NUMERICAL ANALYSIS ON COMBUSTION INSIDE RD-108 ROCKET ENGINE

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MASTER OF SCIENCE (MECHANICAL ENGINEERING)

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ABSTRACT

Understanding the combustion process that happens in a liquid propellant rocket engine is a challenge, in part because of the turbulent nature of the process. In this study, effort is made to gain more knowledge on the subject by studying the characteristics of combustion inside the rocket nozzle and aspects of performance and efficiency of a rocket. These efforts are made possible by conducting a numerical simulation on RD-108 rocket engine using modern simulation software that allows the study of a wide range of subjects in a short time. The simulation is conducted using Computational Fluid Dynamics technique, specifically 2-Dimensional Navier Stokes equation. Result shows that the most stable and ideal simulation of combustion process in RD-108 rocket nozzle occurs when using the default size of combustion chamber, coarse structural grid, k-ε turbulent flow model with re-normalization group, kerosene-air propellants, hybrid initialization and a specific setting to run calculation. A standard model, which contains all of the aforementioned properties is then used to calculate the thrust force and specific impulse. Result shows that while the thrust force deviates from experimental data by over 30%, the specific impulse value has a deviation of 4.46%, verifying the accuracy of the data. Result also shows that the thrust force and specific impulse in hydrogen-air model is more than than kerosene-air model, in agreement with the scientific literature

ABSTRAK

Memahami proses pembakaran yang berlaku dalam mesin roket propelan cecair adalah satu cabaran, kerana sifat proses turbulence yang berlaku di dalamnya. Dalam kajian ini, usaha dilakukan untuk mengatahui secara mendalam mengenai ciri-ciri pembakaran di dalam nozzle roket dan aspek prestasi dan kecekapan roket. Usaha-usaha ini boleh dilakukan oleh sebab program simulasi berangka yang menggunakan teknologi moden yang memungkinkan pembelajaran pelbagai aspek pembakaran dalam waktu singkat. Simulasi dilakukan menggunakan teknik Computational Fluid Dynamics, khususnya menggunakan Navier Stokes 2-Dimensi. Hasil kajian menunjukkan bahawa simulasi proses pembakaran yang paling stabil dan ideal dalam muncung roket RD-108 berlaku apabila menggunakan ukuran ruang pembakaran kecil, grid struktur kasar, model aliran turbulen k-ε dengan kumpulan normalisasi semula, propelan kerosene-oksigen, hibrid inisialisasi dan tetapan khusus untuk menjalankan pengiraan. Model standard, yang mengandungi semua sifat tersebut kemudian digunakan untuk mengira prestasi dan kecekapan roket. Hasil menunjukkan bahawa nilai thrust force menyimpang dari data eksperimen lebih 30%, tetapi nilai specific impulse mempunyai penyimpangan hanya 4.46%, mengesahkan ketepatan data. Hasil kajian juga menunjukkan bahawa nilai thrust force dan specific impulse bagi model hydrogen-oksigen adalah lebih berbanding model kerosene-oksigen, mengesahkan ketepatan dengan journal saintifik.

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APPROVAL

The Examination Committee has met on 4th December 2020 to conduct the final examination of Giri Ram A/L Sreeramlu on his degree thesis entitled ‘Numerical Analysis on combustion inside RD-108 Rocket Nozzle.

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This thesis was submitted to the Senate of Universiti Pertahanan Nasional Malaysia and has been accepted as fulfilment of the requirements for the degree of **Master of Engineering (Mechanical Engineering)**. The members of the Supervisory Committee were as follows.

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UNIVERSITI PERTAHANAN NASIONAL MALAYSIA

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Date of birth : 25/08/1991

Title : NUMERICAL ANALYSIS ON COMBUSTION INSIDE RD-108 ROCKET ENGINE

Academic session : 2019/2020

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LIST OF ABBREVIATIONS

UPNM	Universiti Pertahanan Nasional Malaysia
MINDEF	Ministry of Defence
STRIDE	Science and Technology Research Institute for Defence
CFD	Computational Fluid Dynamics
LPRE	Liquid Propellant Rocket Engine
RANS	Reynolds Average Navier-Stokes
LES	Large Eddy Simulation
DES	Detached Eddy Simulation
RNG	Renormalization Group Theory

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Liquid propellant rocket engines (LPRE) have been studied extensively for well over a century. Numerical modelling and simulation of rocket engines using Computational Fluid Dynamics (CFD) calculations have been studied since the 1940s. With the introduction of computer-aided software, the time taken to process the calculations and number of iterations have become a lot shorter.

However, to the knowledge of the author, few studies have conducted the numerical simulation of rocket nozzle with a modern simulation software that is capable of studying a wide range of combustion characteristics in a short span of time. Most studies focused on one or two characteristics in detail, and one of the reasons could be due to software limitations.

Even fewer studies focused on the combustion characteristics of RD-108 rocket nozzle. This could be in part because it is an old design. Although old, it was found through this study a lot can be learned about the nature of combustion from the numerical simulation of this design of nozzle. It was also found through this study that the benefit of simulating old designs is that there is adequate experimental data to compare simulated data with for accuracy of computation.

Therefore, efforts were made to study the combustion characteristics, performance and efficiency of RD-108 rocket engine.

1.2 Background

1.2.1 Overview

Rocket science and technology have gained tremendous popularity in recent years. This is because of private companies such as SpaceX, Blue Origin and Virgin Galactic, that aim to commercialize space travel in the future, promising to create new industries such as space tourism. As a result, the rate of technological development in this field has accelerated.

For a long time since the Cold War era, the space industry experienced a lack of progress. This is because of the lack of investment and government-funding. Therefore, the recent developments are a positive sign for the industry. If an industry like space tourism is created and thrives, then there is possibility for many countries, including those that are underdeveloped in rocket science and technology, to benefit.

Other than human spaceflights, space exploration has been and still is a major factor in rocket technology development. In the past, the race to land the first human on the moon drove United States of America and the Soviet Union to improve their rocket technology. In the present, there is a competition to land the first human on planet Mars and it has garnered interest. Besides human spaceflight and space exploration, rockets are also used for the purpose of military and launching of satellites.

1.2.2 Rocket Compartments

Rockets can be compartmentalized into four systems, namely the payload, structural, guidance and propellant systems (Andersson, 2019). Payload concerns whatever that is needed to be transported to space, be it astronauts, satellites, missiles, or research materials; the structural system concerns the design and manufacture of various parts of the rocket; the guidance system includes the various communication equipment like radars and sensors that guide rockets in the desired direction; and lastly, the propulsion system includes technologies that enable the rocket to be thrusted from ground to space.

1.2.3 Rocket Propulsion Systems

Rocket propellant engines can be further subdivided into chemical and electric propulsion systems. Electrothermal, electrostatic and electromagnetic propulsion are examples of electric propulsion while liquid, solid and hybrid propulsion are examples of chemical propulsion. Of all the propellant types, by far the most commonly used type for the longest time has been the liquid propellant engine.

The main reason for that is because the liquid propellant engine has notable advantages over the other systems. In comparison, electric propulsion systems provide thrust that is relatively small and inefficient, because the power comes from either battery or solar panels. Meanwhile the solid propulsion system is costly and could not be tested first because of its inability to be reusable. The premixed propellant is also potentially explosive should ignition happen unintentionally.

Hybrid propulsion systems are relatively new and so more research and development are needed, particularly research on switching between liquid and solid propulsion. In some cases, solid propellant boosters are used to assist liquid propellant rocket engines in providing additional thrust during lift-off.

1.2.4 Rocket Propellants

There are monopropellant and bipropellant Liquid Propellant Rocket Engine (LPRE), whereby the former uses a single chemical as a propellant while the latter uses two, namely a fuel and an oxidizer. Comparatively, the monopropellant system has a less complex design because of the single tank, but is relatively inefficient and has low thrust, because of the usage of a catalyst to aid the combustion process.

A further subdivision can be made of bipropellant LPRE, into the thrust chamber, propellant feed, liquid and oxidizer tanks and automatic regulators (Wang, 2016). The propellant feed system channels the propellants from the propellant tanks to the injectors in the combustion chamber. Either high pressure in the tank or a turbo pump could be used to push the propellants into the combustion chamber.

The thrust chamber is where the chemical propellants are converted to mechanical energy to propel the LPRE forwards. It is made up of combustion chamber and nozzle. Propellants would be injected into the combustion chamber and combustion process would occur. The resulting gases would be channelled by the nozzle backwards and outwards and the flow of various gas species in a very high mass flow rate and at supersonic speeds is what provides thrust force for the rocket to move upwards.

The convergent-divergent shape of the nozzle is necessary to enable this process of turning thermal to kinetic energy to occur. Aside from combustion and compressible gas flow, cooling also takes place inside the thrust chamber; its purpose is to ensure that the internal walls of the thrust chamber do not melt from the high temperature generated during combustion that is higher than the critical temperature of the material of the wall. Some examples of cooling are regenerative cooling and radioactive cooling.

1.2.5 History of RD-108 LPRE

RD-108 LPRE, which was developed by the Soviet Union, has four thrust chambers, uses a kerosene variant called RG-1 as fuel and liquid oxygen as oxidizer (Halchak, 2016).

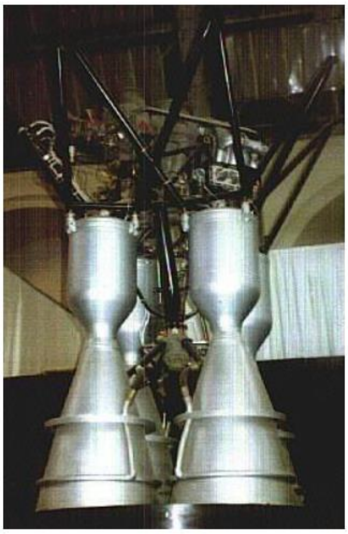

Figure 1.1: Replica of RD-108 LPRE (Wade, 2020)

1.2.6 Computational Fluid Dynamics (CFD)

Numerical simulation is a calculation that is done using mathematical models to a point where the actual event could be simulated. Since the advent of computers, programs in software run the calculation and simulate a predictive outcome of the studied activity.

In the case of numerical simulation of LPRE, three key processes are necessary, namely the combustion process modelling, numerical model solution and simulation results analysis (Wang, 2016). The first process typically includes heat transfer models, combustion models and atomization models. If turbulence is considered then flow turbulence model is included. The second process works on solving using the mathematical models mentioned previously and the addition of boundary, initial and periodic conditions. CFD used in various software like Ansys and Autodesk CFD work on this process. For the third process, various visualization methods aid in examining in detail the characteristic of the combustion process and performance of the engine.

Among the various benefits of conducting numerical modelling and simulation are that the duration of the developmental stage could be drastically shortened, the cost of research could be greatly reduced and depending on the 7 accuracy of the simulation, problems that would otherwise be glossed over could be detected very early and the experimental process could be conducted with more certainty because of the validation provided by numerical simulation.

1.2.7 Combustion Characteristics

Combustion characteristic is defined to be the features of combustion or the specific details of combustion. It is related to the mechanism of combustion, which means the natural processes that take place during combustion.

In this study, the combustion characteristics of RD-108 LPRE include details as to whether there is change to parameters such as velocity, temperature, pressure, mass flow rate in various parts of the rocket nozzle when there is change to geometry of structure, grid of structure, viscosity of flow, types of fuel, simulation methods, boundary conditions and initial conditions.

Based on the observed patterns of simulation result, analysis was also done on combustion stability or instability, for example whether or not there is a shock wave, is there an under-expansion or over-expansion of flame and which part of the nozzle experiences divergence in calculated value.

Certain criteria need to be met in order for a rocket engine to function. The first is, in a convergent-divergent nozzle design, the velocity needs to be subsonic (less than 343m/s) before the nozzle throat, sonic (equals to 343m/s) at throat and supersonic after nozzle throat, as illustrated in Figure 1.2. Second criteria is, the temperature in the combustion chamber needs to be as high as 3500K. Inability to meet either of these criteria could mean that the combustion process is not conducive for rocket propulsion.

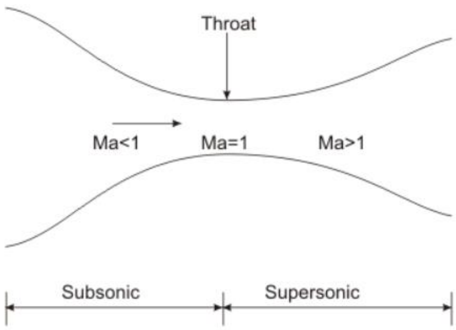

Figure 1.2: The velocity requirement in a convergent-divergent nozzle. (mach number: velocity magnitude = 1 Ma : 343m/s)

1.2.8 Performance and Efficiency

Performance refers to how powerful a certain LPRE is in comparison to other rocket engines. In recent times, due to the focus on cleaner and greener technology, it may also be appropriate to discuss about the role of sustainability and low-emission in the context of LPRE performance. However, for this study only the thrust force of LPRE is used as barometer for performance.

Contrary to popular belief, a high-thrust force is not necessarily desired, this is evidenced by studies such as Chandler (2019) where a low-thrust rocket engine was developed. The reason is because a high thrust rocket engine may not be energy-efficient and could be costly. The idea behind a low-thrust engine is to develop a rocket engine with optimal thrust that is able to escape the velocity barrier of atmosphere but is also efficient and affordable.

Efficiency discusses about how much of the chemical energy from the propellants is converted to thermal energy in the combustion chamber and then kinetic energy that provides thrust to the LPRE. Specific impulse measures how efficiently a certain rocket engine uses propellants.

For this study, the goal is not to improve the RD-108 LPRE performance and efficiency, but to compare the numerically simulated result with available experimental data.

1.3 Objectives

This study embarks on the following objectives:

1. To study the combustion characteristic inside the RD-108 combustion chamber rocket nozzle.
2. To study the performance and efficiency of the liquid propellant rocket engine.

1.4 Research Scope

The scope of research is as follows:

1. The rocket engine is considered to operate in steady state, single-stage and adiabatic condition.

2. The thrust force and specific impulse of numerical simulation needs to tally with reference data with a low margin of error.

3. The velocity at the nozzle needs to be subsonic (Mach number < 1) in the convergence section, sonic at the nozzle throat (Mach number = 1) and supersonic at the divergence section (Mach number > 1).

1.5 Research Limitations

This study is impacted by the following limitations:

1. Low computing power of processor limits the extent to which numerical simulation could be performed in software with Computational Fluid Dynamics program.

2. Due to the short duration of Masters' Thesis project, the numerical study could not be verified by in-house experimental study. However, the reference data was found to be sufficient enough to verify the data from numerical study.