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Solid Fuel Regression Rate Test Device Design and Testing: Developing an Easy-to-Use and Affordable Approach

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Abstract

This research presents the development of a solid fuel regression rate test device for evaluating the burning rate of propellants used in hybrid rocket motors. The device features a combustion chamber with a rectangular recess structure, an adjustable igniter, a pressure measurement port, an air inlet system, a Laval sprayer nozzle, and a fixing slot for the propellant. By adjusting the combustion chamber pressure and oxidant flow, the device enables the investigation of the functional relationship between burning rate and pressure intensity and oxidant flow. The device offers a simplified testing process, with advantages such as a simple structure, low cost, ease of processing, and safe and reliable operation.

Keywords: Solid fuel regression rate, hybrid rocket motor, combustion chamber, pressure measurement, oxidant flow, test device.

Introduction

The development of hybrid rocket motors has gained significant attention in the field of propulsion systems. These motors offer advantages such as increased safety, simplified logistics, and improved performance compared to traditional solid and liquid rocket motors. A critical aspect in the design and optimization of hybrid rocket motors is the characterization of the burning rate of the solid propellant used. The burning rate, or regression rate, of the propellant plays a crucial role in determining the motor's thrust and overall performance. Accurate measurement and understanding of the burning rate are essential for motor design, performance prediction, and combustion stability analysis. Therefore, the need for a reliable and cost-effective test device to evaluate the solid fuel regression rate arises (Alay Hashim et al. 2019).

In response to this demand, this research focuses on the design and development of a solid fuel regression rate test device. The objective is to create a device that offers a simplified testing process, allowing for efficient and accurate evaluation of the burning rate. The device incorporates various features to achieve this goal, including a combustion chamber with a rectangular recess structure, an adjustable igniter, a pressure measurement port, an air inlet system, a Laval sprayer nozzle, and a fixing slot for the propellant.

The key innovation of the proposed test device lies in its ability to adjust the combustion chamber pressure intensity and oxidant flow. By manipulating these parameters, it becomes possible to establish a functional relationship between the burning rate and the pressure intensity and oxidant flow. This functionality reduces the complexity of the testing process and enables a more comprehensive analysis of the propellant's performance (Zhang and Sun 2017). Furthermore, the test device is designed to be simple in structure, cost-effective, easy to process, and operate safely and reliably. These qualities ensure accessibility to researchers and engineers involved in hybrid rocket motor development, allowing for widespread testing and evaluation of various propellant formulations (Petrarolo et al. 2018). The outcomes of this research have significant implications for the advancement of hybrid rocket motor technology. The ability to accurately measure and understand the burning rate of solid propellants enables improved motor design, optimization of performance, and enhanced combustion stability. The proposed test device serves as a valuable tool in this endeavour, offering a practical solution that can be employed with different propellant types (Petrarolo et al. 2018).

In conclusion, the solid fuel regression rate test device presented in this research addresses the need for a reliable and cost-effective method of evaluating the burning rate of solid propellants in hybrid rocket motors. By providing adjustable pressure intensity and oxidant flow, the device simplifies the testing process and enables a thorough investigation of the burning rate's dependence on these parameters. The subsequent sections of this study will detail the design, implementation, and evaluation of the test device, highlighting its practicality, affordability, and effectiveness in characterizing solid fuel regression rates for hybrid rocket motor applications (Xiao, Miao, and Zhong 2018).

Related Work

During past years, hybrid rocket engines have gained significant attention due to their safety, reliability, non-toxicity, low cost, and adjustable thrust capabilities. Unlike solid-liquid rocket engines that rely on a significant amount of oxidizer, hybrid rocket engines feature a solid fuel grain that burns with a flowing liquid or gaseous oxidizer. However, the regression rate, which refers to the burning rate of the fuel grain on the motor's surface, tends to be low. This can negatively impact the engine's burning efficiency and overall performance, making the improvement of regression rate a key focus in solid-liquid engine development. Estimating the regression rate of the fuel and determining the oxygen-to-combustion ratio are crucial factors in optimizing the energy utilization and burning efficiency of the solid-liquid rocket propellant (Alay Hashim et al. 2019).

Previous research has introduced a multi-target-line dynamic combustion performance testing system for solid propellant. This system includes a firing chamber, distribution unit, measurement and control unit, and data acquisition process unit. While this testing system is effective in measuring the combustion speed of solid propellant samples within a certain pressure range, it cannot be used to test the regression rate of the fuel. This is because the fuel does not contain a significant amount of oxidizer, and using the target collimation method in such cases can lead to dangerous accidents when the fuel is exposed to high-concentration oxygen (Alay Hashim et al. 2019). The rate at which the solid fuel regresses is a key parameter in analyzing the performance of hybrid rockets. Previous studies, both theoretical and experimental, have indicated a correlation between the regression rate and the total pressure within the combustion chamber. This relationship is often attributed to the presence of oxygen below the flame zone and the occurrence of heterogeneous reactions on the fuel surface, which influence the pyrolysis process. To investigate this further, an experimental program was conducted at the Space Propulsion Laboratory of Politecnico di Milano. The results obtained within the tested operating conditions, along with their associated uncertainty ranges, demonstrated a neutral trend in the solid fuel regression rate as the pressure increased. The experimental setup involved the use of hydroxyl-terminated polybutadiene as the fuel, combined with gaseous oxygen at pressures ranging from 4 to 16 bar (Ozawa et al. 2019; Sun et al. 2010). To account for the observed pressure dependency, a simplified analytical model that captures the fundamental physics was developed, along with a corresponding numerical simulation. The findings of this model are presented herein. The experimental results were utilized as input for the developed model, enabling the derivation of a semi-empirical pyrolysis rate law that provides insights into the potential influence of pressure.

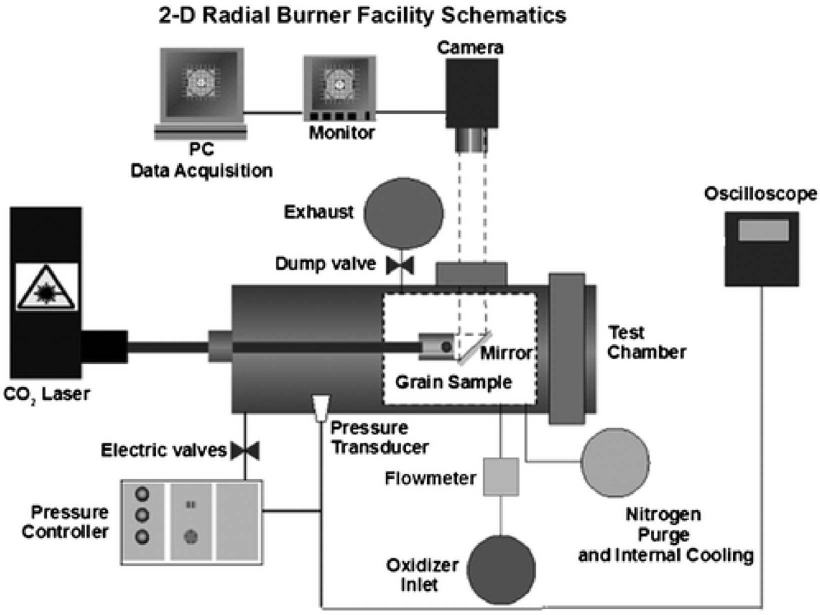

Fig- Solid-Fuel Regression Rate Modeling for Hybrid Rockets

Another approach described in a United States Patent (USP) is an optical fiber sensor for testing the regression rate of solid/mixed rocket engine powder columns. This sensor utilizes fiber bundles inserted into the solid fuel tank or hybrid rocket engine, extending from the fuel powder column wall to the housing periphery. The fiber bundles detect the regression rate and remaining amount of the fuel by monitoring the ignition flame at the fiber's end. This method provides accurate measurement of the regression rate, but it requires special fibers, light-emitting diodes, and photodetectors, increasing the overall cost and complexity of the dynamic testing system (Xiao et al. 2018). Additionally, factors such as environmental conditions and temperature can affect the accuracy of the test, and the high temperatures during fuel combustion can impact the integrity and reliability of the optical components (Shrivastava 2018).

Considering these limitations, there is a need for a solid fuel regression rate test device that overcomes these challenges and provides a practical, cost-effective, and reliable solution. The present research aims to address this need by introducing a novel test device that simplifies the testing process and allows for efficient evaluation of the burning rate of solid fuel in hybrid rocket motors. The device utilizes a combustion chamber with a rectangular recess structure, an adjustable igniter, a pressure measurement port, an air inlet system, a Laval sprayer nozzle, and a fixing slot for the propellant. By adjusting the combustion chamber pressure intensity and oxidant flow, the device enables the establishment of a functional relationship between the burning rate and these parameters. This approach reduces the complexity of the testing process and provides valuable insights into the fuel's performance (Zhang and Sun 2017).

The proposed test device offers several advantages, including a simple structure, low cost, ease of processing, and safe and reliable operation. It provides researchers and engineers in the field of hybrid rocket motor development with an accessible tool for testing the solid fuel regression rate. The device does not impose strict requirements on the propellant and can be used with different propellant formulations as long as they are prepared in a rectangular form (Shrivastava 2018). Overall, the test device presented in this research contributes to the advancement of hybrid rocket motor technology by enabling accurate measurement and evaluation of the solid fuel regression rate, leading to improved motor design, performance optimization, and enhanced combustion stability (Petrarolo et al. 2018).

Research Objective

The objective of this research is to design and develop a solid fuel regression rate test device that allows for efficient and cost-effective testing of the burning rate of propellants used in hybrid rocket motors. The device aims to simplify the testing process by providing adjustable pressure intensity and oxidant flow, enabling the exploration of the functional relationship between burning rate and these parameters. The research also aims to assess the device's performance, safety, and reliability.

Solid Fuel Regression Rate Test Device

The solid fuel regression rate test device consists of various components that allow for efficient testing. It includes a firing chamber, an inlet plate, a draft tube, a counter balance pocket, a pressure measurement mouth, a Laval nozzle, and a draw-in groove. The firing chamber is designed as a rectangular groove, and a rectangular upper cover is placed on top. The upper cover has screws at its front and back ends. The igniter is located at the front of the upper cover and is connected to the firing chamber. The pressure measurement mouth is fixed in the middle of the upper cover and communicates with the firing chamber (DeLuca et al. 2011; Galfetti et al. 2011). The front end of the chamber also has screws, and the draft tube is attached to the front end of the counter balance pocket and connected to the chamber. The inlet plate is positioned between the counter balance pocket and the firing chamber. The Laval nozzle is fixed at the rear end of the firing chamber using a jet pipe cover. The draw-in groove is located in the middle of the inner bottom surface of the firing chamber and serves as a place to put the solid fuel column for testing. The draw-in groove consists of two rectangular parallelepipeds perpendicular to the firing chamber's inner bottom surface. They are adjacent to the two sides of the firing chamber, and the spacing in the groove matches the length of the fuel column. The height of the draw-in groove is half the height of the fuel column. The inlet plate is disc-shaped and has a flaring type air admission hole at the center. Multiple air admission holes of the same flaring type and varying sizes are evenly distributed around the center hole to allow for different airflow rates during testing.

The solid fuel regression rate test device is designed with several components that work together to facilitate efficient testing of solid fuel. Let's take a closer look at each component and its role in the testing process.

1. Firing Chamber: The firing chamber is the main enclosure where the combustion takes place. It is designed as a rectangular groove to provide a suitable space for the fuel column. The rectangular upper cover is placed on top and secured with screws, creating a sealed chamber.
2. Igniter: Positioned at the front of the upper cover, the igniter is responsible for initiating the combustion process. It provides the necessary spark or heat to ignite the solid fuel.
3. Pressure Measurement Mouth: Located in the middle of the upper cover, the pressure measurement mouth allows for the measurement of pressure inside the firing chamber during the testing. It provides valuable data on the combustion process and helps analyze the performance of the solid fuel.
4. Draft Tube and Counter Balance Pocket: The draft tube is connected to the front end of the firing chamber through the counter balance pocket. This configuration ensures balanced airflow and regulates the intake of air and fuel into the firing chamber. It helps maintain controlled conditions for accurate testing.
5. Inlet Plate: Positioned between the counter balance pocket and the firing chamber, the inlet plate plays a crucial role in controlling the airflow rate during the testing process. It is disc-shaped and has a flaring type air admission hole at the center. Multiple air admission holes of varying sizes are evenly distributed around the center hole, allowing for precise control of the airflow rate.
6. Laval Nozzle: Fixed at the rear end of the firing chamber using a jet pipe cover, the Laval nozzle optimizes the flow of gases exiting the chamber. It helps create a controlled and efficient flow pattern, contributing to effective combustion.
7. Draw-in Groove: The draw-in groove is located in the middle of the inner bottom surface of the firing chamber. It serves as a designated space to place the solid fuel column for testing. The groove consists of two rectangular parallelepipeds that are perpendicular to the firing chamber's inner bottom surface. They are positioned adjacent to the two sides of the firing chamber. The spacing within the groove matches the length of the fuel column, ensuring a stable position during testing. The height of the draw-in groove is half the height of the fuel column, providing sufficient space for the combustion process.

The solid fuel regression rate test device is designed with simplicity, cost-effectiveness, and safety in mind. It allows for controlled airflow, precise pressure measurement, and accurate monitoring of the regression rate of solid fuel. The inclusion of components like the draft tube, inlet plate, and Laval nozzle ensures efficient combustion and reliable testing results. With its versatile design, the device can be used for testing the regression rate of solid fuel in various applications, such as hybrid rocket motors.

Conclusion

The developed solid fuel regression rate test device offers a practical and economical solution for evaluating the burning rate of solid propellants in hybrid rocket motors. The device's unique features, including the rectangular recess combustion chamber, adjustable igniter, pressure measurement port, and Laval sprayer nozzle, contribute to its simplicity, low cost, ease of processing, and safe operation. By allowing the adjustment of pressure intensity and oxidant flow, the device facilitates the investigation of the relationship between burning rate and these parameters. The device's versatility and compatibility with various propellants make it a valuable tool for testing the solid fuel regression rate. Its implementation can contribute to the advancement of hybrid rocket motor technology by providing accurate and efficient performance evaluation.

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