学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

Applicability of scaled testing for CAMUI-type hybrid rocket regression modelling
(CAMUI 型ハイブリッドロケットの燃料後退モデルにおけるスケール則の適用性)

In recent years, there has been an increase in the development of new rocket systems using hybrid rocket technology. This trend is due to the essentially non-explosive nature of the hybrid propulsion rocket system. Hybrid rockets are inherently safer than their liquid or solid counterparts when the fuel is stored in the solid-state, and the oxidizer is stored in the liquid state, as is the case in this research. These separate states remove the possibility of uncontrolled mixing, and consequently, an explosion if any part of the engine ruptures. This robustness against explosion is a strongly desirable trait, especially in the operation of small, low-cost launchers, be they for suborbital or orbital flights. Once the cost of the launcher hardware is low enough, the ground costs become the main expense, with a substantial part of this being due to risk reduction associated with the explosive nature of conventional solid and liquid bi-propellant rocket engines. Hybrid rockets avoid this cost but have traditionally had too low fuel regression rates and or too small burning surface areas to produce adequate thrust-to-weight ratios for use as launch rockets or their boosters.

The Cascaded Multi-Stage Impinging Jet (CAMUI) engine achieves the high thrust-to-weight ratio needed using the world’s most used plastic, polyethylene. The CAMUI engine achieves high efficiency through its internal fuel geometry design while keeping the high thrust-to-weight ratio, resulting in a solid contender for a commercial low-cost, low-risk, high-performance rocket engine.

Previous research over the last two decades on this engine type has been limited to smaller engine sizes due to available resources. To move beyond the existing proof of concept to commercial launcher-sized engines, understanding the scalability of the CAMUI hybrid rocket regression models is critical.

This thesis investigates the scaling of the CAMUI regression model over an extensive engine size range for the first time, comparing the model to actual firing data from over 30 hybrid rocket firing tests, ranging from 100 mm-diameter-2.5 kN-class engines to 400 mm-diameter-40 kN commercial class engines. For comparison, the currently highest thrust commercial hybrid rocket engine is 80 kN class.

This work is presented in the following chapters: (1) Introduction; (2) Regression model and design method; (3) Test setup; (4) Uncertainty analysis; (5) Uncertainty reduction; (6) Large scale engine development; (7) Discussion; (8) Conclusion.

Chapter 1 describes the background for the research, including the overall market trend in hybrid rockets and the defining of the target engine size and performance based on previous commercially successful engines. This resulted in the target being set as a 40 kN 20 sec burn time engine. This would allow for a single-engine sounding rocket with a 100 kg payload to reach 120 km altitude.

Chapter 2 describes the baseline mathematical formulas used and touches shortly on their development history. It further goes on to detail how these formulas are incorporated in a new way, namely in a time stepped iterative software regression simulator, allowing for continuous modeling of the regression with the changing geometry of the fuel through the burn as opposed to only modeling the before and after burn time values.

Chapter 3 describes the various test setups used to acquire the data analyzed in this work. HDPE is used as a fuel and LOX as an oxidizer for all the test setups. The systems are pressure fed, and all tests are done with CAMUI style engines. To better control start-up transients, the MSS and O-BASAN test setups have been designed to allow for pre-pressurization of the LOX tank and pre-cooling of the feed-line. This was done by including additional LOX valves in the LOX feed-line.

Chapter 4 describes the uncertainty analysis performed. From this, it was found that the most significant simulator error is from the start-up transients, mainly caused by tank pressurization and the movement of LOX through the feed-line. The start-up transients cause uncertainty in the defined burn time, which substantially affects the total regression error. Other uncertainties such as local gasification, Reynolds number grouping, and the limitation of using the diffusion-limited modeling approach only are also discussed. Lastly, a systematic measurement error in previous work was identified and described.

Chapter 5 describes the four main steps taken to reduce the model uncertainties. These are:

- Inclusion of local gasification through the iterative time stepped modeling approach. This means the inclusion of the fuel gasified on a given burn surface to calculate the regression (gasification) of the fuel on that same surface.
- Development of the equivalent burn time to reduce the uncertainty of large transient times. This method attempts to correct the burn time to better model how the burn would be if there were no transient.
- Changes to the test setups to control the start-up transients. These include valves at strategic locations to allow for pre-pressurization of the LOX tank and pre-cooling of the feed-line.
- Mathematical Data correction of heritage fuel blocks. As the fuel blocks from some of the tests are no longer available and it is believed there was a systematic measurement error in the measurement of the regression rates, a proposed mathematical data correction is described.

Chapter 6 describes how the work mentioned above was used to develop ever-increasing engine sizes to reach the target commercially viable engine size. This 40 kN engine class was successfully fired, and the test results were used to evaluate the overall regression model performance. This showed good scalability of the model with an RMS regression error of 26

Chapter 7 then summarizes the above results and discusses how these potentially can impact the development of hybrid rockets both within the CAMUI technology and outside. Overall many of the findings in the uncertainty analysis are just as valid for any hybrid rocket research though the actual uncertainty values will differ pending on the design. Likewise, the suggested corrections can be used directly or adapted pending the engine design for CAMUI style and non CAMUI style engines. For the further development of the CAMUI engine itself, the model proved to be more than adequate to allow rapid engine development.

Lastly, Chapter 8 concludes this work in the context of the starting goal of developing a commercial-size CAMUI engine. This work satisfies the primary target, which was to develop a scaled regression model that would allow for the rapid development of a large-sized engine, in this case, the 40 kN class. It is worth noting that programmatic risk management regarding other aspects of engine combustion, namely potential ignition instabilities, was the main reason for not developing faster than was done. The model described in this work made it possible to technically develop the end goal 40 kN engine and convince investors and research partners to finance and support the development. The firing of this 40 kN engine finalized the proof-of-concept development for a viable sounding rocket engine.

Further development to mass optimize the engine and push the possible burn time as far as possible is currently underway under the company MSW, which was started in 2020 to develop and commercialize this engine and a future larger engine.