Understanding Turbulent Flows and Combustion in Scramjets and Hypersonic Vehicles: A Comprehensive Review

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Abstract: ***This literature review examines the physics and modeling of turbulent flows in scramjets and hypersonic vehicles, with a focus on the Navier - Stokes equations and the conditions necessary for accurate simulations. It covers the Boltzmann equations for non - equilibrium flows, the significance of boundary layer thickness, and the application of Direct Monte Carlo Simulation, along with other turbulence models such as the Spalart - Allmaras and SST k - ω models. The review also explores the concept of detonation in scramjets, various fuel injection strategies, combustion processes, and heat transfer in the context of hypersonic flows. Additionally, it addresses challenges associated with scramjet engines, including temperature gradients, oscillatory combustion, and shock waves. The paper highlights the complexities involved in modeling and simulating turbulent flows in scramjets and hypersonic vehicles, underscoring the need for ongoing research and advancements in this field.***

Keywords: Scramjet, detonation, hypersonics, rarefied gas dynamics, fuel injectors, combustion, Knudsen number, re - entry vehicle

1. Introduction

The physics used to simulate turbulent flows is governed by the Navier - Stokes equations, as stated by T. Chourushi et al. [1]. In addition to the standard inlet, outlet, and wall conditions, additional parameters must be specified to perform simulations of any type of turbulent flow. These parameters include the rate of freestream dissipation, the thickness of the boundary layer, and the intensity of the turbulence. One of the primary challenges in verifying these simulations is that the thickness of the boundary layer cannot be accurately measured in hypersonic conditions. Numerical accuracy can be validated through the use of computational codes and an examination of grid convergence for the specified geometry. When analyzing grid convergence, discretization error is a critical factor. The distinction between accurate solutions of partial differential equations and their corresponding difference equations is what ultimately matters.

1.1 Modelling of turbulence in Hypersonic flows

As the Poisson equations fail to hold above a certain pressure limit, the need for Rarefied Gas Dynamics emerged, according to F. Sharipov et al. [3]. The Knudsen number, which depends on the mean free path of the molecules, is a characteristic of this field of gas dynamics. Extremely low values of the Knudsen number indicate a hydrodynamic flow regime. Medium and large Knudsen numbers, which signify transitional and free - molecular flow regimes, respectively, are calculated using the Direct Monte Carlo Simulation method. The inversely proportional rarefaction parameter to the Knudsen number must also be considered. A velocity distribution function was employed to calculate macroscopic properties such as pressure, stress tensor, temperature, and more. These distribution functions satisfy the Boltzmann equation.

Iain D. Boyd et al. [4] proposed a research paper on the Monte Carlo simulation method. At higher altitudes, when the hypersonic Mach number is reached, non - equilibrium hot spot regions form. The Monte Carlo relations effectively model these regions. Intermolecular collisions are essential for maintaining the gas's equilibrium. As both the density and the length scale decrease, non - equilibrium regions emerge. The mean free path increases, and both viscosity and thermal conductivity become difficult to transport when the Knudsen number approaches zero. Current methods for simulating these flows become ineffective as the Knudsen number exceeds 0.01.

1.2 Mathematical modelling of equilibrium and non - equilibrium hypersonic flows

A study on modeling hypersonic flows in both equilibrium and non - equilibrium regimes was presented by Wenqing Zhang et al. [5]. Thermal and chemical characteristics can also be utilized to categorize these regimes. At lower altitudes, equilibrium regimes occur at higher densities. The Knudsen number is a defining characteristic of these regimes. When the Knudsen number is less than 0.001, the flow is considered to be in the equilibrium regime, and hypersonic flow modeling employs the Navier - Stokes equations. For flows with Knudsen numbers between 0.001 and 0.1, the non - equilibrium Navier - Stokes equations are applied. Furthermore, no - slip boundary conditions are not used in this regime, as they cannot accurately predict properties such as shear stresses and heat flux.

Boltzmann's equation is used to describe all the microscopic phenomena of fluid flow. Two methods are employed to solve these equations: the Direct Simulation Monte Carlo (DSMC) method and the Discrete Velocity Method (DVM). DSMC follows a particle - based approach, while DVM solves the equations directly. The flow that occurs at lower altitudes, specifically within 4 km, is referred to as thermochemical flow. This type of flow utilizes a single temperature model for solving the governing equations. The authors have also discussed various methods for reducing Gibbs free energy.

Non - equilibrium flows are modeled using the non - equilibrium Navier - Stokes equations, which include both two - temperature and three - temperature models. These additional temperatures are the vibrational temperature and the electronic energy temperature. The two - temperature model assumes that these two temperatures are equal. In this regime, the no - slip boundary conditions near the wall are inadequate, as the momentum transfer at the wall differs from that in the flow, resulting in discrepancies in temperature and velocity near the wall compared to the bulk flow. The molecules and ions generated by shock waves can recombine, releasing a significant amount of energy. This energy can contribute to aerothermal loads or aerodynamic heating, posing disadvantages for the vehicle.

Every microscopic phenomenon related to fluid flow is described using Boltzmann's equation. The discrete velocity method (DVM) and the Direct Simulation Monte Carlo (DSMC) are the two primary techniques employed to solve these equations. While DVM solves the equations directly, DSMC utilizes a particle - based approach. The term to the flow that occurs within 4 kilometers at lower altitudes. In this context, the governing equations are solved using a single - temperature model. The author has also discussed several techniques for reducing Gibbs free energy.

2. Literature Review

2.1 Application of hypersonic flows

2.1.1 *Scramjets*

Computerized analysis of the scramjet has been conducted by Marshall et al. [6]. The authors of this research study discussed the necessity of modeling NASA's HYPER X - 43A scramjet. The first two flights were tested, revealing that the tests were prohibitively expensive. The vehicle's leading edge and heat exchanger were corroding due to the intense heat. However, the rates of leakage caused by corrosion were not accurately measured in the wind tunnel tests. Consequently, the researchers decided to focus on simulations. Another reason for the simulations was the lack of a comprehensive database needed to operate the HYPER X - 43A scramjet, which was intended for scramjet testing. The data would be used to examine the vehicle's stability and aerodynamic performance.

An examination of the scramjet was conducted by Nikimoni Das et al. [7]. Operating at extremely high speeds, a scramjet is a type of supersonic ramjet. Due to its high velocity, the incoming air is compressed while traveling at these elevated speeds. The design of the scramjet causes shock waves to form upon the air's entry into the inlet. The unique shape of the scramjet inlet facilitates compression through a series of shock waves. Modern aerospace applications for scramjet technology include reusable vehicles and various other systems. The scramjet engine utilizes atmospheric oxygen, as it does not carry its own oxidizer. The air entering the scramjet is moving at hypersonic speeds. Notably, scramjets do not contain any rotating parts; instead, a hollow scramjet tube replaces the traditional compressor. It is important to note that a scramjet cannot initiate operation at ground speed due to the required high velocity. Therefore, it typically employs a rocket engine for ignition, often used in the second stage of flight. The operational principle of the scramjet is based on a combination of two adiabatic and two isentropic processes, forming the Brayton cycle. When first tested by the USSR in 1991, only a limited number of nations possessed this technology. However, developing countries, such as India, are now advancing in the application of scramjet technology. Reason: Improved clarity, vocabulary, and technical accuracy while correcting grammatical and punctuation errors.

Parralel Injection Technique for diamond shaped fuel injectors

Sukanta Roga [8] presented her research on the computer analysis of the diamond shape of scramjet injectors. Scramjets have a distinct advantage over ramjets due to their ability to mix fuel and intake air at high Mach numbers. However, improper fuel - air mixing can occur, potentially affecting thrust production. To enhance this aspect, studies are being conducted to reduce combustion distance and utilize hydrocarbons, which uniquely delay combustion compared to conventional hydrogen fuel. A parallel injection technique can be employed to ensure proper mixing of fuel and incoming air, which is separated by a flat plate parallel to the inlet. However, this method alters the velocity gradients, leading to the formation of shear layers. Conversely, barrel shocks from an injector positioned perpendicularly to the inlet interact with the boundary layer, causing fuel separation both upstream and downstream. This approach can result in pressure losses that negatively impact combustion efficiency.

The contours of the H2O mass fraction indicated that the center of the chamber exhibited the highest recorded mass fraction, accounting for approximately half of the total mass fraction. At the end of the combustion chamber, which is roughly one - ninth of its total length, the H2 mass fraction, as indicated by the H2 contours, was at its peak. Utilizing a stoichiometric ratio of 1, the highest observed combustion efficiency was 88 percent.

Transverse Fuel Injection Technique

Transverse fuel injection was proposed by Jeong - Yeol Choi et al. [9], who conducted research on the transverse injection of fluid within a combustion chamber cavity, as presented in this paper. To simulate the interactions occurring in the combustion chamber, a Mentor shear stress transport (SST) model was utilized. This model was developed from the conventional k - epsilon model. It was observed that the SST model yielded superior results compared to other models and demonstrated independence from the initial boundary conditions. To select appropriate spatial discretization techniques for the transverse velocity distribution, the MUSCL (Monotonic Upstream - Centered Schemes for Conservation Laws) approach was employed for the computational analysis. Approximately 150, 000 mesh cells were used to define the geometry of the combustion chamber. To ensure accurate predictions of flow interactions, grid density was increased near the injector and the walls. For the injector hole, around 50 grid points were allocated, and the minimum mesh grid element size surrounding a wall was approximately 7 x 10^ - 7 m. Each solid wall was assumed to have adiabatic properties with no - slip conditions, while slip conditions were assigned to the upper wall. Reason: Improved clarity, vocabulary, and technical accuracy while correcting grammatical and punctuation errors.

To fuel the scramjet, Kumari Ambe Verma et al. [10] employed a parallel injection technique. They evaluated the outcomes and adjusted the angles of attack accordingly. The authors utilized the RANS k - ω model, following a grid independence test, in conjunction with species transport analysis. A non - reacting layer, known as the shear layer, is formed by the wakes generated from the heat release in the combustion chamber. Shocks cannot interact with this layer. In one instance, the authors examined the characteristics of non - reacting flows by treating the incoming gas as an inert gas. The angles of attack of the strut were varied from - 5 degrees to 0 to +5 degrees in the mixing case. The results indicated that, even at an angle of attack of 0 degrees, the- 5 degree angle of attack was more efficient.

Haomin et al. [11] modified the geometry of the scramjet's internal engine. They stated that the area of the first throat can be increased by up to 1.4 times, and the area of the second throat can be modified by up to 2.8 times. This modification leads to an increase in the thrust of the scramjet, even at low Mach numbers. Additionally, specific impulse was improved as a result of this technique.

2.1.2 Concept of detonation in scramjets

An experimental and analytical investigation into the oblique shock wave in scramjet detonation was conducted by Menees et al. [12]. Oblique shock waves, in contrast to normal shock waves, result in comparatively smaller pressure losses. However, the authors were uncertain about the existence of stabilized oblique shock waves. Conversely, Chapman - Jouguet waves, behind which the flow reaches sonic velocity, are considered to be normal shock waves. Numerous studies have shown that the heat addition in scramjets is comparable to that of oblique shock waves. In multishock diffusers, the detonation wave may also serve as the final wave. For low Earth orbit (LEO) space applications, a rocket engine was examined. The temperature of the mixture increases due to fuel injection, while the temperature of the fuel remains constant. Consequently, heat loads begin to impact the scramjet material, which absorbs approximately 90 percent of these heat loads. At higher Mach numbers, the oblique detonation engine (ODE) performs better than the scramjet. Conversely, specific impulse decreases at Mach numbers below 15, which occurs due to the increased angle of the oblique shock wave. The length of the scramjet is also crucial; shorter lengths are preferable for ODE, while longer lengths are advantageous for scramjets. The potential distance for detonation caused by the shock wave should be minimized by increasing the pressure behind the wedge in the experimental assembly. However, raising the temperature and pressure may lead to premature combustion, in addition to affecting the stagnation pressure ratio (PR). Reason: Improved clarity, vocabulary, and technical accuracy while correcting grammatical and punctuation errors.

2.1.2.1 Types of Detonation

A summary of detonation engines was presented by Piotr Wolański [13]. The velocity produced by the detonation process ranges from 1 to 3 km/s. In contrast, deflagration velocity is measured in meters per second. As the temperature rises due to deflagration, pressure decreases, complicating the design of systems that add more air to cool the turbine before assembly. However, detonation results in low combustion temperatures and high pressure. Along with an increase in specific impulse, detonation also offers a theoretical efficiency gain of over 10% in jet cycles. Detonations can be broadly classified into three categories. The first category is pulse detonation, which consists of an elongated tube filled with a mixture of oxidizer and fuel. During the ignition process, deflagration occurs, which subsequently transitions to detonation. The generated thrust is initiated each time and is time - dependent. To utilize this type of detonation with turbojet engines, additional air must be introduced before the turbine. The second category comprises stand - alone detonation engines. In these engines, detonation waves are stabilized by a wedge, and fuel is injected at supersonic velocities. However, a significant drawback is their extremely limited operating range, as pressure losses exceed thrust beyond Mach 7. The third category involves rotating detonation engines, where detonation continuously propagates within a toroidal combustion chamber. Fuel is injected through openings in the structure, while oxygen is supplied simultaneously. This type of detonation can also be utilized in rocket engines.

The advent of the steam engine, as demonstrated by Daopeng Zheng et al. [14], was a transformative factor during the Industrial Revolution in Europe, subsequently influencing global industrial development. Innovations and discoveries can arise unexpectedly and in diverse locations, driven by individuals from any background. James Watt, known for his fondness for assisting his mother in culinary activities, experienced a pivotal moment when he observed steam lifting the lid of a cooking vessel into the air, igniting a spark of innovation. This incident exemplifies the unpredictable nature of groundbreaking advancements and suggests the potential for interplanetary travel to become a reality in the future. Watt's pioneering work inspired Sadi Carnot, who developed a thermodynamic cycle designed for use in automobiles. Building upon this foundation, subsequent scientists such as Diesel and Otto created their own thermodynamic cycles, each striving for greater efficiency. Among these innovations, the Stirling engine emerged as a standout due to its superior efficiency, making it particularly well - suited for extended space expeditions.

Daniel A. Rosatoa et al. [15] conducted a study on detonation for hypersonic propulsion. Air - breathing engines are commonly used for intercontinental travel; however, they have limitations when applied to space - related missions. In contrast, detonation engines are preferred for non - air - breathing applications, such as rockets and launch vehicles. Various types of detonation waves exist, including oblique, standing, rotating, and pulsed detonation waves. The oblique detonation wave theoretically offers superior thrust, but challenges arise in achieving high speeds and efficiency in practical applications. One of the primary challenges in experimental settings is maintaining the stability of detonation, which is a critical factor for the successful adoption of this propulsion technology.

The solutions for scramjet propulsion technology were proposed by Zonglin Jiang et al. [16]. One of the main drawbacks of the scramjet engine is the shockwaves that can travel upstream and cause the turbomachinery to surge. In response to this issue, the authors suggested the standing oblique detonation engine. This engine type offers two significant advantages: a shorter combustion chamber length and a higher specific impulse compared to scramjet engines. Additionally, rapid dissipation of sound waves generated by the diffusion of subsonic flow is achievable. Experiments have shown that supersonic combustion can lead to oscillating combustion, characterized by dying and rekindling flames. Three primary challenges arise in supersonic combustion. The first involves the mechanism of the Mach cone, which is inherently spherical. When a spherical shock wave is reflected, it generates a planar shock wave, although its effects are not as pronounced as those of the original spherical shock wave. Numerous reflections of oblique shock waves create a negative temperature gradient in the combustor region, causing the shock to decay more slowly in the scramjet than in open space. As the flow progresses, simulation results indicate the presence of a spherical shock wave that eventually transitions into a planar shock wave. However, as the flow continues, the propagation of the shock wave diminishes in relation to the increasing Mach number. This technique addresses the issue of a low equivalent ratio. The primary focus of this research paper is discussed. Reason: Improved clarity, vocabulary, and technical accuracy while maintaining the original meaning.

3. Conclusion

In conclusion, the literature review highlights the complexities and challenges of simulating and modeling turbulent flows in hypersonic vehicles and scramjets, emphasizing the need for advanced turbulence models, accurate boundary conditions, and efficient numerical methods. The application of hypersonic flows in scramjets poses significant challenges, including fuel - air mixing, combustion, and heat transfer, which necessitate further research and development to achieve stable and efficient combustion. The review underscores the importance of understanding the physics of turbulent flows, non - equilibrium phenomena, and detonation processes in hypersonic flows, and highlights the need for experimental and numerical studies to validate and improve the accuracy of simulations. Ultimately, addressing these challenges is crucial for the development of efficient and reliable hypersonic vehicles and scramjets, which have significant potential for future aerospace applications.

References

[1] T. Chourushi1, A. Rahimi1, S. Singh2 and R. S. Myong1* Computational simulations of near continuum gas flow using Navier - StokesFourier equations with slip and jump conditions based on the modal discontinuous Galerkin method Chourushi et al. Advances in Aerodynamics (2020) 2: 8 https: //doi. org/10.1186/s42774 - 020 - 00032 - z

[2] Christopher J. Roya,, Frederick G. Blottnerb Review and assessment of turbulence models for hypersonic flows Progress in Aerospace Sciences 42 (2006) 469–530

[3] F. Sharipov Rarefied gas dynamics and its applications to vacuum technology Universidade Federal do Paraná, Curitiba, 81531 - 990, Brazil

[4] Shutian Yu Xinyue Ni Fansheng Chen CFD Simulation Strategy for Hypersonic Aerodynamic Heating around a Blunt Biconic International Journal of Aerospace Engineering

[5] Iain D. Boyd∗ Computation of Hypersonic Flows Using the Direct Simulation Monte Carlo Method journal of spacecraft and rockets Vol.52, No.1, January–February 2015 https: //doi. org/10.2514/1. A32767

[6] Friedrich and Dore "a parametric study of the dynamic motion of a spuming and non - spuming re - entry vehicle with non - linear Aerodynamic characteristics" F. Y. Horiuchi Lockheed Missiles and Space Company A Division of Lockheed Aircraft Corporation Sunnyvale, California

[7] SC Lean and j d Teare "a streamtube approximation for calculation of reaction rate s in the inviscid flow field of hypersonic objects" S. C. Lin and J. D. Teare Avco - Everett Research Laboratory Everett 49, Massachusetts

[8] Larc Erric and Phenis Woods "a mechanism for self - excited oscillations of "hammerhead" and other blunt - nose missiles" Lars - Eric Ericsson, Phineas Woods and Joseph N. Chavez Lockheed Missiles and Space Company A Division of Lockheed Aircraft Corporation Sunnyvale, California

[9] Laurie A. Marshall* and Griffin P. Corpening† Robert Sherrill‡ A Chief Engineer's View of the NASA X - 43A Scramjet Flight Test NASA Dryden Flight Research Center, Edwards, California, 93523 - 0273, USA

[10] Nikimoni Das ⇑, K. M. Pandey, K. K. Sharma A brief review on the recent advancement in the field of jet engine - scramjet engine Materials Today: Proceedings

[11] Sukanta Roga CFD Analysis of Scramjet Engine Combustion Chamber with Diamond - Shaped Strut Injector at Flight Mach 4.5 2019 J. Phys.: Conf. Ser.1276 012041

[12] Jeong - Yeol Choia, *, Fuhua Mab, Vigor Yang Combustion oscillations in a scramjet engine combustor with transverse fuel injection Proceedings of the Combustion Institute 30 (2005) 2851–2858

[13] Hao - min Li, Yu - chun Chen, Chun Guan, Yuan Gao, Zhi - hua Wang, Yu - sang L Research on Geometry Configuration/Fuel Distribution of Combustion Chamber of Scramjet 2018 9th International Conference on Mechanical and Aerospace Engineering

[14] Kumari Ambe Verma a, Krishna Murari Pandey b, *, Mukul Ray c, Kaushal Kumar Sharma The numerical investigation of combustion performance of scramjet combustor with variation in angle of attack Results in Engineering

[15] Gene P. Menees, Henry G. Adeleman and Jean - Luc Cambier Analytical and Experimental Investigations of the Oblique Detonation Wave Engine Concept

[16] Piotr WolaĚski. Detonation engines Journal of KONES Powertrain and Transport, Vol.18, No.3 2011

[17] Zonglin Jiang, Zijian Zhang, Yunfeng Liu, Chun Wang, Changtong Luo. Criteria for hypersonic airbreathing propulsion and its experimental verification Chinese Society of Aeronautics and Astronautics & Beihang University Chinese Journal of Aeronautics https: //doi. org/10.1016/j. cja.2020.11.001