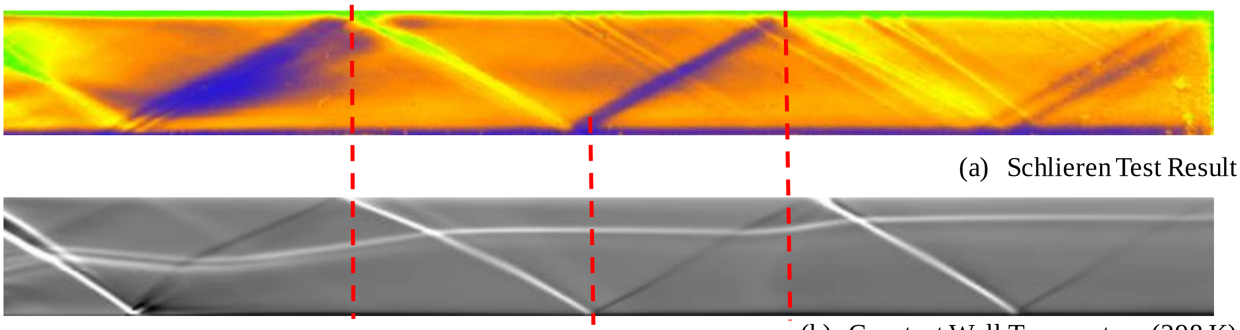

Figure 11: Comparison of 3D scramjet combustor schlieren test data and numerical schlieren (a) Schlieren test result (b) Constant wall temperature (298 K)

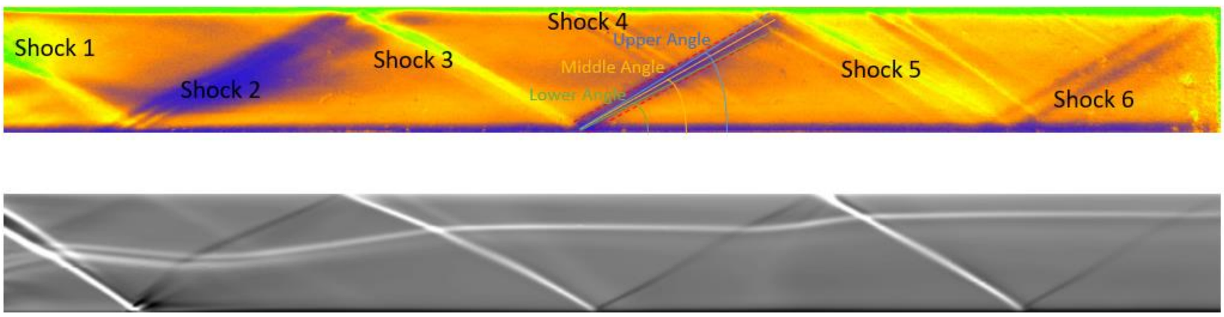

Figure 12: Comparison of shock angles with test data

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Table 5: Calculation of shock angles

Shock Number	Experimental Results Middle Angle (Stanford)	Numerical Results (SAGE)
1	$31.78_{-3.37}^{2.95}$°	31.84°
2	$28.15_{-1.39}^{2.04}$°	29.75°
3	$28.65_{-1.77}^{2.02}$°	28.50°
4	$28.45_{-1.44}^{1.95}$°	28.08°
5	$28.66_{-1.14}^{1.23}$°	29.79°
6	$29.19_{-1.31}^{2.22}$°	29.00°

3 Experimental investigation

3.1 Introduction

Expansion tube is a test apparatus that can easily generate conditions within a wide range of temperature, pressure, and Mach numbers. It is frequently used for the investigation of high-enthalpy flows. The sudden expansion tube consists of a driver section, a driven section, an expansion section, a test section, and an exhaust section (Figure 13).

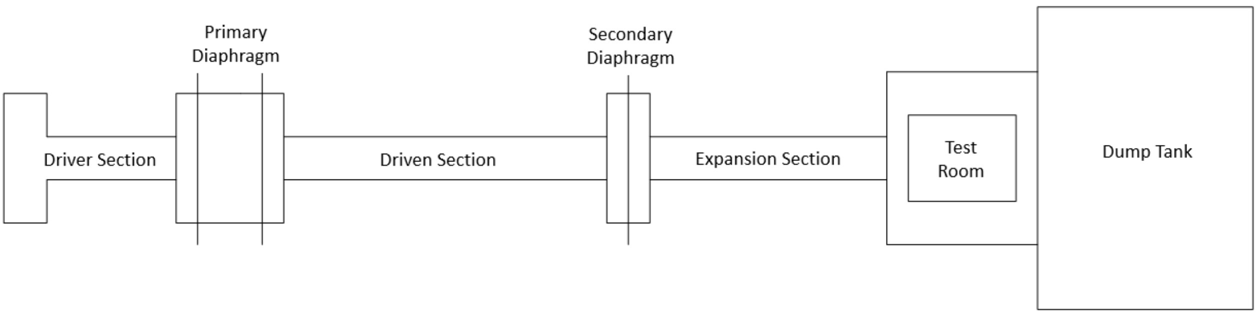

Figure 13: Schematic representation of the shock expansion tube test facility

The driver section is separated from the driven section using a double diaphragm, while the driven section is separated from the expansion section using a single diaphragm prior to the test. The test section is where the model is placed, and measurements are taken. The dump tank is the section where the test gases are released. The properties of the test gas within the shock expansion tube can be optionally modified and adjusted only by controlling the filling pressure at each section.
Unlike other test apparatuses based on the principle of sudden impulse, such as shock tubes, and shock tunnels, the expansion tube does not disrupt the flow chemistry or subject the test gas to high intermediate temperatures, allowing for more realistic conditions in the test section. Additionally, the addition of fast-acting valves to this test facility enables the investigation of reactive or non-reactive flows interacting with the test gas.

In a shock expansion tube, diaphragms made of plastic or thin metal separate the sections from each other (Figure 13). The driver section is filled with a lightweight gas such as helium at high pressure. The driven section is filled with the desired test gas, such as air, at a lower pressure. The third section, called the expansion section, is filled with a very low-pressure lightweight gas, such as helium.

An x-t diagram (Figure 14) is used to examine the operating principle of the shock expansion tube and the sequence of events that occur within it. The horizontal axis represents distance along the shock expansion tube, while the vertical axis represents time.

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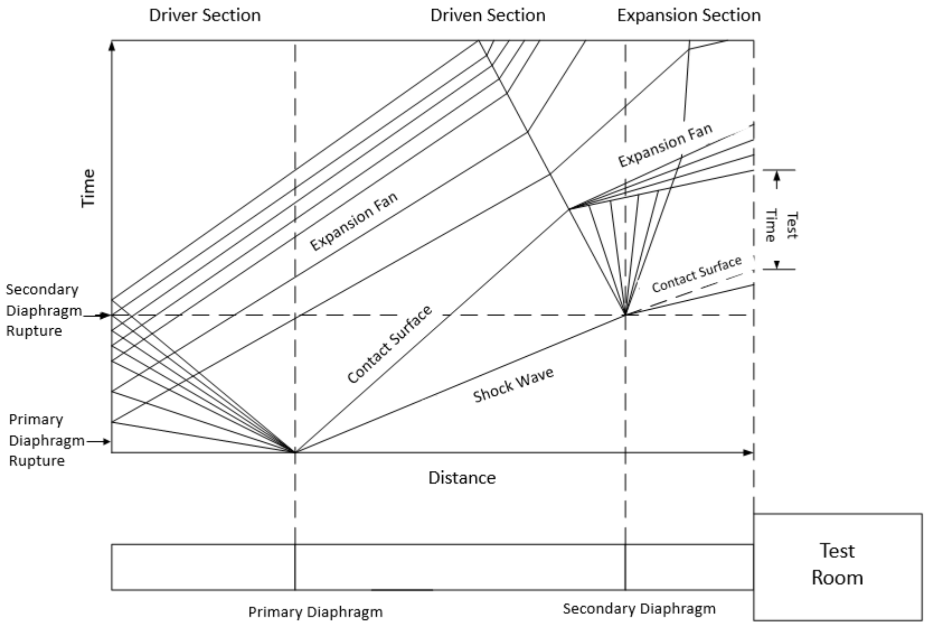

Figure 14: Shocks and reflections inside the test facility [16]

When the first diaphragm between the driver and driven sections ruptures (t=0), the high-pressure driver gas spreads into the lower pressure driven section. A shock wave propagates through the test gas, increasing its temperature, pressure, and density. This shock also creates an intermediate velocity (relative to the laboratory reference frame) within the test gas. When the initial shock reaches the end of the driven section, it ruptures the second diaphragm and enters the expansion section, experiencing acceleration. The shock wave generates high pressure, temperature, and density in the accelerated gas. Meanwhile, the previously shocked test gas simultaneously transitions from the driven section to the low-pressure expansion section, undergoing cooling and deceleration. This state of the test gas represents a high Mach number flow at low temperatures. During the time interval between the arrival and departure of this flow in the test section, desired measurements can be performed [16].

3.2 Experimental facility

TS-ETF was designed to reach enthalpy values from 0.5 MJ/kg to 7.4 MJ/kg and Mach number values from 2 to 10. Test setup has five section as driver section, driven section, expansion section, test section and dump tank. The expansion tube features a double-layer metal diaphragm between the driver and the driven sections and a mylar film between the driven and the expansion sections. The test room has dimensions of 30 cm x 30 cm x 30 cm and it has three quartz windows to characterize the flow in test model. Schlieren system is used to visualize shock structure in test model [Figure 15]. This test setup also allows OH PLIF and OH* chemiluminescence measurements thanks to quartz windows at three side of test section.

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Figure 15: SAGE Expansion Tube Test Facility with schlieren setup (1: Light source, 2: Test section, 3: First parabolic mirror, 4: Knife-edge, 5: Camera, 6: Second parabolic mirror).

3.4 Experimental results

3.4.1 Calibration run

In order to calibrate TS-ETF, a double-wedge test article with 20˚ angle is designed and tested with the same filling pressures as Gamba [7]. Oblique shock angle for 2.8 Mach case is visualized with schlieren system and measured shock angles are shown with error bands in Table 6. To show repeatability of the Expansion Tube, 2.8 Mach case is performed for three times. Consistent data is obtained for three test results as Gamba [7].

Table 6: Calibration of SAGE expansion tube

	Test 1	**Test 2**	**Test 3**
Shock Angle [°]	38.75±1.25	38.60±1.30	39.18±1.25
Mach	2.88±0.13	2.89±0.15	2.83±0.13

3.4.1 Cross flow field imaging

To show the consistency of test facilities same operating condition was created in TS-ETF as Stanford Expansion Tube [7]. Schlieren images were acquired for the case of no injection test case in order to identify shock structure within the model. SAGE expansion tube test results have compared with Stanford non-reacting case. When the test is quasi-steady condition, an image was post processed and compared with Stanford test results [7]. Comparison of results are presented in Figures 16 for the case without fuel injection. These results show the first step of our experimental study. We will perform a detailed post process of test images to determine shock location and shock angle.

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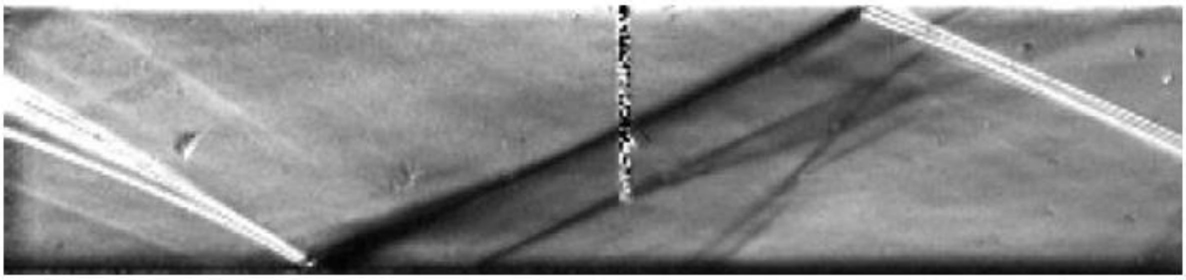
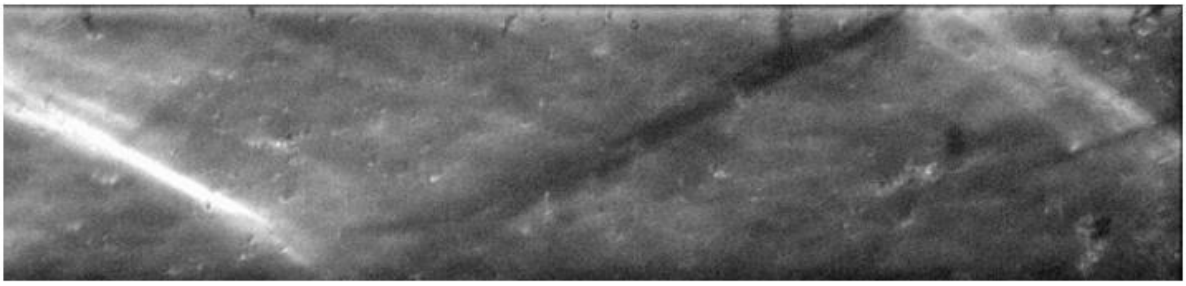


(a) Schlieren Test Results, Stanford [7]



(b) Schlieren Test Results, TS ETF

Figure 16: Comparison of non-reacting schlieren test results (a) Schlieren Test Results, Stanford [7] (b) Schlieren Test Results, TS ETF

4. Conclusion and discussion

In this study, numerical and experimental studies of a scramjet model and calibration of SAGE expansion tube have been presented.

It was obtained consistent results with test data when 5 million elements grid was used in the 2D analysis. Turbulence model study was also conducted with same grid and it was found that the SST k-ω model provided results closer to the test data.

In the 3D analysis, shock angles were calculated by using numerical schlieren images and it was observed that shock angle deviation is in error band limits.

In experimental study, non-reacting case of 2.8 Mach case is performed in SAGE Expansion Tube Facility. Flow field is visualized with schlieren system and results are compared with Stanford test results. It was obtained consistent results as qualitatively.

In future we will study reactive numerical analysis for hydrogen jet transversely injected into an air freestream. We will conduct experimental study with OH PLIF and OH* Chemiluminescence in SAGE Expansion Tube for different momentum flux ratios. Pressure measurements from top wall of the combustor will also be acquired and we will compare the experimental and numerical results to validate the numerical combustion model.

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