

ANALYSIS OF SHOCK WAVE IMPACT ON MIXING RATE OF HYDROGEN GAS

Submitted in partial fulfilment of the requirements for the award of
Bachelor of Engineering degree in
Aeronautical Engineering

By

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SATHYABAMA

**INSTITUTE OF SCIENCE AND TECHNOLOGY
(DEEMED TO BE UNIVERSITY)**

Accredited with grade “A” by NAAC

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BONAFIDE CERTIFICATE

This is to certify that this Project Report is the bonafide work of ARJITH PRAISON (Reg. No. 37260006) and CARTHY E. (Reg. No. 37260008) who carried out the project entitled "**ANALYSIS OF SHOCKWAVE IMPACT ON MIXING RATE OF HYDROGEN GAS**" under our supervision from September 2019 to April 2020.

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SIGNATURE OF THE CANDIDATE

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ABSTRACT

This study is carried out to analyse the mixing rate of hydrogen under the influence of shock waves at supersonic conditions. A right angled triangular shaped shock generator is placed near the inlet to generate shock waves when the incoming flows hit the wedge. Angle of the wedge is varied to produce different shocks and the mixing rate effect of hydrogen was studied for different angles of the shock wave generator. The primary aim of this research work is to perform computational fluid analysis to determine the impact of the shock interaction produced by the presence of the shock generator on the rate of mixing of fuel jets. Hence Mach numbers in the supersonic regime are only considered for this study. The results are compared using the mass fraction of hydrogen for the different angles of wedge. The testing was done for six different models and for the different case conditions the mixing rate of the hydrogen compared. The maximum boundary layer thickness was found to be between the second and the third inlet. The best wedge size is the 9-degree wedge model as for the lesser angles the mixing rate is not much pronounced. The higher degree models have more vorticity and choking effects came into attack. Hence for the efficient mixing rate of hydrogen a 9-degree wedge can be introduced a small distance right above the point when the hydrogen is introduced.

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LIST OF SYMBOLS AND ABBEREVIATIONS

CFD	Computational Fluid Dynamics
M	Mach
θ	Theta – Wedge Angle (Degree)
β	Beta – Shock Angle (Degree)
γ	Gamma (Specific Heat Ratio)
SST	Menter’s Shear Pressure Transport (SST)
SWG	Shock Wave Generator
MJs	Microwave Jets
VOF	Volume of Fluid
ρ	Density (kg/m ³)
ω	Omega – Turbulent Kinetic Energy (m ² /s ²)
Pa	Pascal

CHAPTER 1

INTRODUCTION

1.1 EXISTING MODELS

There are many models that are presently used to generate shock waves. A shock wave is usually generated to get improved pressure and other parametric performance. A few of the existing models that are utilized to artificially generate shock waves are considered and listed below.

1.1.1 Wedge Model

A wedge is a triangular body as shown in Fig 1.1 which is sharp at one end and it causes the supersonic flow to generate a shock wave. The wedge when passed through gas, the molecules are deflected around the object. If the object is travelling at a speed higher than that of the supersonic flow, then the density remains constant.

A shock wave is generated when the Mach number of the supersonic stream is considerably high enough and the wedge angle is considerably low enough. An oblique shock wave is usually generated when the above conditions are met and the shock is usually attached to the sharp leading edge of the wedge. The resulting Mach is usually greater than that of the inlet Mach of the supersonic flow. Even the pressure ratio is drastically increased by the influence of these wedge models.

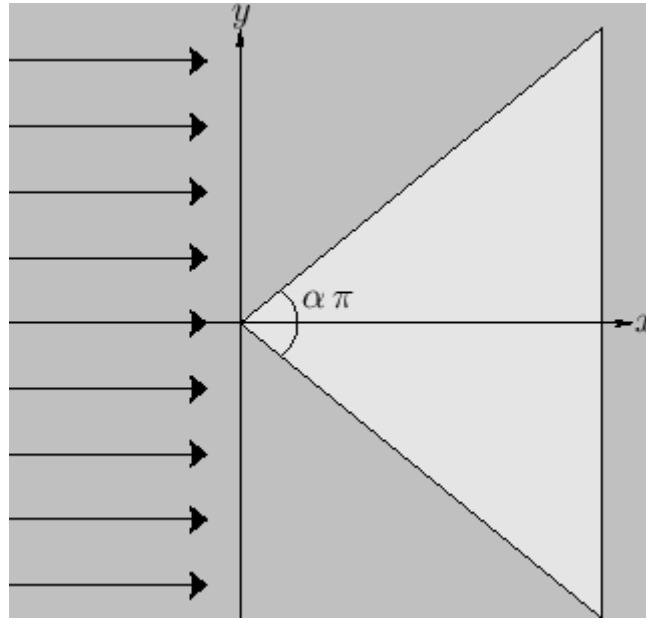


Fig 1.1 Single Wedge Model

There are two basic types of wedge which are currently being in use and they are

1. Single Body Wedge
2. Double Body Wedge

1.1.1.1 Single Body Wedge

In this type of body only a single wedge is placed in front of a supersonic flow mostly a single oblique shock is produced in this type. The front body is usually a very sharp body placed normal to the flow as shown in Fig 1.2

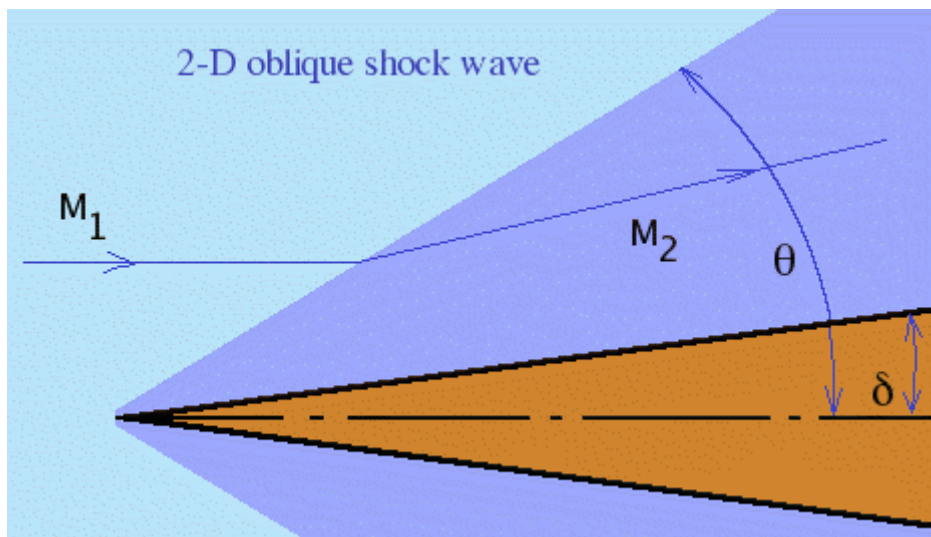


Fig 1.2 Shock on a Single Wedge Model

1.1.1.2 Double Body Wedge

In this type of model, a double wedge placed with two adjacently placed wedge as shown in this figure and this model produces two oblique shock waves and one expansion fan as shown in the Figure 1.3

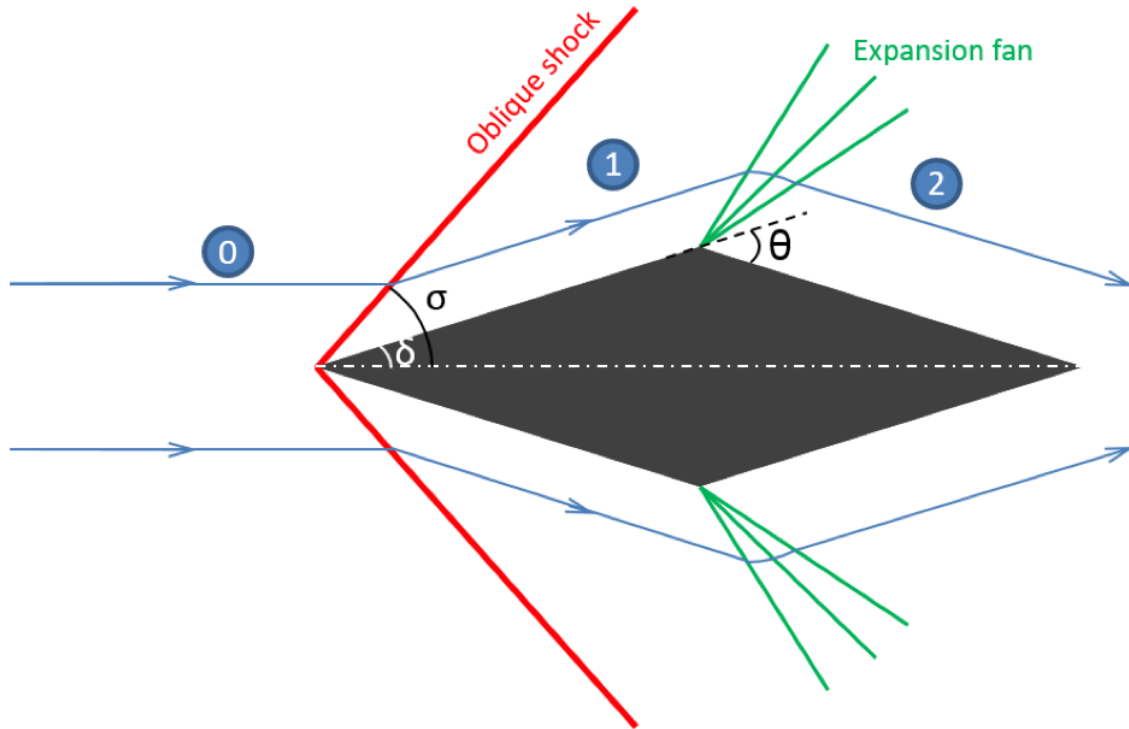


Fig 1.3 Double Wedge Model

1.1.2 Sinusoidal Model

Another model that is currently in investigation for visualization of shock wave is the sinusoidal model as shown in Figure 1.4 where the amplitude of the sinusoidal wave is changed and correspondingly the shock wave generated also gets varied. There had been many such models which are used in the field of Computational Fluid Dynamics research of the shockwaves. The produced shock waves yield a bow shock which is comparatively lesser than that of the oblique and normal shock waves which are generated by the wedge models. The bow shock generated using the sinusoidal model also have different impact and the intensity of these shock wave can be controlled by varying the amplitude of the sine wave.

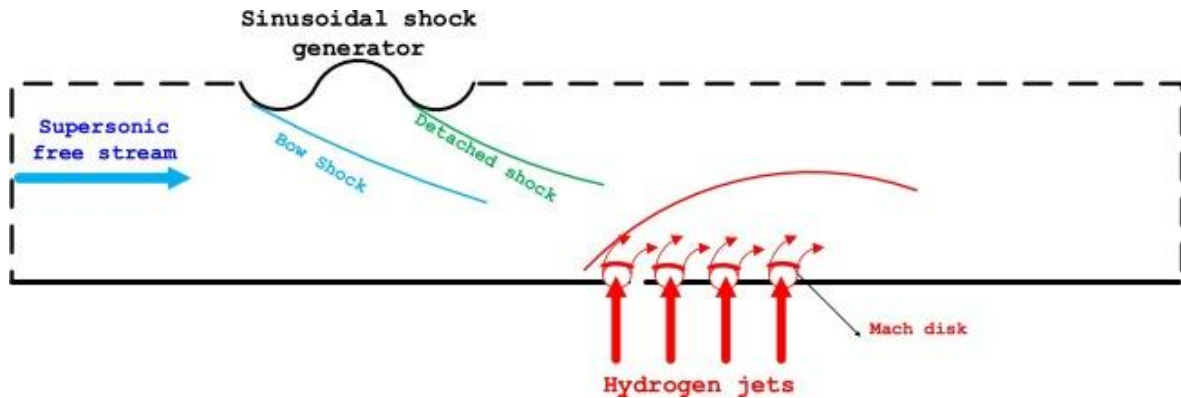


Fig 1.4 Sinusoidal Wedge Model

1.2 SHOCK WAVE

Shock waves are the waves that travel greater than the speed of waves in the medium of supersonic regime. Shock waves are strong pressure waves. Shock waves occur when the velocity of an objects exceeds the speed of sound. Shock waves are discontinuous waves which are propagating disturbance in the supersonic flow. The characteristics of shock waves are change in temperature, velocity and density. Shock waves can also be in the form of compression waves or expansion waves. Shock waves are responsible for creating drag forces in the supersonic regime. Shock waves are considered to be strongly irreversible process. The amplitude of the speed of shock waves varies with the speed of sound waves comparatively. If the normal speed of an object equals to speed of shock waves then it reduces to normal sound waves. At supersonic regime the shock wave which forms over an object will be a cone shaped and form a overlapping of spherical wavefront.

1.2.1 Normal Shock Wave

These are the kind of shock waves which produces shocks normal to the air flow direction as shown in Figure 1.5. If the incoming airflow turned by a large angle or large amount the shock waves occur in front of the supersonic body and it cannot remain attached to the object. The normal shock waves occur in most of the supersonic regime. At this supersonic regime the velocity or Mach number of the shock wave decreases whereas the pressure and density increase.

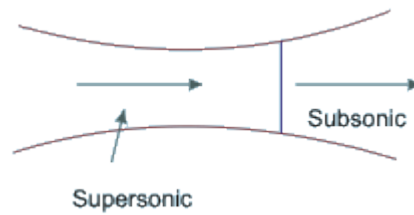


Fig 1.5 Normal Shock

1.2.2 Bow Shock Wave

These are the shock waves with large angle and its referred as detached shock waves or otherwise normal shock waves. These shock waves occur when there is a high deflection in the flow direction as shown in Figure 1.6. This shock wave follows a curved path which has disturbance in the air flow. This shock waves occur over the body in the supersonic regime. This shock wave decreases the velocity of the flow from supersonic to the velocity of the subsonic regime. When the shocks occur, there will be a significant increase in the drag of the body.

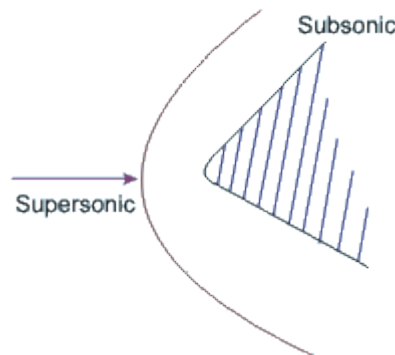


Fig 1.6 Bow Shock

1.2.3 Oblique Shock Wave

These are the inclined shock waves with at some angle as shown in Figure 1.7. The direction of the inclined shock waves depends on the shape of the object and speed of the object. A ramp or wedge with a sharp edge turns the incoming flow into the duct effectively and compress it and uses its high pressurized gas and high-density gas to compress the gas inside the duct. The possibility of having heavy drag in the object is comparatively less compared to the other types shock waves.

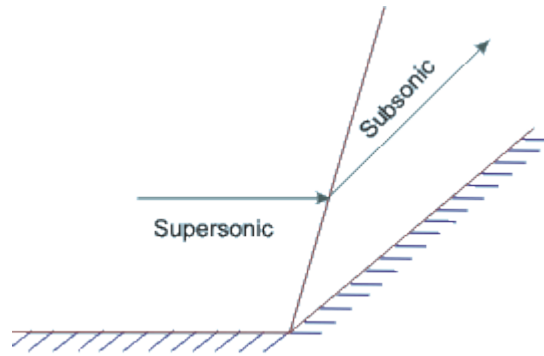


Fig 1.7 Oblique Shock

1.2.4 Mach Number

Mach number is parameter which plays an important role when it comes solve or to get better understandings of shock waves. Mach number does not have any units it's a dimensionless quantity. It helps us to define the flying object regime at various compressibility effects. It is the ratio of local velocity of an object to the speed of sound in the medium. Mach number indicates the Mach regimes of a flying object at different types.

1.2.5 Classification of Mach Regimes

Table 1.1 Classification of Mach Regimes

Mach Number	Less than 0.8	0.8 to 1.2	Equals to 1.0	1.0 to 5.0	5.0 to 10	Greater than 10
Condition	Subsonic	Transonic	Sonic	supersonic	Hyper sonic	High hyper sonic

1.2.5.1 Subsonic

Subsonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is very much less than the velocity of sound. It is the region where the Mach number of the flying object is less than 0.8 as shown in Table 1.1. The range of Subsonic speeds are less than 530 knots and in terms of mph it is less than 605 mph and less than 980 km/hr and less than 273 m/s. Since it is very much less than $M \ll 1$, the compressibility effects are negligible and the

density of air remains constant for this subsonic speed. Propeller driven aircrafts and commercial turbofan will mostly fly in this regime at low speeds. At this low speeds, propeller driven aircrafts are more efficient. The subsonic aircraft wings are mostly rectangular in planform.

1.2.5.2 Transonic

Subsonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is more or less equal to equal to the velocity of sound. It is the region where the Mach number of the flying object lies between 0.8 to 1.2 as shown in Table 1.1. The range of transonic speeds are lie between 530 to 784 knots and in terms of mph it lies between 605 to 914 mph and lies between 980 to 1470 km/hr and it lies between 273 to 409 m/s. At this region the speed of a flying object that generates the regions of both subsonic and supersonic regimes. At transonic region the object will experience strong shock waves where the velocity of an object depends on the critical Mach number, so that it starts experiencing instability around an object. At this region the drag force and wave drag increases abruptly by causing a large separation in the airflow.

1.2.5.3 Sonic

Subsonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is equal to the velocity of sound. It is the region where the Mach number of the flying object is equal to 1 as shown in Table 1.1. At this sonic regime, the supersonic expansion waves fan produces immense total pressure and temperature around an object at various points. At this regime the aircraft engine will begin chocking at throat, where the flow stops at some point or experience resistant force it mostly occurs in convergent – divergent nozzle. At this regime the drag force increases greatly and lift decreases at a given altitude. The shock wave characteristics differs radically from the subsonic levels

1.2.5.4 Supersonic

Supersonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is higher than the velocity of sound. It is the

region where the Mach number of the flying object is greater than one and lies between 1 to 5.0 as shown in Table 1.1. The range of Subsonic speed lies between 794 to 530 knots and in terms of mph it lies between 915 to 3806 and lies between 1740 to 6126 km/hr and lies between 410 to 1702 m/s.

1.2.5.5 Hypersonic

Hypersonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is very much higher than the velocity of sound. It is the region where the Mach number of the flying object is greater than five and lies between 5 to 10.02 as shown in Table 1.1. The range of Subsonic speed lies between 3308 to 6615 knots and in terms of mph it lies between 3806 to 7680 and lies between 6126 to 12251 km/hr and lies between 1702 to 3403 m/s.

1.2.5.6 High-hyper sonic

High-Hypersonic is one the Mach regimes which is mentioned above in the table. At this regime the velocity of an object is very much higher than the velocity of sound. It is the region where the Mach number of the flying object is greater than ten and lies between 10 to 25.0 as shown in Table 1.1. The range of Subsonic speed lies between 6615 to 16537 knots and in terms of mph it lies between 7680 to 19031 and lies between 12251 to 30626 km/hr and lies between 3403 to 8508 m/s. At this regime, the flow has high temperature.

1.3 SHOCK WAVE CHARACTERISTICS

When the shock waves occur, there will be a drop in velocity or Mach number of the object whereas there will be a significant increase in pressure, density and temperature of the object. The upstream static pressure of an object will be lower than the downstream static pressure. The upstream static density will be lower than the downstream static density. The upstream static temperature will be lower than the downstream static temperature. The upstream total pressure will be greater than the downstream total pressure. The upstream total temperature will be equal to the downstream total temperature. The upstream total density will be lower than the upstream total density

1.4 SHOCK WAVE INVESTIGATIONS

In the last fifty years there had been works of research on the shock wave boundary layer effects and their interactions. There had been a wide and debated research survey work that is presently being carried out in this field the knowledge of understanding the effects and interactions of these shock waves play a mighty role on the understanding and has further applications in this domain. A few of the applications of these are

- a) The general features of these waves can be analysed
- b) Different cross section of the test section can be tested for the boundary layer interaction
- c) The source of these waves can be found out
- d) Thermal related studies can be carried out
- e) shock waves' controlling capacities can be carried out

1.4.1 Shock waves Applications

1. Reflection of a shock wave is employed to get rid of micrometre size dirt particles from the surface of semiconductor wafers.
2. Shock waves are employed in medical aid in medical science and for breaking excretory organs.
3. Shock waves are employed in pencil industries to impregnate preservatives into wood slats.
4. Shock waves are employed in cell transformation.
5. Shock waves are employed in geophysical science.
6. Shock waves are employed in shoe oil extraction

1.5 MATHEMATICAL EQUATIONS GOVERNING SHOCK WAVES

The mathematical equations have been framed to calculate the Mach waves and its relations as shown in Figure 1.8. Oblique shockwave relation already has an existing formula given below, variable shock angle, wedge angle, inlet Mach are taken. According to these data's formula is structured reversed we give that and beta to find the Mach angle, data contains everything, to which theta which Mach, generate formula in the table.

$$\tan(\theta) = 2 \cdot \frac{1}{\tan(\beta)} \cdot \frac{M_1^2 \cdot \sin(\beta)^2 - 1}{M_1^2 \cdot (\gamma + \cos(\beta)^2) + 2}$$

Fig 1.8 Oblique Shock Wave Relation

Θ = Mach angle

β= Shock angle

γ= Heat capacity ratio

M₁= Inlet Mach number

1.6 FUELS USED IN AVIATION

Aviation fuels are made from petroleum-based products or petroleum or blends of synthetic fuel to power aircrafts. JP-8 and Jet A-1 are the commonly used aviation fuels and they are kerosene-based fuels used to power Gas turbine powered aircrafts. The aviation fuels must have certain fuel parameters to perform well such as low viscosity or low density.

1.6.1 Jet fuels

Jet fuels are kerosene-based fuels namely Jet A-1 or JP-8 which can also be used as fuel in compression ignition engines or gas turbines. These fuels are used in propeller aircraft, gas turbines and helicopters. Modern commercial airliners use Jet A to power aircrafts and it is a mixture of extremely refined kerosene and burns at the temperature of 49 degree Celsius, the flash point of the kerosene-based fuels have higher than the petroleum-based fuels which implies it requires high temperature to ignite it, the characteristics and performance makes it high quality fuel to use in modern aviation. Jet fuels have low viscosity at low temperature, they have limited ranges of density and calorific values and burn cleanly and remain chemically stable when heated to high temperature.

1.6.2 Hydrogen Gas

Hydrogen gas can also be used as jet aviation fuel because of its good performance and its three times efficient than the normal jet fuels in terms of energy-density-per-unit mass, because of the burning properties and molecular structure it is an efficient alternative fuel. Hydrogen gas can be used in gas turbines and helicopters even in internal combustion engine. The emission characteristics of hydrogen gas as fuel are very much lesser than others. Density of hydrogen is very much lesser than the actual aviation fuel such as Jet fuels. While hydrogen combustion the gaseous hydrogen is burned in a recreated gas turbine engine to produce thrust. Hydrogen has a wide flammability range as wide range of fuel-air mixtures. Hydrogen fuels can also provide motive powers to liquid-propellant rocket and in trains, aircrafts and in boats also.

1.7 MIXING RATE

Mixing rate of the fuel is the air-fuel ratio of the air and the fuel and it is the mass ratio of air to a gaseous fuel in a combustion process. The air-fuel ratio finds whether the fuel is combustible, how much energy is being released during the combustion process and it also determines how much wanted things are produced in the reaction. The ratio is called as Stoichiometric mixture if the enough air is provided to burn completely all the fuel. The air-fuel ratio lower than stoichiometric ratio are considered as 'rich' and the ratio higher than the stoichiometric are considered as 'lean', these lean mixtures are more efficient but which may cause high temperature and it leads to forming nitrogen oxides.

CHAPTER 2

LITERATURE SURVEY

J.E Green (1970) This audit is worried about the liquid mechanics of the connection between a shock wave and a tempestuous limit layer at speeds going from transonic to high supersonic. Our current comprehension of the designs of the different types of this collaboration is illustrated, and our capacity to foresee different highlights of the connection is evaluated. In passing, some potentially productive roads for additional exploration are shown.

Murakami.M (1987) In this paper the self-comparative arrangement, steadiness of circular meeting shock wave is contemplated. A thorough direct irritation hypothesis is created, in which the development pace of bother is given as an element of the round symphonies number ℓ and the particular warms proportion γ . Mathematical computation uncovers the presence of a γ -subordinate cut-off mode number ℓ_c , with the end goal that all the Eigen mode irritations for $\ell > \ell_c$ are spread out as the shock wave merges at the middle. The investigation is applied to halfway round calculations to give huge ramifications for various start plans of inertial restriction combination. Two-dimensional hydrodynamic re-enactments are performed to confirm the hypothesis.

J. Keller (1990) Analysed the interaction of normal shock wave with a compressible turbulent flow. They used a speckle photographic method to analyse a compressible flow with various density variations. spot photographic strategy, which is touchy to changes of slopes in liquid thickness, is applied for breaking down a compressible fierce wind current with thickness vacillations. Spatial connection coefficients, fierce length scales, and energy spectra are resolved under the supposition of homogeneous isotropic choppiness. The trials are acted in a stun tube where the stream is gone through a disturbance lattice. Estimations are taken when the tempestuous system cooperates with the typical stun wave reflected from the cylinder's end divider. Enhancement of the choppiness power by the shock waves

communication measure is checked quantitatively and is demonstrated to be confined to the lower wave numbers in the range.

K. Takayama (1994) In this research papers, some direct comparisons have been made for several occurrences of oblique shock waves reflections. The sequences of mathematical calculations evaluated to assess the utility of the present numerical method in constructing the reflection-transition of shock waves lines, wedge –point and Mach number for inviscid flows for various conditions. A hyper speed shock tube and mathematical outcomes got by utilizing a current computational strategy for settling the Euler conditions.

G.A Bird (2005) this paper talks about the investigation of typical shock waves through theoretical calculation with a recreated gas on a computerized PC is stretched out to paired gas blends. The blend is recreated by two arrangements of unbending flexible circle particles with the proper mass and breadth proportion. however, there is no underlying speed increase of the argon in blends containing a little beginning mole part of this gas. The temperature profiles are like those for the speed in that the argon profile lingers behind the helium profile. Nonetheless, when there is a little extent of weighty gas, the profiles get over and the temperature of the substantial gas overshoots the Rankine-Hugoniot downstream worth. For solid shock waves, the general stun thickness communicated in upstream mean freeways expands, however the profiles are for the most part like those for the medium strength waves.

Datta Gaitonde (2015) Ongoing advances in shock wave limit layer communication research are evaluated in four zones: (i) seeing low recurrence instability, (ii) heat move expectation capacity, (iii) marvels in complex (multi-shock limit layer) collaborations and (iv) stream control strategies. Generous achievement has been accomplished in portraying the phenomenology of low recurrence insecurity, remembering connections and lucid designs for the detachment bubble, through integral exploratory and mathematical investigations on 2-D collaborations. These perceptions have been parlayed to propose basic instruments dependent on swaying, enhancement and upstream limit layer impacts. For heat move

expectation ability, efficient examinations directed under the support of AFOSR and RTO-AVT exercises have shown that for axisymmetric laminar circumstances, heat move rates can be estimated, and as a rule anticipated, sensibly precisely even within the sight of high-temperature impacts. Progress in complex associations envelop two of the significant marvels influenced by SBLI in scramjet flow paths: unstart and mode change from ramjet (double mode) to scramjet. Control examines have endeavoured to use the better comprehension of the central wonders with latent and dynamic methods, the last abusing the predominant properties of fresher actuators. Targets remember decrease for size of the partition area. At long last, SBLI contemplates have profited liberally from fruitful ground and flight test crusades related with the HIFiRE-1 and HIFiRE-2 missions, results from which are woven into the conversation, as are restrictions in current ability and comprehension.

Wei Huang (2016) The mixing and combustion method plays a crucial role within the realization of the scramjet engine, and also the crosswise injection from a wall passageway is wide used for the only and most promising of its configurations. within the current survey, the analysis progress on the crosswise jet in supersonic crossflows has been summarized consistently from four aspects, specifically single injection, multiport injection, interaction between jet and vortex generator, and interaction between jet and wave, and also the fundamental principle of the crosswise injection has been provided in addition. At last, some promising recommendations are planned, specifically the refined vortex structure capture, the blending and combustion method within the novel appliance and multiport flow fields, particularly with the incident wave interaction, and also the combinatorial operative and optimisation method between the fuel injection system and also the vortex generator.

A.Anazadehsayeda (2017) Investigated the transverse hydrogen jet by injecting micro air jets in supersonic crossflow to improve mixing rate. A three-dimensional mathematical simulation has been performed to determine the effects of miniature air fly on blending of the hydrogen stream in a Mach 4.0 crossflow with a equal

proportion of 0.5. Navier–Stokes equations were used in this paper to find the flow properties at different air stream conditions up conditions with Menter's Shear Pressure Transport (SST) choppiness model. While at the mixing rate they have Complex stream collaborations were found in the downstream locale with an assortment of stream highlights relying on the point of miniature air fly. As per the outcomes, without air, blending happens at a low rate. At the point when the air fly is introduced in the downstream of fuel stream, huge increment (up to 300%) happens in the blending execution of the hydrogen fly at downstream. In multi fuel streams, the blending execution of the fuel fly is expanded over 200% when the miniature air fly is infused.

Wei Peng (2017) has done thermal analysis on the shock wave. The wedge geometry used in this section is a one similar to the one that had been used by our research. In this paper he has measured and visualized the thin film cooling of the hydrogen by giving hydrogen in an inlet and the air in another inlet, the main purpose of this paper is to estimate the effect of shock wave on the thin film cooling, the basic geometry of this research work is taken as the reference for our cross-sectional model as well.

Lang-quan Li (2018) In this research paper they investigated the transverse hydrogen flow with the micro ramp located at the upstream wall. They have considered four design variables width, length and height of the micro ramp and the distance between the orifice wall centre and the trailing point of the micro ramp. In this paper we learnt three optimizations, the mixing length has been minimized and the penetration length has been maximized and the stagnation pressure loss had been minimized by the end of the experiment they laid an optimal strategy for ramp in the supersonic combustor.

Sang- Hyeon Lee (2018). In this paper, the cross over hydrogen infusion stream field with a miniature slope found upstream of the divider hole has been examined mathematically dependent on the code approval. There are four plan factors considered in the current investigation, in particular the width, length, and tallness

of the miniature incline and the distance between the focal point of the divider hole and the following mark of the miniature slope. Three streamlining cases are gotten, and they have various destinations, to be specific the minimization of the blending length, the amplification of the infiltration profundity and the minimization of the stagnation pressure misfortunes. The stream designs of all cases have been talked about and analysed. The quantitative assessment aftereffects of three advancement cases show that the extraordinary distinction investigation approach is a proficient parametric examination technique, and it can get the ideal procedure for the miniature incline inside scramjet combustors.

Marta Zocca (2019) They did an experimental study on observing shock waves in non-ideal flows. The diamond-shaped aerofoil is placed in the test section to find oblique shock waves for various stagnation conditions of shock state. With respect to the wind tunnel dimensions the flow deviation angles are obtained by changing the altitude and model. They have used Schlieren visualization to get the direct measurements of the Mach number of the flow. The experimental result matches with the theoretical values of two-dimensional analysis. The measurements dependent on non-ideal pressure ratio across the stagnation condition and also dependent on pre-shock Mach numbers, specific ratios and flow deviation angle at various conditions.

Yicheng Li (2019) did the research analysis work on the very same topic of mixing rate of hydrogen under the influence of sinusoidal shock wave generator. This was taken as the base paper for this research work. The inlet Mach was considered to be of that of Mach 4 in the inlet a geometry of similar cross section is chosen with the length of the section to be much longer than that of the height of the cross section. The mixing rate was calculated using the different mass fraction by varying the amplitude of the sinusoidal wave and comparing its impact on the mixing rate by comparing the mass fraction of the hydrogen gas. The same inlet and physics conditions that was used by Yicheng Li was considered even for our research work and the results are compared.

Li Yan (2020) analysed the boundary layer interaction in the presence of a recirculation jet in the presence of a supersonic flow, this research work evaluated numerically the boundary layer interaction with the introduction of a recirculation jet. In this approach the boundary layer bleed and the flow has been sucked and the flow control efficiency have been analysed in detail. The secondary shock wave system is also introduced and the mixing augmentation of the fuel seem to be more than that of the default conditions the fuel. The dimensions of the bleed and suction slots have only a slight impact on the recirculation and the interaction on the mixing rate of the hydrogen gas.

Bin An (2021) This paper is all about enhancing the flame stabilization in supersonic combustor by injection micro jets. They have used micro jet exhibit and traditional shock wave generator to enhance the chemical reaction in supersonic combustion. The combustor was powered by hydrogen and kerosene. The recirculation flow was essential to stabilize the flame at the strut base. The additional shock waves added by MJs and SWGs to expand the envelope of the combustor. The introduced shock waves effectively enlarged recirculation chemical reaction. Comparing to SWGs, MJs have the potential to provide a proper flame stabilization.

G. Degrez This paper introduced the oblique shock wave/laminar limit layer connection. The Mach number was 2.15, the Reynolds number was 105 and the general pressing factor proportion was 1.55. The interaction has been shown to be laminar and ostensibly two-dimensional. Test results incorporate pressing factor conveyances on the plate and single segment Laser-Doppler velocimetry speed estimations both in the appended and isolated regions. The mathematical outcomes have been acquired by settling the full compressible Navier-Stokes conditions with the verifiable inexact factorization calculated.

CHAPTER 3

AIM AND SCOPE OF THE PRESENT INVESTIGATION

3.1 AIM

This research is aimed to analyse the mixing rate of hydrogen at different inlets in the presence of a shock wave generator. The wedge angle has been varied and hence the intensity of the shock wave varies and correspondingly it's impact on the mixing rate is studied.

3.1.1 Operating Conditions

A set of 6 different Wedge angle has been chosen and their operating conditions i.e., the Upstream Mach number, Downstream Mach number, Oblique shock wave angle and static pressure ratio.

The following table 3.2 lists all these values

Table 3.1 Data for Different Models

S.No	Wedge angle	Upstream Mach number	Downstream Mach number	Oblique shock wave angle	Static pressure ratio
1	5 degree	4	3.63825	18.0212	1.61992
2	7 degree	4	3.49756	19.6287	1.93976
3	9 degree	4	3.35689	21.3400	2.30525
4	10 degree	4	3.28605	22.2341	2.50604
5	12 degree	4	3.14393	24.0949	2.94447

S.No	Wedge angle	Upstream Mach number	Downstream Mach number	Oblique shock wave angle	Static pressure ratio
6	15 degree	4	2.92906	27.0626	3.69720

3.2 DATA PLOTS

3.2.1 Models vs Downstream Mach Number

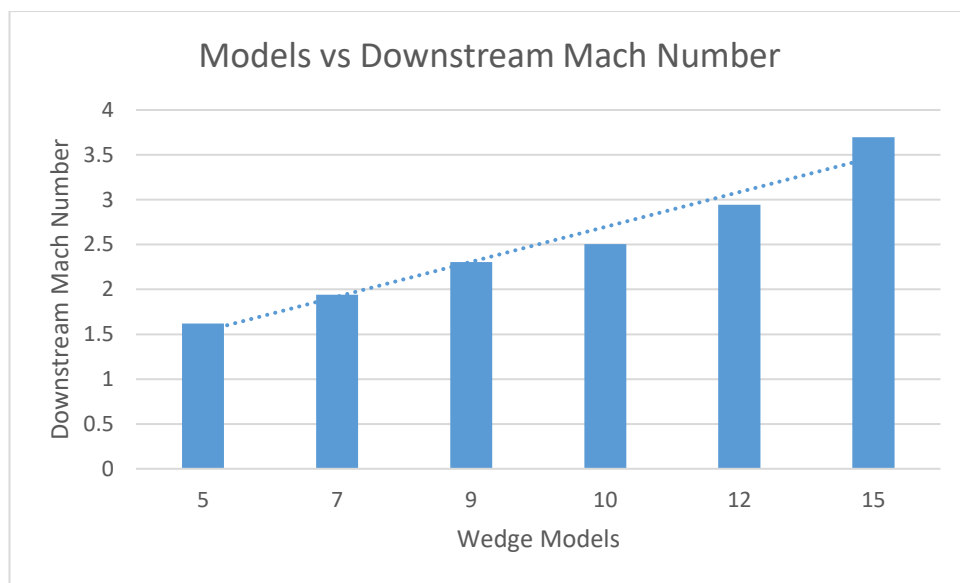


Fig 3.1 Plot between Models and their Downstream Mach Number

This figure 3.1 shows the how the Oblique shock wave angle varies for the respective wedge models. There is a progressive change in the oblique shock wave angle.

3.2.2 Models vs Oblique Shock Wave

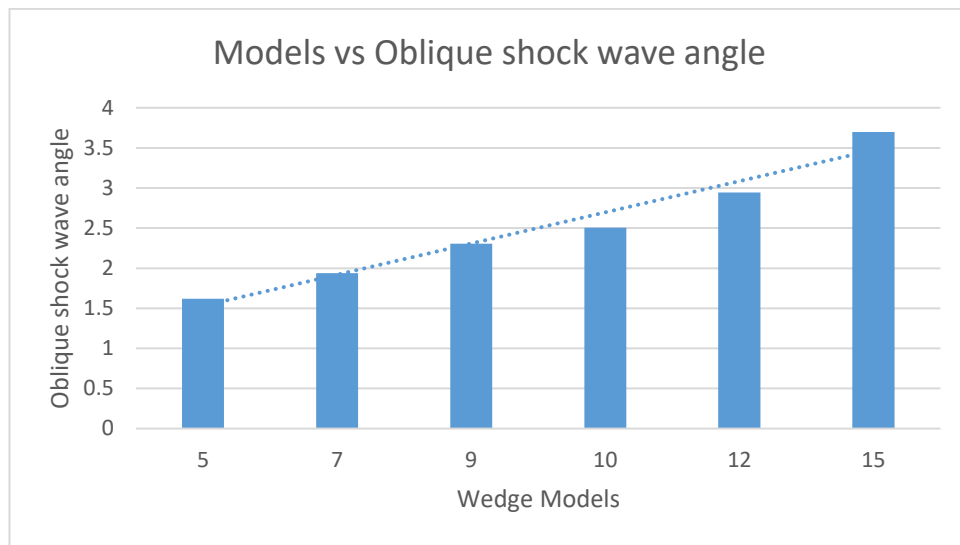


Fig 3.2 Plot between Models and Oblique Shock Wave Angle

This figure 3.2 shows the how the Oblique shock wave angle varies for the respective wedge models. There is a progressive change in the oblique shock wave angle.

3.2.3 Models vs Static Pressure Ratio

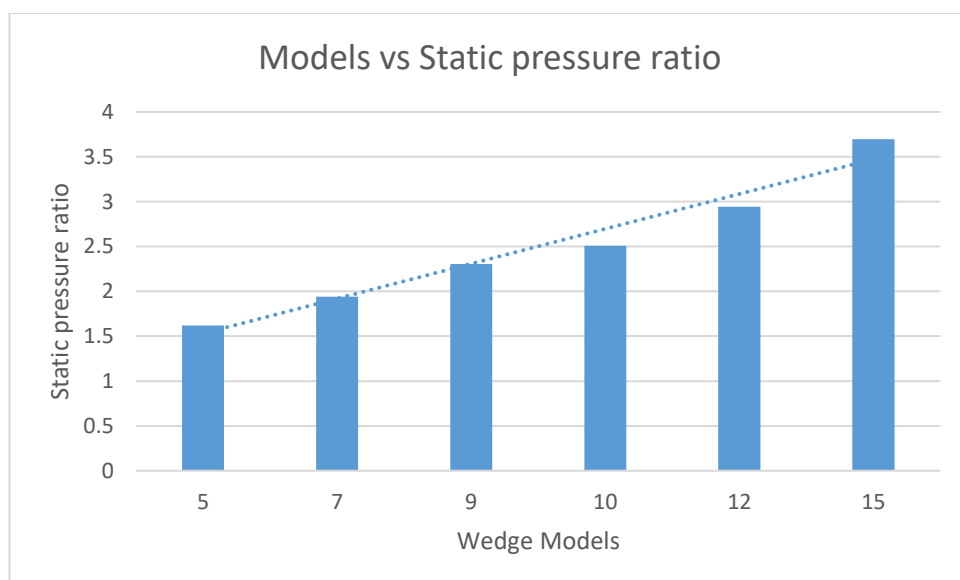


Fig 3.3 Plot between Models and Static Pressure Ratio

This figure 3.3 shows the how the static pressure ratio varies for the respective wedge models. There is a progressive change in the static pressure ratio.

3.3 PRESENT INVESTIGATION

Currently there are quite a number of research work going on understanding the impact of the boundary layer interactions of the shock wave. A similar research work has been carried out in the presence of a sinusoidal shock wave generator where the amplitude was varied and their corresponding impact on the mixing rate was studied.

3.4 FUTURE SCOPE OF THIS WORK

This research works lays down a framework on understanding and studying the impact of shock wave on the mixing rate of hydrogen gas. This basic work can be used to enhance performance of the hydrogen gas.

CHAPTER 4

EXPERIMENTAL SETUP

4.1 MODEL

After consideration of different shock wave models the optimum model which generates the maximum shock waves. The shock waves of higher intensity according to many studies was the wedge-based shock wave and hence such a model was considered for our experiment as shown in Figure 4.1, 4.2 and 4.3.

This model was chosen after considering two similar research papers. The long channel enables the flow to be more streamline and steady.

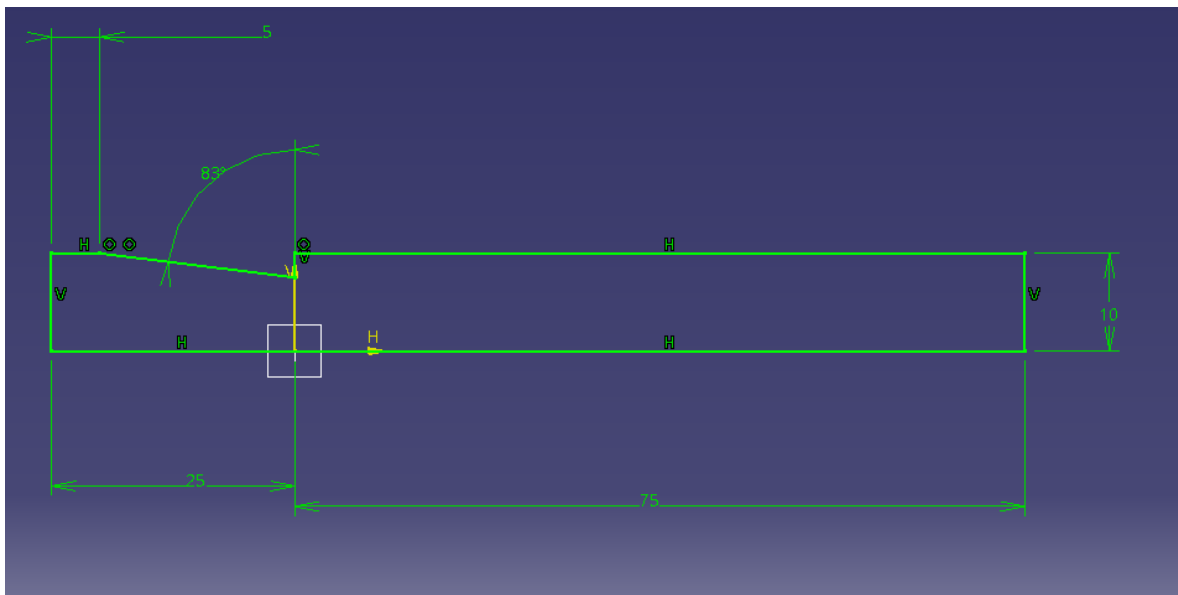


Fig 4.1 CAD Sketch

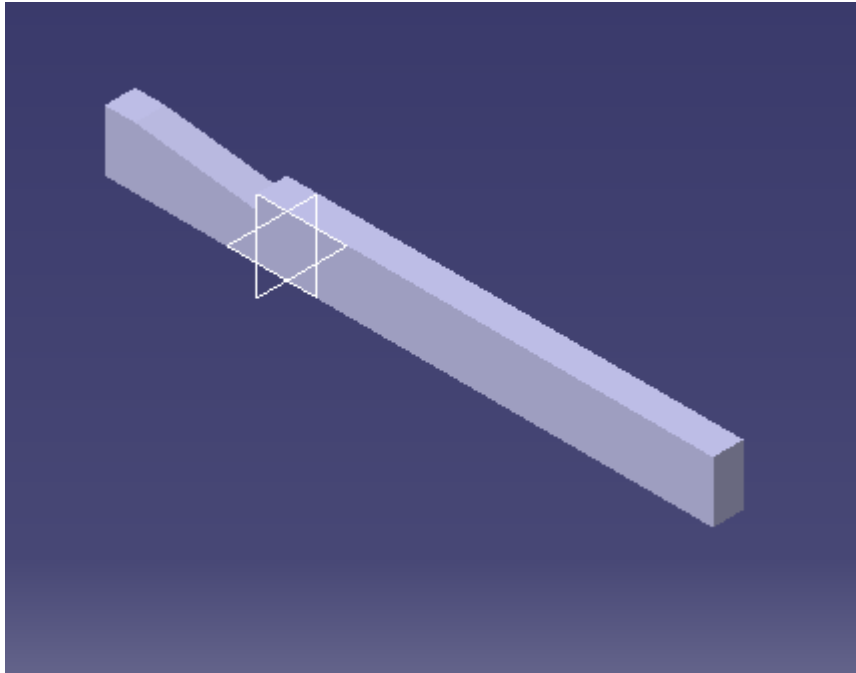


Fig 4.2 3D Model

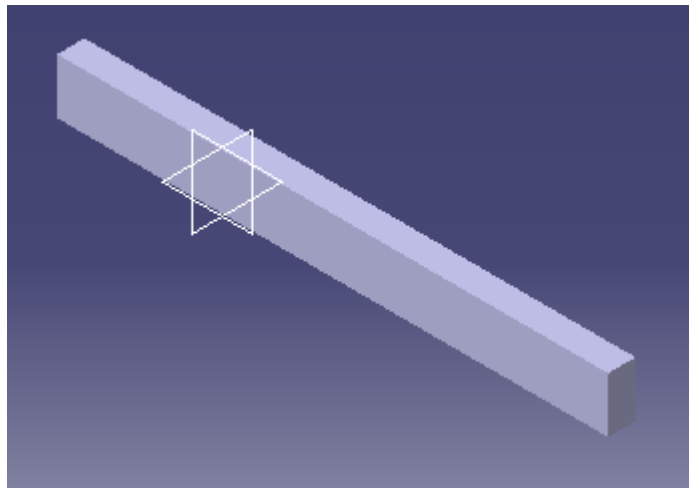


Fig 4.3 Model for comparison

4.1.1 Parameters Varied

The model was a long channel with the inlet given at a higher Mach from the left extreme and the outlet placed at a larger length when compared to the width of the model. The angle of the wedge was varied. The list of the angles of wedges that were considered are

1. 5 Degree
2. 7 Degree
3. 9 Degree

4. 10 Degree
5. 12 Degree
6. 15 Degree

4.1.2 Hydrogen Inlet

The hydrogen was given in through four inlet of diameter 2.5mm evenly spaced and the inlet was placed at the same location where the wedge was introduced to get the shock wave to make sure to utilize the maximum potential of the shock wave and to evaluate the impact of that on the mixing rate and other factors of the hydrogen gas as shown in Figure 4.4

For the Hydrogen gas, a subsonic velocity was given in order to avoid choking of the supersonic inlet stream and this flow, the hydrogen flow was a constant density flow.

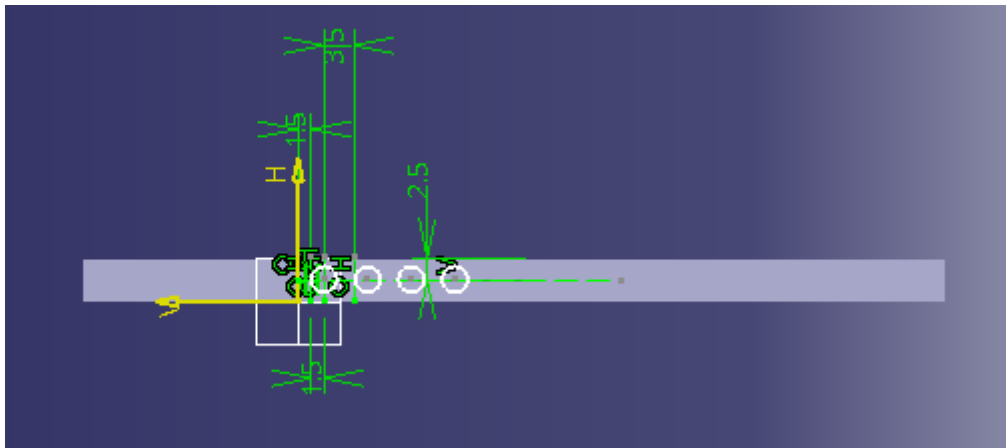


Fig 4.4 Hydrogen Inlet at the bottom

4.1.3 Model Dimensions

The whole channel was of the length was 100mm and the length of other things are given in detail in Table 4.1.

Table 4.1 Model Dimensions

S.No		
S.No	Inlet Position	X = - 25mm
1	Outlet	X = 75mm
2	Wedge Slope Starting Point	X = 10mm
3	First Hydrogen Inlet	X= 1.5mm

	Distance Between two hydrogen Inlets	$X = 2\text{mm}$
	Radius of a Hydrogen Inlet	$X = 1.5\text{mm}$

The wedge model dimensions were chosen with from a earlier research work carried in investigation of recirculation of jet and the overall geometry was taken from a research involving the analysis of mixing rate of hydrogen in the presence of sinusoidal shock generator.

4.2 Mesh

Meshing is the process of breaking down the geometry into finer particles and the finer the mesh is the better will be the Computational Fluid Dynamics Results will be hence the following meshing models were considered for the meshing to be finer

1. Surface Remesher
2. Polyhedral Mesher
3. Surface Wrapper

The finer and smaller the mesh size will be they better they can be used as discrete local approximations of the larger domain. However, due to hardware limitations, time constraints and software limitations the meshing base size was chosen to be $4.0\text{E-}4\text{ m}$.

A surface mesher was chosen for this geometry because it triangulates the surface according to the required length and the geometry is made up of many surfaces hence this model was opted for. In addition, this also provides a higher quality of discretized mesh for the solver

A surface wrapper is also chosen to provide a closed and manifold surface mesh and is hence suitable for a geometry like this as shown in Fig 4.5.

The meshing process is one of the most critical process in the whole computational fluid dynamics analysis. There are certain parameters which define a mesh to be a good mesh

- **Shape and Size of the domain:** The domain is the region in which the equation and the problem statement are solved.

- **Discretization:** In simple terms, this means the spacing between each point in the solution space
- **Domain Boundaries:** During the solver set up we need to define the boundary setup as well.

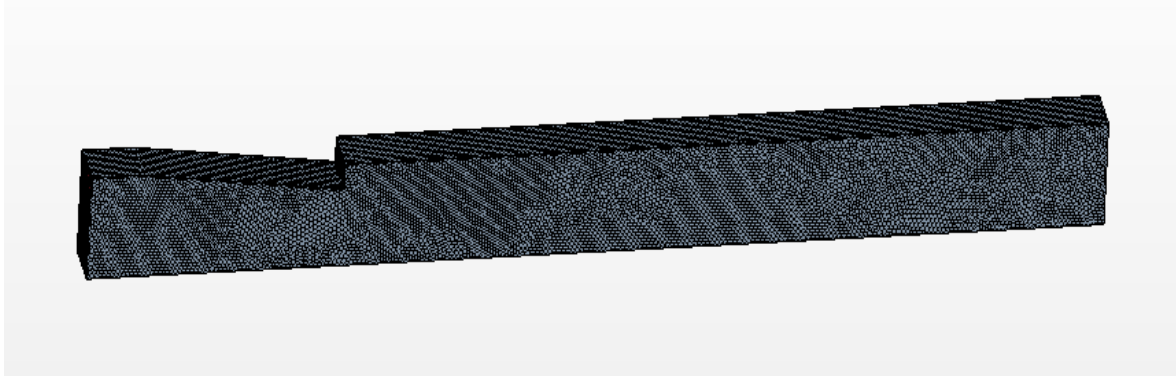


Fig 4.5 Meshed Model

4.2.1 Automatic Surface Repair Parameters

As the name suggests these parameters are given to govern the Machine to give proper parameters to be performed under automatic surface repairs. A overview of the list of the functions given bellow are discussed with their meanings and their values.

4.2.1.1 CAD Projection

The Computer aided design files were design in a different designing software and were brought into the Simulation software and the CAD model was made to project to the original CAD files.

4.2.1.2 Surface Curvature

The curvature is the amount by which a curve is different from a straight line. A surface curvature is the measurement of how much curved a surface is compared to a linear model.

The following Table 4.2 gives a value of list of Surface Curvature values given during the meshing

Table 4.2 Surface Curvature Values

Enable Curvature Deviation Distance	False
Points/Circle Ratio	36
Maximum Points per Circle	200
Curvature Deviation Distance	0.01m

4.2.1.3 Surface Growth Rate

Surface growth rate refers to the maximum rate to which a meshed cell can grow with respect to the next cell. The value of the Surface Growth Rate is given to be 1.3, so that means that if the size of one cell is 0.0004m the size of the next cell adjacent or its nearest neighbour at maximum will be 0.00052m.

4.2.1.4 Surface Proximity

The following table lists the details of the surface proximity meshing values that were given as follows in Table 4.3

Table 4.3 Surface Proximity Meshing Values

Search Floor	0.0m
Points in gap	2
Enable Search Ceiling	True
Search Ceiling	1.0E10 m

4.2.2 Surface Size Parameters

There are various parameters for the mesh surface size. Two of those parameters were given and others were given default values. The ones whose values are varied are given below

1. Polyhedral Density
2. Polyhedral Volume Blending

A polyhedral mesher was chosen for this model mainly because in this type of mesh each cell has many surrounding cells in its immediate environment. This type of mesher is less sensitive to the stretching and yields a better mesh quality and hence eventually gives a better numerically stable model.

4.2.2.1 Polyhedral Density

This defines the density and growth factor for the polyhedral meshes. The following table 4.4 lists the values of Polyhedral Density

Table 4.4 Polyhedral Density

Density	1
Growth Factor	3.3

4.2.2.2 Polyhedral Volume Blending

It defines the volumetric control volume bending factor and for this particular CFD problem the Blending ratio was given a value of 1.1 against the default value of 1.

4.3 PHYSICS MODELS

In any Computational Fluid Dynamics work the physics models needs to be given to the simulation. The solver needs to be defined the type of problem and hence the physics conditions of the problem statement need to be carefully given for the proper execution of the simulation. There are three basic types of values which need to be predefined for the physics models and they are

1. Models
2. Reference Values
3. Initial Conditions

4.3.1 Models

The basic physics models which were defined in solving this problem statement is listed below with a brief explanation about each and every model. The primary type of physics model is a multiphase model of mixture of gases; hence a Eulerian multiphase model was chosen. Other models which were chosen and their implications are discussed below: -

4.3.1.1 Eulerian Multiphase Model

This is the most complex solver of the other two solvers – Volume of Fluid (VOF) Model and Mixture Model. Unlike the other two models, this model was chosen because it employs momentum and continuity equation for each of the two phases – hydrogen and air. Coupling of flow is also achieved in this model. This problem statement has wall and fluid (Solid – fluid) interaction so this model has been considered as it provides a better handling method for granular flows like these.

The Eulerian Multiphase model with two phases – hydrogen and air were chosen for this simulation and both the model was chosen to be of constant density and the values of their dynamics viscosity are listed in the Table 4.5 bellow

Table 4.5 Eulerian Multiphase Model

Air	
------------	--

Density	1.18415 kg/m ³
Dynamic Viscosity	1.85508E-5 Pa-s
Hydrogen	
Density	0.08237 kg/m ³
Dynamic Viscosity	8.87789E-6 Pa-s

The Turbulence Schmidt Number is chosen to be 0.9.

4.3.1.2 Other Physics Model

Some of the other physics models which were chosen are listed bellow

1. All y + Wall Treatment
2. Exact Wall Distance
3. Gradients
4. K-Omega Turbulence
5. N-Phase Mixture
6. SST (Menter) K-Omega
7. Segregated Flow
8. Steady
9. Turbulent
10. Three Dimensional
11. Multiphase Interaction
12. Reynold's Averaged Navier Stokes

4.3.2 Reference Values

There are two reference values which were altered and the other values were taken to be of constant value and the values of those two altered reference values are listed in the table 4.6 bellow

Table 4.6 Reference Values

Minimum Allowable Wall Distance	1.0E-6 m
Reference Pressure	101325.0 Pa

Other reference values were taken to be constant. The wall and fluid interaction are an important factor while solving this. Since this is a granular flow the Minimum Allowable Wall Distance is chosen to be as low as possible.

4.3.3 Initial Conditions

There are certain initial conditions which needs to be set for the solver to solve the problem. The following table 4.7 lists the Initial Conditions that were set for the solver setup.

Table 4.7 Initial Conditions

Pressure	101325.0 Pa
Turbulence Intensity	0.01
Turbulence Specification	K + Omega
Turbulent Velocity Scale	334 m/s
Turbulent Viscosity Ratio	10.0
Velocity	[0.0, 0.0, 0.0] m/s
Volume Fraction	[1.0, 1.0]

4.4 SOLVERS

Any Computational Fluid dynamics setup requires a set of solvers to be operated and so was this problem. The set of solvers that was required to solve this problem is listed below

1. Steady
2. Partitioning
3. Wall Distance
4. Segregated Flow
5. Segregated N-Phase Mixture
6. K-Omega Turbulence
7. K-Omega Turbulent Viscosity

4.4.1 Steady

The flow was considered to be steady flow. The flow is considered to be that kind of flow where the fluid at a particular point do not change along with the course of time. Hence, even with the course of time the fluid properties remain same.

A steady flow is chosen for this problem statement because there is no complex flow and body interactions involved.

4.4.2 Partitioning

The domain partitioning is one of the solvers that needs to be predefined and there are two basic options for partitioning one of the options is per region and the other option is per-continuum. We went with the former domain partitioner for this problem statement

4.4.3 Wall Distance

The following list of values were given for the Wall Distance Solver.

Table 4.8 Wall Distance

Solver Frozen	False
Wall Distance Solver Option	Implicit Tree
Verbosity	0
Minimum Tree Size Threshold	500000

4.4.4 Segregated Flow

There are two specific CFD Solver for solving the problem numerically and they are

1. Segregated Flow
2. Coupled Flow

A segregated flow CFD Solver is more suited to solve multiphase problems since this involves interaction of two phases hydrogen and air this type of flow is chosen. Furthermore, the velocity and pressure flex cycle values had to be defined and the values are tabulated below

Table 4.9 Flex Cycle Values

Velocity	
Restriction Tolerance	0.9
Prolongation Tolerance	0.5
Sweeps	1
Pressure	

Pre-Sweeps	1
Post Sweeps	1
Max Levels	50

4.4.5 Segregated N-Phase Mixture

The values for this solver were given the same as that of pressure solver of segregated flow

Table 4.10 Flex Cycle Values for N-Phase Mixture

Pre-Sweeps	1
Post Sweeps	1
Max Levels	50

4.4.6 K-Omega Turbulence

The values for this solver were given the same as that of velocity solver of segregated flow

Table 4.11 Flex Cycle Values for K-Omega

Restriction Tolerance	0.9
Prolongation Tolerance	0.5
Sweeps	1

4.4.7 K-Omega Turbulent Viscosity

The following values were given for setting up the K-Omega Turbulent Viscosity solver

Table 4.12 Solver values for K-Omega Turbulent

Under-Relaxation Factor	1.0
Maximum Ratio	100000.0
Solver Frozen	False

4.5 REPORTS

There are many reports that can be generated in the simulation software. The following reports were generated for graphing and comparison purpose were generated: -

1. Mass Flow
2. Element Count
3. Mass Flow Averaged
4. Pressure Drop
5. Maximum Mass Fraction of Hydrogen in a Plane
6. Maximum Mass Fraction of Air in a Plane
7. Maximum Pressure of Hydrogen in a Plane
8. Maximum Pressure of Air in a Plane
9. Maximum Velocity of Hydrogen in a Plane
10. Maximum Velocity of Air in a Plane

4.6 VISUALISATION

The flow needs to be visualized to see the amount of hydrogen that is getting mixed – the primary objective of this project. A plane was inserted which splits the geometry into exact half as shown in Figure 4.6.

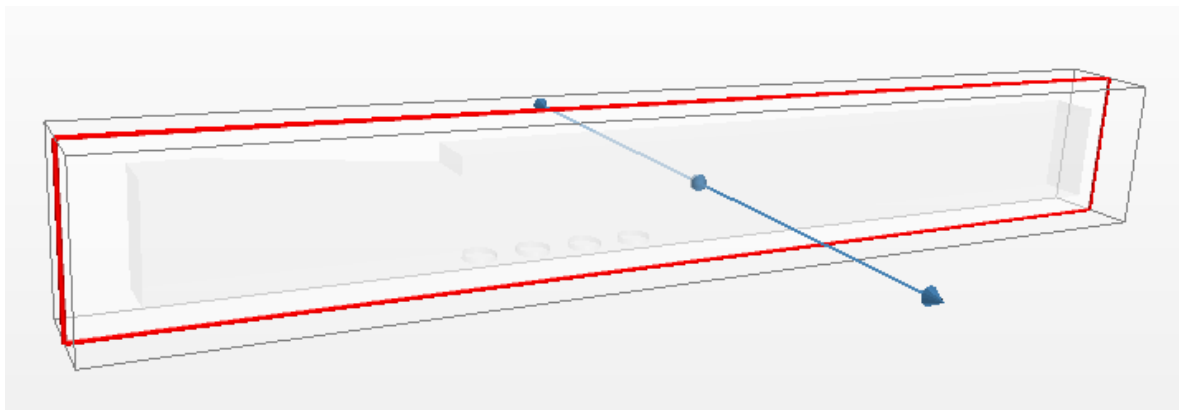


Fig 4.6 Plane to visualize the flow

This plane was used for the visualisation of different field functions like mass fraction and volume fraction of the hydrogen gas to analyse the mixing rate of fuel as shown in Fig 4.6.

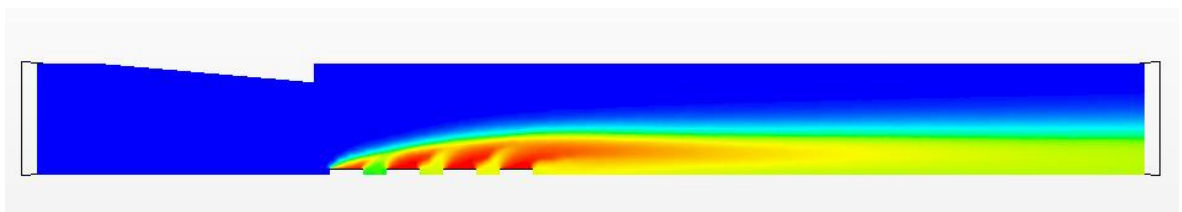


Fig 4.7 Volume fraction of Hydrogen

4.7 POST PROCESSING

The following parameters were considered for the post processing of the Computational fluid Dynamics and there are two basic types of post processing methods to refine the visualization of the mixing rate of hydrogen and air.

1. Outline
2. Scalar

4.7.1 Outline

The outline of the flow visualization has the following parameters and they have been listed in the table

Table 4.13 Outline Parameters

Mesh Colour	Black
Parts	Mid-Section Plane
Animations	Off
Shading Angle	30

4.7.2 Scalar

The Scalar scene has been visualized in the mid-section plane and the scalar field which was primarily seen is the volume fraction of hydrogen and the point size in pixels are chosen to be 10.

The detailed list of colour bar variations that were listed are tabulated in the table below for the reader's reference

Table 4.14 Scalar Parameters

Colour Map	Blue-red
Levels	512
Width	0.6
Font	Lucida Sans Italic
Background	True
Background Colour	White
Shadow	True

Reverse	False
Text Position	Preceding
Height	0.044
Title Height	0.0275
Label Height	0.024
Orientation	Horizontal
Position	[0.3,0.05]
Visible	True
Scale Mode	Linear
Text Colour	Black
Opacity	1
Label Format	Default
Ramp Type	Square root
Number of labels	6

CHAPTER 5

RESULTS AND DISCUSSION

5.1 VOLUME FRACTION

The Volume fraction of both the phases of gases is one of the most important analysis and visualisation technique which needs to be seen for the comparison of the fuels

5.1.1 Volume fraction of Hydrogen of Different Models

The images of the Volume fraction of hydrogen for different models are shown here:

1. Volume fraction of Hydrogen for 5 Degree Wedge Model is shown in Fig 5.1

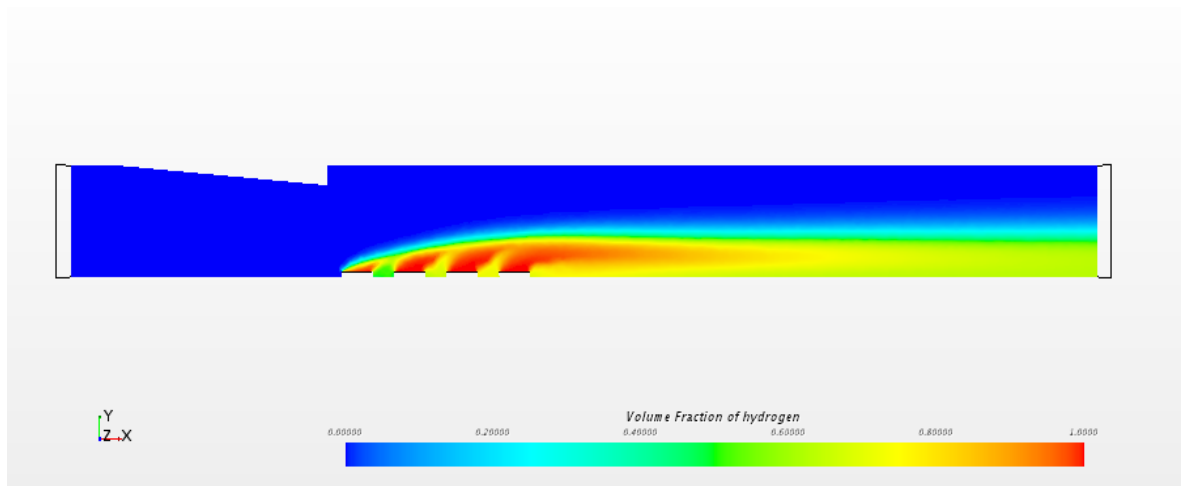


Fig 5.1 Volume fraction of Hydrogen for 5 Degree

2. Volume fraction of Hydrogen for 7 Degree Wedge Model is shown in Fig 5.2

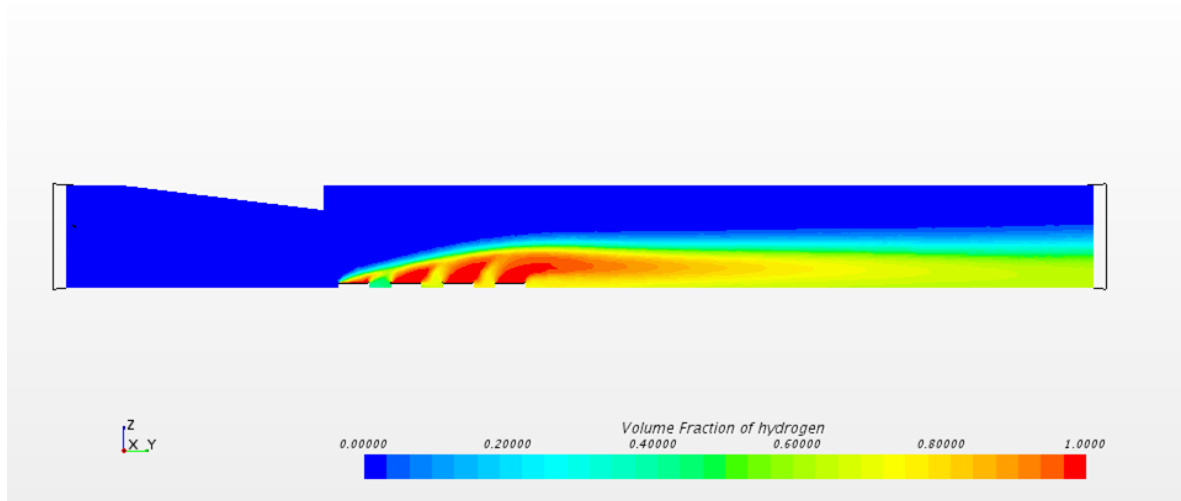


Fig 5.2 Volume fraction of Hydrogen for 7 degree

3. Volume fraction of Hydrogen for 9 Degree Wedge Model is shown in Fig 5.3

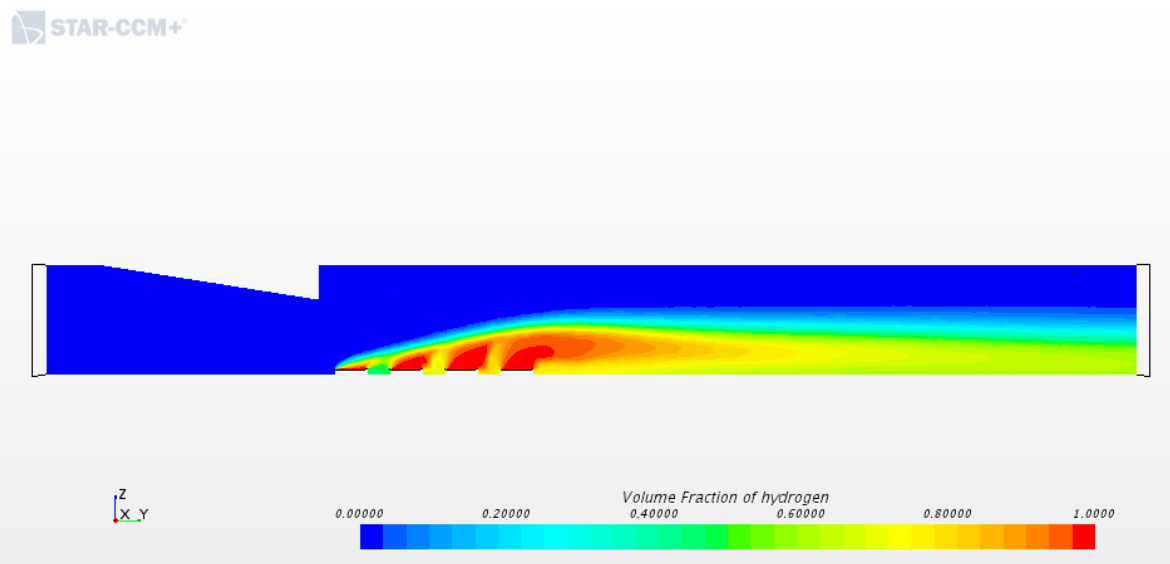


Fig 5.3 Volume fraction of Hydrogen for 9 degree

4. Volume fraction of Hydrogen for 10 Degree Wedge Model is shown in Fig 5.4

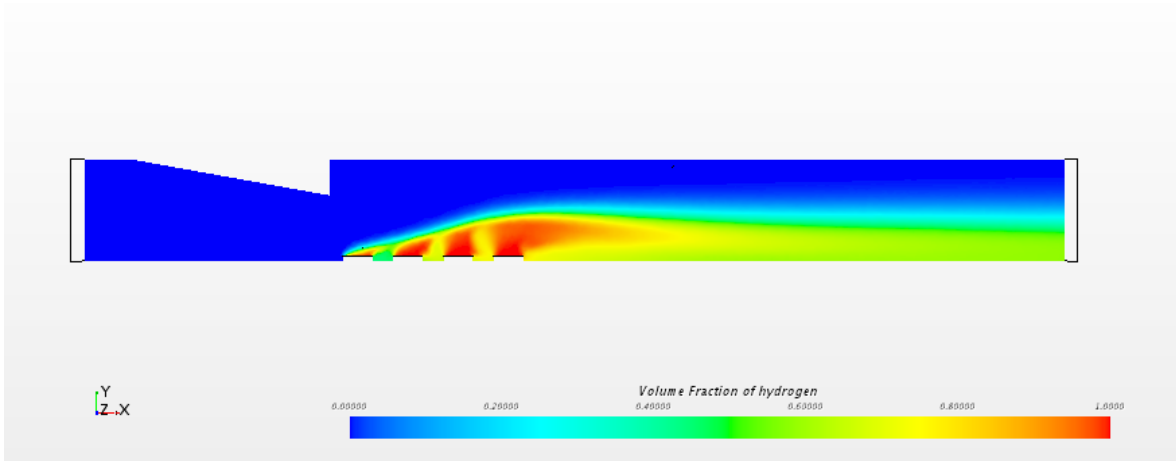


Fig 5.4 Volume fraction of Hydrogen for 10 degree

5. Volume fraction of Hydrogen for 12 Degree Wedge Model is shown in Fig 5.5

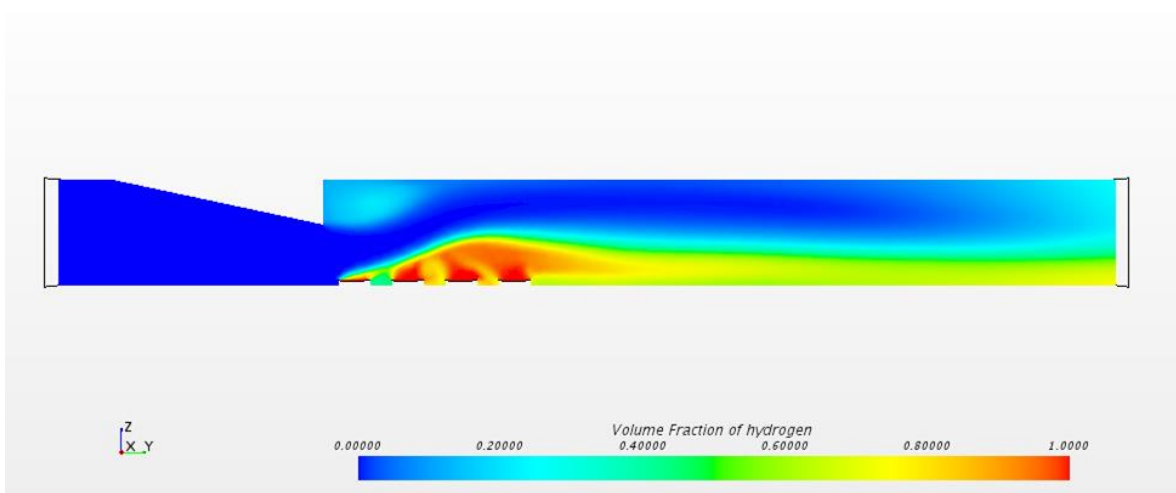


Fig 5.5 Volume fraction of Hydrogen for 12 Degree

6. Volume fraction of Hydrogen for 15 Degree Wedge Model is shown in Fig 5.6

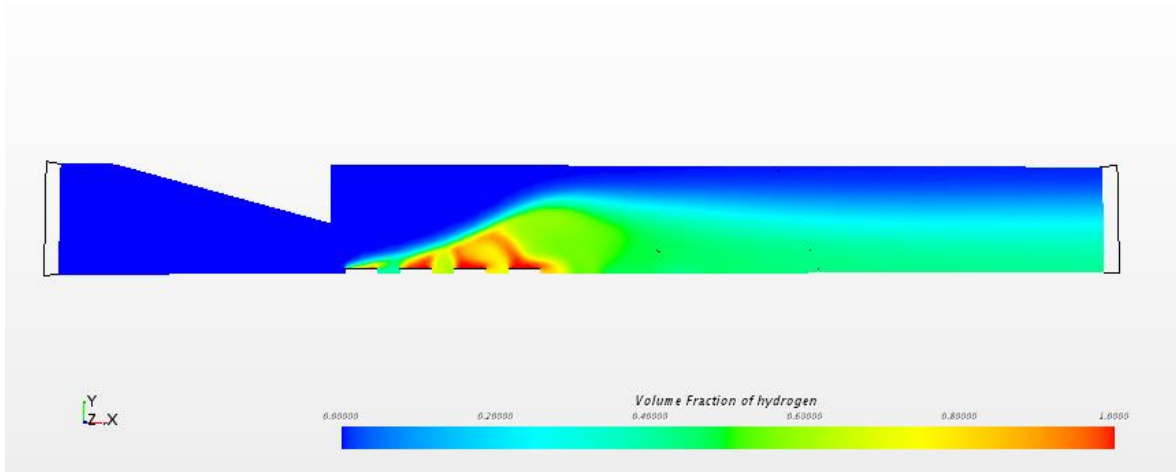


Fig 5.6 Volume fraction of hydrogen for 15 degree

5.1.2 Volume fraction of Hydrogen Results

The visualization and reports of volume fraction of hydrogen is visualised and then the following data were drafted as listed in Table 5.1

Table 5.1 Models and their Boundary Layer Height

Maximum Boundary Layer Height	Model
0.40625	5 Degree
0.5	7 Degree
0.53125	9 Degree
0.5625	10 Degree
0.6875	12 Degree
0.75	15 Degree

The boundary layer thickness of the incoming flow is tabulated in the above table using the different simulations carried out using the following table and this graph in Figure 5.7 is discussed.

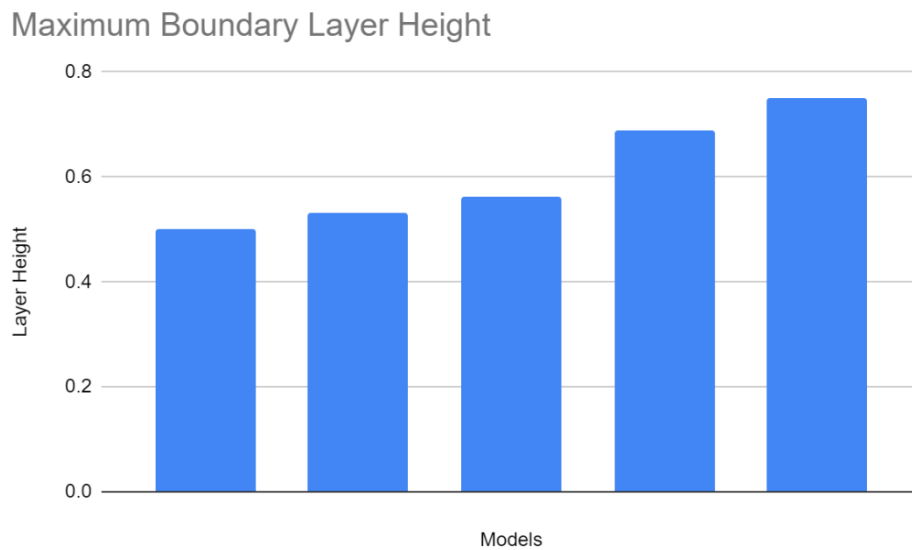


Fig 5.7 Plot between and Models and Layer Height

5.1.3 Result Comparison

The boundary layer thickness is compared for different models and the following observations were

- The boundary layer thickness is linearly increasing
- The boundary layer thickness is minimum for the 5-degree wedge model
- The boundary layer thickness is maximum for the 15-degree wedge model

However, there are more parameters like vorticity and individual inlet boundary layer thickness also needs to be taken into consideration and is done further

5.2 MASS FRACTION OF HYDROGEN AT DIFFERENT INLETS

The mass fraction of hydrogen at the first, second, third and fourth inlet are compared.

The following data was generated using the CFD Reports

Table 5.2 Boundary Layer at different inlets

Boundary Layer at different inlets	1st	2nd	3rd	4th
5 Degree	0.125	0.25	0.34375	0.40625
7 Degree	0.125	0.28125	0.34375	0.4375
9 Degree	0.125	0.25	0.4375	0.53125
10 Degree	0.125	0.25	0.375	0.46875
12 Degree	0.125	0.21875	0.40625	0.5625
15 Degree	0.125	0.1875	0.25	0.65625

The observations that can be concluded from the Figure 5.8 data are:

- The thickness at the first inlet is comparatively low for the first inlet.
- It has been constant right throughout for all the models
- The first inlet gave out up to only 12.5 % of the hydrogen gas as inlet
- The second Inlet gave out more amount of hydrogen gas than when compared with the hydrogen inlet
- The second inlet at an average gave around 25% of the hydrogen gas this is almost as double as the amount of hydrogen as seen in the first inlet
- The third inlet has some vorticity effects and choking of the flow coming into play however still the boundary layer was the strongest among the other two inlets in this region
- The maximum boundary layer thickness was found to be between these two
- The third inlet at an average gave around 35.93% of the hydrogen gas this is a little more than that of the second inlet
- The vorticity and other effects come into play when considering the hydrogen from this inlet and hence the previous trend of linear increase is not shown in this inlet
- The final and fourth inlet has more of these vorticities and choking effects but still gave the highest boundary layer.

- The fourth inlet at an average a little over 51 % of the hydrogen gas this is very much smaller than the growth seen earlier.

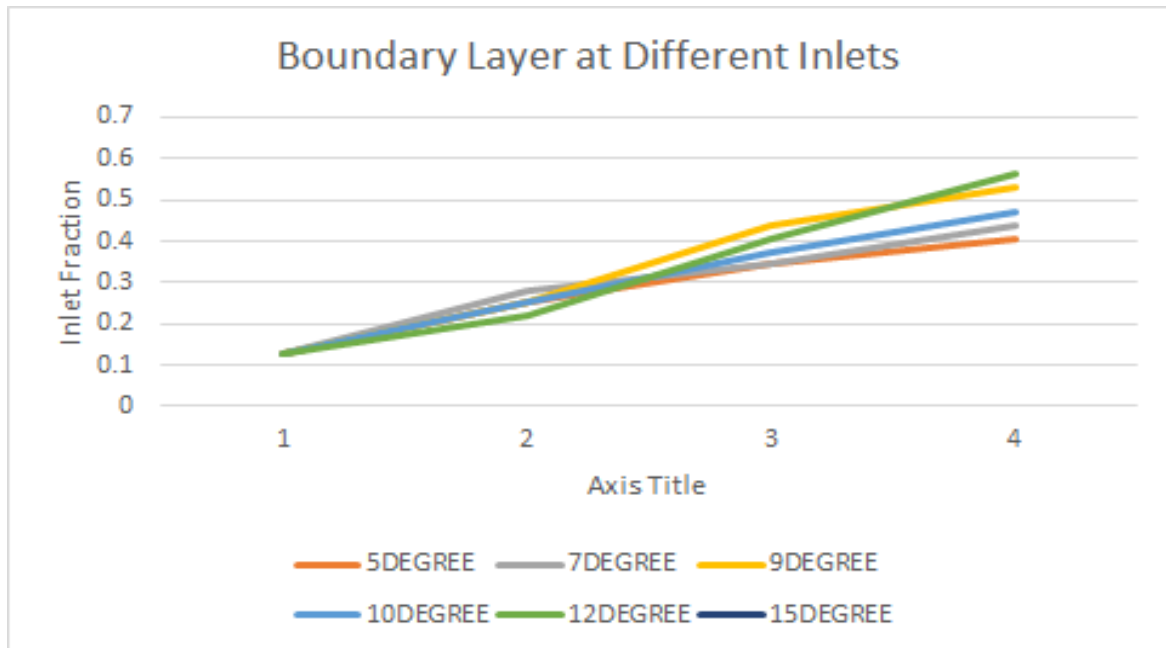


Fig 5.8 Plot between Inlet Fraction and Boundary Layer

This Figure 5.8 shows the how the boundary layer height varies for the respective wedge models, Wedge model 15th has the highest boundary layer separation compared to others. There is a progressive change in the boundary layer height.

CHAPTER 6

SUMMARY AND CONCLUSION

6.1 SUMMARY

The computational fluid dynamics experiment for analysis the mixing rate of the hydrogen was analysed using the inlet conditions that was given in the earlier chapters. The geometry was chosen to be that as shown at the end then the experiment was carried out using the earlier provided reference and initial conditions were used and tested. The model with different shock angle was tested taking into consideration the volume of the hydrogen gas as the primary indicative to gather information about the mixing rate of hydrogen. The different wedge angle were employed to gather the information about the impact of the different types of shock angle and their impact on the mixing rate of the hydrogen. The results of different shock angles are compared

6.2 CONCLUSION

The testing was done for six different models and for the different case conditions the mixing rate of the hydrogen compared.

- The maximum boundary layer thickness was found to be between the second and the third inlet.
- The best wedge size is the **9-degree** wedge model as for the lesser angles the mixing rate is not much pronounced. The higher degree models have more vorticity and choking effects came into attack
- Hence for the efficient mixing rate of hydrogen a 9-degree wedge can be introduced a small distance right above the point when the hydrogen is introduced.

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