Hybrid Rocket Engine Thrust Prediction and Verification

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A. Introduction

A key facet of engine design is the capability to predict the thrust profile of a given engine burn. Before a given engine configuration is tested, thrust predictions are made using a theoretical model. After multiple rounds of testing are completed, raw thrust profiles can be extrapolated and adjusted to be used as a derived model. SRT has developed a theoretical design model and a derived model method in conjunction with an in-house post processing suite to quickly and accurately develop thrust curves to be used by the dynamics subteam in trajectory analysis. Each method comes with its own set of assumptions and each model plays a critical role in the design processes of hybrid rocket engines developed by SRT.

B. Thrust Profile Features

The basis for this abstract will assume a Nitrous Oxide-HTPB, pressure-driven, hybrid rocket engine utilizing a circular port. This is critical for the definition of the thrust curve and assumptions made to develop various portions of the models discussed. A thrust curve produced by the aforementioned system is a regressive burn and has four defining phases termed as follows: start-up phase, liquid phase, liquid-gas transition phase, and gas phase. The start-up phase is defined by the start of chamber pressure build-up to peak chamber pressure. The liquid phase is the portion of the burn governed by the liquid oxidizer flowing through the engine plumbing. The liquid-gas transition is characterized as a steep drop in chamber pressure until it reaches the gas phase where the pressure decrease rate slows until unchoking of the nozzle. All the models follow this general profile and are confirmed by multiple hot fire engine tests of two different engine scales exhibiting the same profile. Verification as used in context of this paper indicates, at a minimum, loose correlation to visibly identified trends.

C. Theoretical Engine Model

The theoretical engine model developed by the team is a comprehensive oxidizer flow and combustion model of a hybrid engine. With inputs of propellant type, loaded propellant weight, circular fuel grain dimensions, and starting oxidizer temperature, the model exports a thrust curve among other parameters graphed against time (system pressures, mass flowarates, Oxidizer-to-Fuel ratio, etc.). Hardware parameters are given to the model allowing the team to quickly analyze multiple engines and configurations.

The model separates the engine into the two parts, part one being the oxidizer tank to the injector coin where the resulting oxidizer flowrates are passed to the second part of the algorithm where the oxidizer flow rates couple with the fuel flowrates drive the combustion parameters. This occurs within one time step in an iterative loop until unchoking of the combustion chamber.

Of the four oxidizer phases described earlier, this model simulates just two of the phases identified: the liquid phase and the gas phase. The liquid phase is governed by a slightly modified algorithm from *Propellant Tank Pressurization Modeling for a Hybrid Rocket*.[1] In summary, this model utilizes the Ideal Gas Law, Rasoults Law (partial pressures), and Conservation of Energy in the form of a forward difference to determine the phase composition, temperature (pressure from temperature derived by the Clausius-Clayperon equation), and mass flow rate of the oxidizer out of the tank. To model the gas phase, an modified algorithm of *Modeling the nitrous run tank emptying*[2] iterates on a guessed value of vapor density

to satisfy the Ideal Gas Law with an estimated compressibility factor. The combustion portion of the model uses curve-fitted data from algorithms based on a constant pressure, constant temperature reactions, minimizing Gibbs Free Energy (system energy). This combustion chemistry data is derived by the oxidizer to fuel ratio which is in-turn driven by the oxidizer mass flux through the injector. Potential energy is transfered to kinetic energy through the nozzle based on isentropic expansion principles and the frozen flow assumption. It is critical to understand that the results of this model are the theoretical maximum for the given system. Real life effects such as heat transfer, combustion inefficiencies, hardware imperfections, etc. will cause losses to the system not captured by this model. The team uses this model in the design stages to set internal and performance parameters (chamber pressure, flow rates, burn time, thrust) that translate to hardware specifications (injector area, chamber dimensions, nozzle throat, etc.).

D. Derived Thrust Model

The derived thrust model or flex curves uses specific curve-fits for each of the afore mentioned oxidizer phases. Additionally, key variables in each curve equation are linked to thrust curve characteristics for controlling thrust features. With fits of the thrust curve phases and known testing parameters (initial propellant weight, fuel lost, oxidizer starting temperature/pressure), ratios from these parameters are used to vary the thrust profile in affected phases. These effects will be discussed with each curve-fit discussion.

The start-up phase is fitted to a logistic function or population curve where the carrying capacity becomes tied to the peak thrust. Variations in starting oxidizer tank pressure/temperature vary the peak thrust of the curve. The start-up time has been identified by engine tests to be directly related to the opening time of oxidizer ball valve, with negligible variations in response to peak thrust variations, so start-up time is fixed to the profile. The actual correlation between peak thrust and starting tank temperature/pressure is assumed to be linear and requires at least two engine tests in identical configurations. These results have been confirmed by theoretical calculations, but requires more than just the two empirical tests to derive the correlation. With an increase in peak thrust the burn time decreases to accommodate a higher mass flow rate (or vice versa), so the relative time difference is taken comparing current curve starting tank pressure and a quadratic curve fit of engine cold flow and hot fire duration times related to starting tank pressure.

The liquid phase is modeled as a linear curve fit features of burn slope and liquid burn time. The burn slope is taken directly from the raw curve and is related to the efficiency of the burn/system (small sample size - need more data). Therefore, it is assumed constant across any variation of peak thrust or oxidizer input mass variation. The liquid burn time is directly related to the amount of starting oxidizer in the tank and the peak thrust. More oxidizer means a longer burn duration and a higher peak thrust means a reduced burn duration. It is important to note a finding that the oxidizer mass holds a direct relation to the impulse. Variations in peak thrust with the same oxidizer weight and similar burn characteristics will yield a negligible difference in the overall impulse. This idea is the reasoning for applying duration variations to the liquid burn phase only.

The liquid-gas transition phase is fitted linearly, connecting the liquid end point with the quadratically-fitted gas phase. Besides variations in liquid-gas transition start, these phases are assumed to be nearly constant across variations of peak thrust and burn duration. Engine testing confirms this idea.

E. Results, Conclusions, and Follow-On Work

Understanding the operating principles of a hybrid engine are critical to being able to model and ultimately predict the performance of a given engine system. SRT has conducted numerous cold flow and hot fire tests to provide some verification to the theoretical work done in prediction of a hybrid rocket engine performance. Currently, duration modeling has been measured to within 1% of actual results in cold flow testing. Hot fire testing varies slightly more with various in the neighborhood of 5%. This indicates the flowrates operating principles and variables (Cd, oxidizer pressure relations, density and phase estimates, etc.) are being accurately modeled. However, combustion parameters require some additional testing to better understand variations seen with theoretical models. The derived model requires more rigorous testing and variable variations (peak thrust, tank pressure, engine configuration) to be adequately validated. The Spaceport America Cup will provide some of this additional testing for these thrust prediction methods and will add a new dimension by integrating these thrust predictions with trajectory predictions and results. Future work will include rigorous controlled hot fire testing as mentioned before along with additional flights to test the ultimate capability of the methods and the team.

References

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