UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL AND NUMERICAL INVESTIGATION ON SOLID PROPELLANT ROCKET MOTOR PERFORMANCE

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By

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Application of Computational Fluid Dynamics (CFD) in studying solid propellant rocket motor have been growing steadily. This is due to the fact that experimental work will cost more time and money. Other than that, the industry needs more understanding to guide designer for more reliable technical solution and less expensive in order to design solid rocket motor for missiles and space launchers. To bring new knowledge for solid rocket propulsion, CFD has been important and dependable. However, to validate the dedicated models and numerical simulation, experimental procedure was important. For the design process, solid propellant rocket with medium thrust produced been focused in the current work. The works are including experimental and CFD simulation approaches. For the experimental work, the static firing test will be used. As for the fabrication of the propellant grain, it been conducted at the authorized centre by the Malaysian authority. Meanwhile for the CFD simulation, the work will be focus on the internal flow inside the nozzle. The findings show that data has significant errors due to the failure of the SRM bulkhead during experimental analysis. Due to the Covid 19 pandemic, the experimental work cannot be repeated and therefore was presented as it was. Next findings show the normal nozzle with different throat length simulation. It was found that the throat length has significant impact on the performance of the nozzle flow. Finally, findings from parametric study about the dual bell nozzle. The results show that the dual bell nozzle can increase the effectiveness of the nozzle flow. In overall, the work has covered all the intended objectives and CFD analysis has been prove as useful design tools used to lessen the amount of physical testing that must be done to validate a design and measure its performance.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

SIASATAN EKSPERIMEN DAN NUMERIK TERHADAP PRESTASI MOTOR ROKET PROPELLANT PEPEJAL

Oleh

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Aplikasi Computational Fluid Dynamics (CFD) dalam mengkaji motor roket propelan pepejal telah berkembang dengan mantap. Ini disebabkan oleh fakta bahawa kerja eksperimen akan memakan lebih banyak masa dan wang. Selain daripada itu, industri memerlukan lebih pemahaman untuk membimbing pereka bentuk penyelesaian teknikal yang lebih dipercayai dan lebih murah untuk mereka bentuk motor roket pepejal untuk peluru berpandu dan pelancar angkasa. Untuk membawa pengetahuan baharu untuk pendorongan roket pepejal, CFD adalah penting dan boleh dipercayai. Walau bagaimanapun, untuk mengesahkan model khusus dan simulasi berangka, prosedur eksperimen adalah penting. Untuk proses reka bentuk, roket propelan pepejal dengan tujahan sederhana yang dihasilkan telah difokuskan dalam kerja semasa. Kerja-kerja itu termasuk pendekatan eksperimen dan simulasi CFD. Untuk kerja eksperimen, ujian tembakan statik akan digunakan. Bagi fabrikasi bijirin propelan, ia dijalankan di pusat yang diberi kuasa oleh pihak berkuasa Malaysia. Manakala bagi simulasi CFD, kerja akan tertumpu kepada aliran dalaman di dalam muncung. Dapatan menunjukkan bahawa data mempunyai ralat yang ketara disebabkan oleh kegagalan sekat SRM semasa analisis eksperimen. Disebabkan oleh pandemik Covid 19, kerja eksperimen tidak boleh diulang dan oleh itu dibentangkan seperti sedia ada. Penemuan seterusnya menunjukkan muncung biasa dengan simulasi panjang tekak yang berbeza. Didapati bahawa panjang tekak mempunyai kesan yang ketara terhadap prestasi aliran muncung. Akhir sekali, dapatan daripada kajian parametrik tentang muncung loceng dwi. Keputusan menunjukkan muncung loceng dwi boleh meningkatkan keberkesanan aliran muncung. Secara keseluruhan, kerja telah merangkumi semua objektif yang dimaksudkan dan analisis CFD telah terbukti sebagai alat reka bentuk yang berguna yang digunakan untuk mengurangkan jumlah ujian fizikal yang mesti dilakukan untuk mengesahkan reka bentuk dan mengukur prestasinya.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

AF	accelerating flow
ALE	arbitrary lagrangian eulerian
avg	average
BD	blended bifferencing
BF	boundary fitted
CD	central cifferencing
CFD	computational fluid dynamics
CPU	central processing unit
CT	computed tomography
CURVIB	curvilinear immersed boundary method
DES	detached eddy simulation
DF	decelerating flow
DFG	Deutsche Forschungsgemeinschaft (German Research Association)
DNS	direct numerical simulation
DWDN	Drinking Water Distribution Networks
EFD	experimental fluid dynamics
FCT	flux corrected transport
FD	fictitious domain
Fs	safety factor
FVM	finite volume method
GCI	grid convergence index
IB	immersed boundary
IIM	immersed interface method

IMM	immersed membrane method
LBM	lattice boltzman method
LES	large eddy simulation
LUD	Linear upwind differencing
MPI	message passing interface
MULES	Multi-dimensionsal limiter for explicit solution
NBF	non-boundary fitted
NBF-VOF	non-boundary fitted/volume of fluid
PDEs	partial differential equations
PF	peak flow
PIV	particle image velocimetry
PLIC	piecewise linear interface construction
RANS	reynolds average navier stokes
RBC	red blood cell
RC	right coronary
RSS	reynolds shear stress
WDN	Water Distribution Netwo

CHAPTER 1

INTRODUCTION

1.1 Overview

Solid Propellant Rocket Motor (SRM) is a non-trivial part in aerospace technology. It is not a new technology but very reliable and being used as part of the space rocket launching around the world. The rocket motor is a fundamental piece of a rocket that used to boost a rocket [1]. It comprises of a case, insulator, cap, nozzle, igniter, and so forth (see Figure 1). It works utilizing standards, for example, pressure vessels since it stores the fuel. Rocket motor working conditions could be in high temperature and pressure [2].

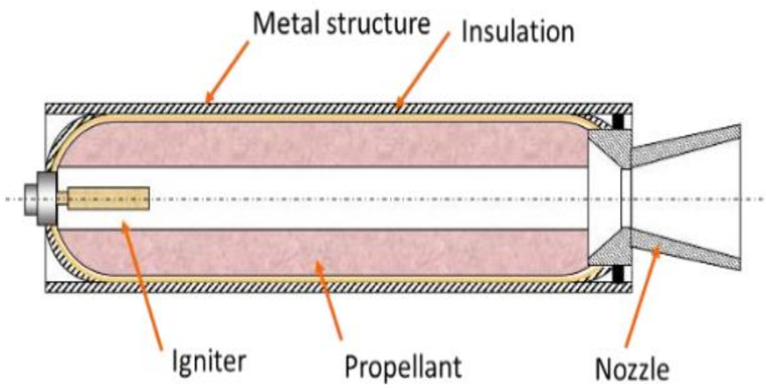

Figure 1.1: Major component of the SRM.

Solid propellant rocket motor is one of many available methods to propel space vehicles, rockets and ballistic purposes. They generate high-temperature gaseous products during combustion to provide thrust to the rocket and convert chemical energy into kinetic energy. It is composed of few chemical components such as oxidizer, fuels, binders, plasticizers, curing agents, stabilizers and cross linkers [2]. The benefits of solid rocket fuels include: (i) simplicity, which is significant for upkeep expenses and savings in high creation rate systems; (ii) storage stability, with administration lifetimes that can be up to 30 years;(iii) protection from unintended explosion; (iv) dependability, identified with their simplicity and chemical stability; and (v) high mass flow rates during launch, and thus high thrust (drive power), a prerequisite for the underlying period of rockets, all of which utilize solid propellant boosters. Two disservices of solid propellants are the trouble in differing thrust on request (i.e., solid fuel rockets for the most part cannot be throttled or worked in start-stop mode) and generally low specific impulse (time indispensable of the thrust per unit weight of propellants), Isp, in examination with fluid fuel motors.

The historical background of rocket (and along propellant) development is firmly identified with military applications. Be that as it may, other than military applications, from the earliest starting point of development, rockets with solid propellants have discovered a variety of non-military uses like signaling and fireworks. Current solid propellants have advanced the field of utilization of rocket missiles for common/logical use to sounding rockets and launch vehicles (see Figure 2). A sounding rocket is the most popular type of rocket at the moment. This is due to the fact that it is an experimental rocket that is used to perform scientific experiments and to carry the scientific instruments. NASA is one of the pioneer in this technology in 1950s and then it now become a tool for the universities around the world to test their scientific experimental works related to the micro gravity phenomenon. Another factor that makes sounding rocket is popular because it is cheaper than to the real space rocket that can cost a multi millions of dollars or Ringgit.

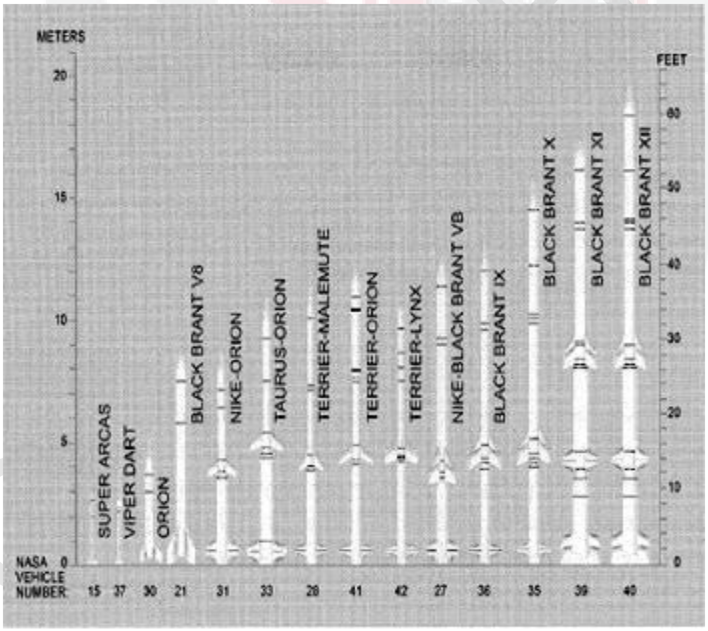

Figure 1.2: NASA Sounding Rocket Family (Sounding rocket, Marcello Lappa, in Fluids, Materials and Microgravity, 2004).

As solid propellants after ignited can create huge amounts of gas for a brief timeframe, it can likewise be utilized to deliver force (i.e., mechanical work) or power. This application has prompted the expansion other application in recent years in various security devices with purposes in the automotive and aviation industries, among them inflators in airbags. Different applications included different partition components, pyrotechnic valves and actuating devices, emergency frameworks, and devices intended to guarantee auxiliary propulsion.

Solid propellant rocket motor is utilized for propelling various missiles and aerospace vehicles including the space shuttle and Titan launch vehicle. These rocket motors include a motor case which surrounds a solid propellant having a star or other shaped hollow core which defines a combustion chamber, an igniter assembly, which is usually mounted on top of the propellant, and a bottom mounted nozzle assembly [1]. The igniter assembly initiates burning of the propellant generating hot combustion gases which travel through the core, initiating combustion along the exposed propellant surfaces. The propellant then burns radially towards the motor case, generating additional hot gases which exit through the nozzle assembly, thereby providing forward thrust. A rocket motor does not require air for combustion of the fuel and such motor produces thrust at all speeds, including take-off [2].

1.2 SRM Component

In general, the SRM is divided into two main part namely the rocket motor and its propellant. The rocket motor case design relies on the inside pressure factor and material been used. A thick-walled chamber been used for high internal pressure area in rocket motor case. The higher yield strength of the materials, the thinner walled chamber can be used in the rocket motor design [3]. To ensure the success and safety of the SRM, the design and testing processes should be done thoroughly. Computational Fluid Dynamics (CFD) tool has been used as part of the design tool since the beginning of its existence. This is because the tool is cheap but with acceptable accuracy and can be used without any safety issue. Recent progress in numerical approach and computing power also contribute to the accuracy of CFD results [4].

The propellant grain or it is called the solid fuel. The grain consists of three main materials namely the fuel, the oxidizer, and the binder. Some grain includes the inducer or some amplifier to hasten the combustion process. A propellant grain depends on the size and the shape of the mold. This will determine the burn time, amount of gas, and rate produced from the burning propellant and, consequently, thrust vs time profile. The shape is the main factor that determines the burn type. There are three main burns namely progressive regressive and neutral burn. Progressive burn uses a star shape, regressive burn uses cylinder shape and neutral burn uses single perforation shape (see Figure 3).

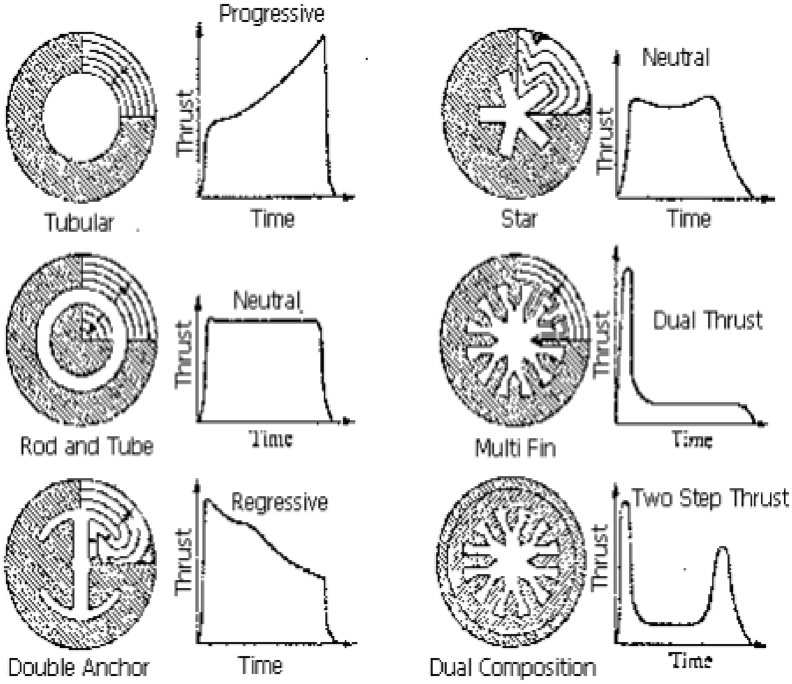

Figure 1.3: Core shape and its influence on the output thrust.

1.3 Motivation

Even though many research work has been carried out into the area of solid propellant rocket, there are many reasons why the author feel it is still important topic to be ventured into. The first reason is that the lack of related local scientific work in the local and regional regions. Many published works were conducted in well-established facilities in either in developed countries such as Europe, the US, or China. Consequently, they managed to develop the capabilities in terms of human resource, facilities, and knowledge. Hence, they can use it for space technologies for the telecommunication and also for defense technologies to be used especially for border security. Therefore, it is important to develop the local capabilities in order to stay relevant or at least to catch up with the world leader.

Another reason why this work is important is because there is no documented standard operating procedure exists in Malaysia. From the discussion with the Ministry of Defense and the Police, any work related to explosive materials should get approval from the authorities and the testing facilities should also be approved before any tests should be conducted. The only facility for such requirement in Malaysia is located at Batu Arang, belongs to STRIDE, the research wing of the Malaysian Ministry of Defense. Therefore, with a documented SOP, it will become a reference to all researchers that wanted to endeavor into this research area.

1.4 Problem Statement

There are many factors affecting SRM design such as thrust requirement, material requirement, rocket body requirement, and weight requirement among others. The critical part of the SRM is the connecting part where usually bolts connection were used. It is proposed that the SRM can be used for several times so that cost of the experiment can be reduced hence reducing the overall cost to design SRM. This bolt connection however is not strong enough to withstand several combustion processes. Usually, the bolt will fail after 1 or 2 static firing tests. Therefore, it is proposed that a new bolt connection to solve this problem.

In addition to that, nozzle design plays an important role in enhancing the performance of the SRM. Popular approach is by using a clean without any flow control device nozzle. This approach however is producing a type of thrust flow that difficult to be controlled. This is due to the fact that a flow control device is the only way to control fluid flow. Therefore, by installing a flow control device inside the nozzle, it is hypothesized that it can alleviate the performance of the SRM.

The major problem statement is due to the fact that experimental work will cost more time and money. Hence, using CFD during the design phase will reduce time and money consumption to design SRM. Other advantage of using CFD to analyze the flow properties is it will validate the performance of the SRM design before it been fabricated. Since there is restriction in any work related to explosive materials and the testing facilities, using CFD to design SRM will give a huge advantage in the rocketry industry.

1.5 Aim and Objectives

The aim of this project is to investigate the performance of the new design of SRM. To achieve this aim, there are three main objectives which are as follow:

1. To improve the SRM by installing a flow control mechanism into the nozzle and enhancing the bolt connection of the nozzle.
2. To evaluate the reliability of the proposed bolt connection performance.
3. To assess the effect of the flow control mechanism into the rocket performance.

1.6 Novelty

To the author's knowledge, there is no reported or published work that focusing on bolt connection of the SRM nozzle and the flow control device at the divergence part of the nozzle. The present work attempt to fill up the gap of this research opportunities. Besides that, there is also no CFD simulation work on the controlled nozzle flow, where the flow control device is located. The application of this new SRM design will be for short distance rocket where it is estimated to travel between 1-3 kilometers.

In short, the main novelties of this work are:

1. The new bolt connection between the SRM nozzle and the cylinder part. There is no reported or published data on this particular topic. There is also no reported experimental work on this topic also.
2. The implementation of the flow control device on the divergence part of the SRM nozzle. There is no CFD simulation work on this topic yet.

1.7 Scope of Research

The author set the scope of research according to the work's objectives. They are listed as follow:

1. The flow control device was only located at the divergence area of the nozzle and the new bolt connection of the nozzle only being implemented in the fabricated model
2. The investigation methods will do via CFD simulation and static firing test only. In the CFD simulation, the grid will be generated at sufficient size and numbers. The CFD setup will be based on the previous investigators, therefore no parametric study in CFD method.
3. The turbulent model that was used is based on the Boussinesq approach where it follows the molecular viscosity model and it was the two-equation turbulent model. The flow will be treated as steady flow and only partial of the SRM will be simulated
4. The propellant grain will be limited to potassium nitrate, ferric oxide and epoxy. The mixing of the grain will be done at an approved center by the Malaysian authority. The location for the static firing test was also conducted at the approved center by the Malaysian authority.

1.8 Thesis Organization

The thesis is arranged in a regular format of PhD thesis following the requirement from UPM. Chapter 1 introduces to the background of SRM and its application in the rocket technology. It also highlights the motivation for the study, outlining the aim and objectives of the research. It also discusses about the scope of research work.

Chapter 2 summarises the literature available on SRM. A detailed in-depth review has been carried out in this chapter. The chapter deals with various studies incorporating CFD to study the different parameters related to SRM. The chapter also discussed about the related experimental work that focused on SRM. A summary is provided at the end of the chapter.

Chapter 3 presents the flow chart of the current study. It also presents about the two methods that were used namely the experimental work and the CFD simulation. Furthermore, it presents about the setup used in the experimental and procedure to perform the experimental work. Besides that, it also presents about the CFD setup, and also the manual for simulating the SRM nozzle flow.

Chapter 4 reports about the results. There are two types of results namely the experimental results and the CFD results. The experimental result only focuses on the static firing test. Meanwhile the CFD results will focus on the flow control device that was installed at the divergence shape of the nozzle. The validation and verification of the numerical results was also reported. The results of the parametric study were also discussed. Finally, Chapter 5 concludes the finding of the current work.

REFFERENCES

[1] Dinesh Kumar B, Shishira Nayana B, Design and Structural Analysis of Solid Rocket Motor Casing Hardware used in Aerospace Applications, Aeronaut Aerospace Eng 2016, 5:2

[2] Dennis Moss Pressure vessel design manual (3rdedn), Gulf professional publishing Burlington USA.

[3] Davanas GE, Jensen DW, Netzer (1996) (eds.) Solid rocket motor design chapter 4 of tactical missile propulsion progress in aeronautics and astronautics AIAA 170: 323379.

[4] Shalini Chaturvedi, Pragnesh N. Dave. Solid propellants: AP/HTPB composite propellants. Arabian Journal of Chemistry (2015).

[5] Bryant, G. J. and Lawrence, Evan K.: A Method for Predicting Ignition Energy Requirements of Practical Propellant Systems. Part III, NAVORD Report 6134, Naval Ordnance Lab., Feb. 2, 1959 (Confidential)

[6] Von Elbe, G., Theory of Solid Propellant Ignition and Response to Pressure Transients, Bulletin of the Interagency Solid Propulsion Meeting, Vol. III, July 1963.

[7] William R. Harrigan, Fluid-Structure Interaction Effects On Mass Flow Rates In Solid Rocket Motors, California State Polytechnic University, 2015.

[8] Murdock, John W.; Johnston, William A. “Flow-Structural Interaction in Solid Rocket Motors” NATO RTO-EN-023, Belgium, 2002.

[9] S. Contadin, A. Conte, A. C. Karp, E. T. Jens, D. Vaughan, and D. G. Pastrone. Thermal analysis of a hybrid rocket propulsion system for interplanetary CubeSats. EUCASS Paper, European Conference of Aeronautics and Aerospace Sciences Association, July 2017.

[10] A. Conte. Performance evaluation and thermal analysis of a hybrid rocket propulsion system for interplanetary CubeSats. MSc thesis in press, Politecnico di Torino, Turin, Italy, 2017.

[11] Kuentzmann, P. & Laverdant, A. Experimental determination of the response of a solid propellant to high-frequency pressure oscillation. Res. Aerospatale, 1984, l 1, 39-55.

[12] Lupoglazoff, N. & Vuillot, F. Simulations of solid propellant rocket motor instability including propellant propellant combustion response. In the 6th

International Conference on Sound and Vibration, Lyngby (Denmark), 1999. ONERA –TP-1999-133.

[13] Anthoine, J. & Mettenleiter, M. Influence of adaptive control on vortex-driven instabilities in a scaled model of solid propellant motors. J. Sound Vibration, 2003, 206, 1009-1046.

[14] Javed, A. & Chakraborty, D. Damping coefficient prediction of solid rocket motor nozzle using computational fluid dynamics. J. Propulsion Power, 2013, 30(1), 19–23. doi:10.2514/1.B35010

[15] Jacob, E.J. & Flandro, G.A. Thrust oscillations in large solid rocket boosters. AIAA Paper No. 2008-4601.

[16] Fabignon,Y.; Dupays, J.; Avalon, G.; Vuillot, F.; Lupoglazoff, N.; Casalis, G. & Michel, P. Instabilities and pressure oscillations in solid rocket motors. Aerospace Sci. Technol., 2003, 7, 191–200. doi:10.1016/S1270-9638(02)01194-X

[17] Guéry, J. Numerical modeling of internal flow aerodynamics part 2: Unsteady flows. in internal aerodynamics in solid rocket propulsion, RTO educational notes EN-023 AVT-096, AVT-VKI presentation on 27-31 May 2002 in Rhode-Saint-Genèse, Belgium.

[18] Chakravarthy, V. Kalyana; Iyer, Arvind & Chakraborty, Debasis. Quasi-one-dimensional modeling of internal ballistics and axial acoustic oscillations in solid rocket motors. J. Propulsion Power. (Online: April 15, 2016) doi: 10.2514/1.B35754

[19] Jackson, T.L. Modeling of heterogeneous propellant combustion: A survey. AIAA Journal, 2012, 50(5), 993-1006.

[20] Shimada, T., Sekiguchi, M., and Sekino, N., "Numerical Analysis of Flow inside a Solid Rocket Motor with Relation to Nozzle Inlet Ablation," AIAA 2006-3891, 36th AIAA Fluid Dynamics Conference and Exhibit, 5-8 June 2006, San Francisco, California. Also, to be published in AIAA Journal.

[21] Sabnis, J.S., "Numerical Simulation of Distributed Combustion in Solid Rocket Motors with Metallized Propellant," Journal of Propulsion and Power, Vol. 19, No.1, 2003, pp. 48-55

[22] Shimada, T., Daimon, Y., and Sekino, N., Computational Fluid Dynamics of Multiphase Flows in Solid Rocket Motors, JAXA Special Publication, JAXA-SP-05-035E, March 2006.

[23] Sekino, N. and Shimada, T., "Eulerian-Lagrangian Approach for Numerical Simulation in Solid Rocket Motors," Proceedings of 24th

International Symposium on Space Technology and Science, Miyazaki, Japan, May 30-June 6, 2004, ISTS 2004-a-22, pp.57-63, 2004.

[24] Henderson, C.B., “Drag Coefficient of Spheres in Continuum and Rarefied Flows,” AIAA Journal, Vol.14, No.6, 1976.

[25] Kavanau, L. L. and Drake, R. M., Jr., “Heat Transfer from Sphere to a Rarefied Gas in Subsonic Flow,” Univ. of California, Rept. HE-150-108, p.9, 1953.

[26] Gordon, S. and McBride, B.J., “Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations,” NASA-SP-273, 1971. also, Mcbride, B. NASA Center for AeroSpace Information (CASI), LEW-15113, 19940101; Jan 1, 1994.

[27] Hermsen, R.W., “Aluminum Combustion Efficiency in Solid Rocket Motors”, AIAA-81-0038, 1981.

[28] Widener, J.F. and Beckstead, M.W., “Aluminum Combustion Modeling in Solid Propellant ombustion Products”, AIAA-98-3824, 1998.

[29] Beckstead, M.W., “Modeling Aluminum Combustion,” RTO AVT/VKI special course, Von Karman Institute for Fluid Dynamics, May 2002.

[30] Salita, M, “Quench Bomb Investigation of Al2O3 Formation from Solid Rocket Propellants (Part II): Analysis of Data,” 25th JANAF Combustion Meeting, CPIA 498 (Vol. I), 1988.

[31] Sutton, George P. (2001)., “Solid Propellant Rocket Fundamentals,” Rocket Propulsion Elements, 7th ed., John Wiley and Sons, pp. 474-475.

[32] Sutton, George P. (2001), ““Nozzle Theory and thermodynamic relations,” Rocket Propulsion Elements, 7th ed., John Wiley and Sons, pp. 46.

[33] J. Szmelter, “Burning surfaces evolution in solid propellants: a numerical model”, JAERO102, Proc. IMechE, Vol. 221, Part G: J. Aerospace Engineering.

[34] G. Young, “Modelling of Rocket Motor Ballistics for Functionally Graded Propellants”, Proc. of 40th JANNAF Combustion Meeting, 2003.

[35] S.M. Ivanov, “Estimate of the Dynamic Characteristics of Unsteady Combustion of a Solid Propellant in a Semi-Closed Volume from Measurements of Variable Pressure”, translated from Fizika Goreniya i Vzryva, Vol. 38, No. 1, Jan.-Febr. 2002, pp. 80-91.

[36] S.T. Surzhikov, “Quasi-One-Dimensional Model of Combustion of Sandwich Heterogeneous Solid Propellant”, Teplofizika Vysokikh Temperatur, Vol. 39, No. 4, 2001, pp. 629-639.

[37] Richard A. Nakka, “RNX Composite Propellant,” Richard Nakka‟s Experimental Rocketry Web Site [online], http://www.nakka-rocketry.net/rnx_int.html [retrieved September 2019].

[38] Richard A. Nakka, “Solid Propellant Rocket Motor Design and Testing,” April 1984.

[39] Richard A. Nakka, “Igniter Systems,” Richard Nakka’s Experimental Rocketry Web Site [online], http://www.nakka-rocketry.net/igniter.html [retrieved September 2019].

[40] Richard A. Nakka, “Solid Rocket Motor Theory - Impulse and C-star,” Richard Nakka‟s Experimental Rocketry Web Site [online], http://www.nakka-rocketry.net/th_imp.html [retrieved September 2019].

[41] Richard A. Nakka, “Solid Paradigm Rocket Motor,” Richard Nakka‟s Experimental Rocketry Web Site [online], http://www.nakka-rocketry.net/paradigm.html [retrieved September 2019]

[42] Gorden E. Jensen and David W. Netzer, “Tactical Missle Propulsion,” Vol. 170, Progress in Astronautics and Aeronautics, AIAA, July 1996, pp. 191-192.

[43] Charles D. Brown, “Spacecraft Propulsion,” AIAA Education Series, 1996, pp. 135-136.

[44] FAA, System Engineering Manual Version 3.1, Section 4.6, Trade Studies, Federal Aviation Administration, 2006.

[45] F. S. Billig, ‘‘Tactical Missile Design Concepts,’’ in Tactical Missile Propulsion, G. E. Jensen and D. W. Netzer, Eds., American Institute of Aeronautics and Astronautics, Reston, VA, 1996.

[46] C. E. Carr, A. Neri, and R. E. Black, Aerospace Am. 54, 59 (2016).

[47] P. Kuentzmann, Introduction to Solid Rocket Propulsion, RTO-EN-023 (2004).

[48] S. A. Rashkovskiy, Y. M. Milyokhin, and A. V. Fedorychev, ‘‘Combustion of Solid Propellants with Energetic Binders,’’ in Chemical Rocket Propulsion: A Comprehensive Survey of Energetic Materials, L. T. DeLuca, T. Shimada, V. P.Sinditskii, and M. Calabro, Eds., Springer, New York, 2017.

[49] H. G. Ang and S. Pisharath, Energetic Polymers: Binders and Plasticizers for Enhancing Performance, Wiley, New York, 2012.

[50] G. E. Jensen and D. W. Netzer, ‘‘Tactical Missile Propulsion,’’ AIAA Progress in Astronautics and Aeronautics, Vol. 170, American Institute of Aeronautics and Astronautics, Reston, VA, 1996.

[51] J. D. Hunley, ‘‘History of Solid Propellant Rocketry. What We Do and Do Not Know,’’ presented at the 35th AIAA/SAE/ASME Joint Propulsion Conference and Exhibit, Los Angeles, CA 1999.

[52] R. Carlisle, Powder and Propellants: Energetic Materials at Indian Head, Maryland 1890-2001, 2nd ed., University of North Texas Press, Denton, 2002.

[53] T. L. Moore, ‘‘Assessment of HTPB and PBAN Propellant Usage in the United States,’’ presented at the AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Seattle, WA, 1997.

[54] N. Fishman and J. A. Rinde, ‘‘Solid Propellant Mechanical Properties Investigations,’’ Quarterly Progress Report No. II, SRI Project No. PRU-4142, 1962.

[55] T. H. Duerr and B. P. Marsh, ‘‘Solid Propellant Grain Structural Behavior,’’ in Tactile Missile Propulsion, G. E. Jensen and D. W. Netzer, Eds., American Institute of Aeronautics and Astronautics, Reston, VA, 1996.

[56] Singh S (2013) Solid rocket motor for experimental sounding rockets advances in aerospace science and applications 3: 199-208.

[57] Mehmet Özer Havlucu, Kadir Kırkköprü, “Numerical Simulation of Flow in a Solid Rocket Motor: Combustion Coupled with Regressive Boundary”. Journal of Multidisciplinary Engineering Science and Technology (JMEST), Vol. 3 Issue 1, January – 2016, Page 3790-3798.

[58] M. Yumusak, “Non-reacting and reacting flow analysis in propulsion systems”, Ph.D. Dissertation, The Middle East Technical University at Ankara, 2000.

[59] M. Yumusak, “Analysis and design optimization of solid rocket motors in viscous flows”, Computers and Fluids, Vol. 75, pp. 22-34, 2013.

[60] Q. Li, G. He, P. Liu, and J. Li, “Coupled simulation of fluid flow and propellant burning surface regression in a solid rocket motor”, Computers and Fluids, Vol. 93, pp.146-152, 2014.

[61] R. C. Rogers and W. Chinitz, “Using a global hydrogen-air combustion model in turbulent reacting flow calculations”, AIAA Journal, Vol 21. No.4, pp. 586-592, 1982.

[62] ANSYS/Fluent, Software Package, Ver. 15.0, ANSYS, Canonsburg, PA, 2013.

[63] D. Greatrix, “Numerical evaluation of the use of aluminum particles for enhancing solid rocket motor combustion stability”, Energies, Vol. 8, pp. 1195-1215, 2015.

[64] J. Montesano, K. Behdinan, D.R.Greatrix, Z. Fawaz, “Internal chamber modeling of a solid rocket motor: effects of coupled structural and acoustic oscillations on combustion”, Journal of Sound and Vibration, Vol. 311, pp. 20-38, 2008.

[65] L. Wang, Z. Wu, H. Chi, C. Lui, H. Tao, Q.Wang, “Numerical and experimental study on the solid-fuel scramjet combustor”, Journal of Propulsion and Power, Vol. 31, No.2, pp. 685-693, 2015.

[66] M. J. Ward, S. F. Son, and M. Q. Brewster, “Role of gas- and condensed-phase kinetics in burning rate control of energetic solids”, Combustion Theory and Modeling, Vol. 2 (3), pp. 293–312, 1998.

[67] P. Kuentzmann, “Introduction to solid rocket propulsion”, Internal Aerodynamics in Solid Rocket Propulsion, RTO Educational Notes EN-023, 2004.

[68] P. Alavilli, J. Buckmaster, T. L. Jackson, and M. Short, “Ignition-transient modeling for solid propellant rocket motors”, AIAA, Vol. 3567, pp. 1-9, 2000.

[69] M. Uygun, K. Kirkkopru, “Numerical simulation of unsteady flows in solid rocket motors with dual time stepping”, ITU Journal/d: Engineering, Vol. 8(2), pp. 41-52, 2009.

[70] J. Terzic, B. Zecevic, S. Serdarevic-Kadic, and A. Catovic, “Numerical simulation of internal ballistics parameters of solid propellant rocket motors”, 15th Seminar “New Trends in Research of Energetic Materials”, University of Pardubice, Part II, pp. 881-892, 2012.

[71] S. Apte, and V. Yang, “Unsteady flow evolution and combustion dynamics of homogenous solid propellant in a rocket motor”, Combustion and Flame, Vol. 131 (1-2), pp.110-131, 2002.

[72] W. A. El-Askary, S. A. Wilson, and A. Hegab, “Simulation of reactive fluid flow in a solid rocket motor combustion-chamber with/without nozzle”, CMES, Vol. 76 (4), pp. 235-266, 2011.

[73] J.B. PAUTRIZEL, A. ROBLIN, P. PEREZ, V. RIALLAND - Absorption-Scattering Coupling for the Infrared Signature of an Aluminized Solid Rocket Motor. Proceedings of the 6th International Symposium on Radiative Transfer, Antalya, Turkey, 13-19 June 2010.

[74] J.B. DARGAUD, J. TROYES, J.M. LAMET, L. TESSé, F. VUILLOT, C. BAILLY - Numerical Study of Solid-Rocket Motor Ignition Overpressure Wave Including Infrared Radiation. Journal of Propulsion and Power, 30(1), pp. 164-174, 2013.

[75] J. DUPAYS, Y. FABIGNON, P. VILLEDIEU, G. LAVERGNE, J.L. ESTIVALEZES - Some Aspects of Two-Phase Flows in Solid-Propellant Rocket Motors. Solid Propellant Chemistry, Combustion, and Motor Interior Ballistics, Vol. 185, Progress in Astronautics and Aeronautics, AIAA, Reston, 2000, pp. 859-883.

[76] J. DUPAYS, F. GODFROY, O. ORLANDI, P. PRéVOT, M. PRéVOST, S. GALLIER, S. BALLEREAU, Y. FABIGNON - Inert Condensed Phase Driving Effect of Combustion Instabilities in Solid Rocket Motor. Space Propulsion 2008, May 5-9, 2008, Heraklion, Greece.

[77] L. PASCAL, P. PRéVOT, P. REULET, J. DUPAYS, J. ANTHOINE - Development of a Test Facility for Investigating the Solid Rocket Motor Base Region in Representative External Flow Conditions. To be presented at Space Propulsion 2016, Roma, Italy, 2-6 May 2016.

[78] S. GALLIER, F. GODFROY - Aluminum Combustion Driven Instabilities in Solid Rocket Motors. Journal of Propulsion and Power 25 (2) 509-521, 2009.

[79] D. DAVIDENKO, Y. FABIGNON - Some Aspects of Detailed Modeling of Solid Rocket Composite Propellants. 6th EUCASS, Krakow, Poland, 29 June - 3 July 2015.

[80] M. PLAUD, S. GALLIER, M. MOREL - Simulations of Heterogeneous Propellant Combustion: Effect of Particle Orientation and Shape. Proceedings of the Combustion Institute, Vol. 35, 2015, pp. 2447-2454.

[81] M.L. GROSS, T.D. HEDMAN, S.F. SON, T.L. JACKSON, M.W. BECKSTEAD - Coupling Micro and Meso-Scale Combustion Models of AP/HTPB Propellants. Combustion and Flame, Vol. 160, 2013, pp. 982–992.

[82] Brewster M. Q., Mullen J. C., 2011, Burning-rate behaviour in aluminized wide-distribution AP composite propellants Combustion, Explosion and Shock Waves; 47, 2, 200-208.

[83] Beckstead M.W., Puduppakkam K., Thakre P., and Yang V., 2007, Modelling of combustion and ignition of solid-propellant ingredients. Prog. Energy Combust. Sci., 33(6), 497–551.

[84] Boldyrev V.V., 2006, Thermal decomposition of Ammonium Perchlorate; Thermochim. Acta, 443, 1.

[85] Brill, T.B. and Budenz, B.T., 2000, Flash pyrolysis of ammonia erchloratehydroxylterminated- polybutadiene mixtures including selected additives. Solid Propellant Chemistry, Combustion and Motor Interior Ballistics, Progress in Astronautics and Aeronautics, AIAA, NY, Vol. 185, 3–23.

[86] Chen, J.K. and Brill, T.B., 1991, Chemistry and kinetics of hydroxylterminated polybutadiene (HTPB) and diisocyanate-HTPB polymers during slow decomposition and combustion-like conditions. Combust. Flame, 87, 217–232.

[87] Chu, W. and Yang, V., 1996, Combustion of AP-based composite propellant in a rocket motor flow environment. 32nd Joint Propulsion Conference, AIAA, 96–2885.

[88] Cai, W.D., Thakre, P. and Yang, V., 2008, Model of AP/HTPB composite propellant combustion in rocket motor environments. Combust. Sci. Tech., 180, 2143–2169.

[89] Galfetti L., Severini F, DeLuca L.T., Marra G.L., Meda L., Braglia R., 2004, Ballistics and Combustion Residues of Aluminized Solid Rocket Propellants, Proceedings of the 9-IWCP, Novel Energetic Materials and Applications, vol. 18.

[90] Jackson, T.L. and Buckmaster, J., 2002, Heterogeneous propellant combustion. AIAA J., 40(6), 1122–1130.King, M.K. (1978) Model for steady state combustion of unimodal composite solid propellants. AIAA Paper 1978-216.

[91] Sharad N. Pachpute, Combustion in Rocket Engine and Its CFD Modeling https://cfdflowengineering.com/rocket-engine-combustion/, retrieved on 11/11/2021

[92] Beckstead, Merrill W., R. L. Derr, and C. F. Price. "A model of composite solid-propellant combustion based on multiple flames." AiAA Journal 8, no. 12 (1970): 2200-2207.

[93] Lee, Sung-Taick, Edward W. Price, and Robert K. Signan. "Effect of multidimension al flamelets in composite propellant combustion." Journal of Propulsion and Power 10, no. 6 (1994): 761-768.

[94] Hegab, A. M., H. H. Sait, A. Hussain, and A. S. Said. "Numerical modeling for the combustion of simulated solid rocket motor propellant." Computers & Fluids 89 (2014): 29-37.

[95] Raun, R. L., A. G. Butcher, and M. W. Beckstead. "Slope break and high pressure combustion instability." In 28th JANNAF Combustion Subcommittee Meeting Proceedings. Chemical Propulsion Information Agency (CPIA) Publication, vol. 573. 1991.

[96] Binauld, Quentin, Jean-Michel Lamet, Lionel Tessé, Philippe Rivière, and Anouar Soufiani."Numerical simulation of radiation in high altitude solid propellant rocket plumes." Acta Astronautica 158 (2019): 351-360.

[97] Sams IV, Oliver C., Joseph Majdalani, and Tony Saad. "Mean flow approximations for solid rocket motors with tapered walls." Journal of Propulsion and Power 23, no. 2 (2007): 445-456.

[98] Toro, Eleuterio F., Michael Spruce, and William Speares. "Restoration of the contact surface in the HLL-Riemann solver." Shock waves 4, no. 1 (1994): 25-34.

[99] Dombrovsky, Leonid A., and Truc-Nam Dinh. "The effect of thermal radiation on the solidification dynamics of metal oxide melt droplets." Nuclear engineering and design 238, no. 6 (2008): 1421-1429.

[100] Tseng, Charles C., and Raymond Viskanta. "On the hypothesis of internal phase change." International communications in heat and mass transfer 32, no. 10 (2005): 1267-1272.

[101] Godunov, Sergei Konstantinovich. "A difference method for numerical calculation of discontinuous solutions of the equations of hydrodynamics." Matematicheskii Sbornik 89, no. 3 (1959): 271-306.

[102] Carlson, Donald J., and Richard F. Hoglund. "Particle drag and heat transfer in rocket nozzles." Aiaa Journal 2, no. 11 (1964): 1980-1984.