Title	Mechanisms of Graphite Nozzle Erosion in Hybrid Rockets [an abstract of dissertation and a summary of dissertation review]
Author(s)	KAMPS, Landon Thomas
Citation	北海道大学. 博士(工学) 甲第13787号
Issue Date	2019-09-25
Doc URL	http://hdl.handle.net/2115/75904
Rights(URL)	https://creativecommons.org/licenses/by/4.0/
Type	theses (doctoral - abstract and summary of review)
Additional Information	There are other files related to this item in HUSCAP. Check the above URL.
File Information	KAMPS_Landon_Thomas_abstract.pdf (論文内容の要旨)

学位論文内容の要旨

博士の専攻分野の名称　博士（工学）　氏名　KAMPS Landon Thomas

学位論文題名

Mechanisms of Graphite Nozzle Erosion in Hybrid Rockets
(ハイブリッドロケットにおける黒鉛ノズル浸食機構の解明)

Hybrid rockets are the focus of countless industrial and academic aerospace propulsion projects worldwide. Hybrid rockets are particularly attractive for use in small-scale space propulsion vehicles and passenger spacecraft because of the cost savings associated with their inherent safety and ease of handling. The design of hybrid rocket nozzles that effectively expand hybrid rocket combustion gas is crucial for the realization of such aerospace vehicles. Key components of hybrid rocket nozzles are most commonly manufactured from carbon-based materials such as graphite and carbon-carbon composites. However, carbon-based materials are prone to thermochemical erosion in combustion gas flows containing oxidizing species which are prevalent in hybrid rockets. No previous studies have comprehensively investigated the thermochemical erosion of nozzles in hybrid rockets even though it is known to be an issue of grave importance.

This study elucidates the mechanisms of thermochemical erosion in hybrid rocket nozzles for the first time by analyzing data from over 60 hybrid rocket firing tests at various scales and thrust classes ranging from motors that are 50 mm to 300 mm in diameter at thrusts from 10 N to 2,000 N, respectively. This was only possible through the development and validation of a new data reduction methodology that enabled the determination of time-resolved nozzle throat erosion, equivalence ratio and nozzle throat wall temperature from measurements of thrust, chamber pressure, oxidizer mass flow rate, overall fuel mass consumption, final nozzle throat diameter, and two thermocouple measurements from within the nozzle body. Empirical analysis led to the formulation of a predictive model for nozzle erosion rate based on heterogeneous combustion theory and turbulent mass transport theory. This work is introduced in the following six chapters: (1) Nozzle Erosion in Chemical Rockets; (2) Model of Chemical Erosion; (3) Comprehensive Data Reduction; (4) Hybrid Rocket Motor Operation; (5) Static Firing Test Results; (6) Impact on Hybrid Rocket Development.

Chapters 1 and 2 explain the internal ballistic conditions of a typical hybrid rocket motor, and how these conditions lead to thermochemical erosion of the nozzle. The mass fractions of oxidizing species are shown to be twice as high when oxygen is used as the oxidizer than when nitrous oxide is used. It is also shown that a maximum nozzle erosion rate is expected to occur in slightly oxidizer rich conditions, and that erosion rate is expected to tend to zero with increasing equivalence ratio. The model introduced in Chapter 2 is an abstraction of the Arrhenius equation. The exponential temperature dependency of heterogeneous reaction rate on surface temperature is preserved, but a novel treatment of the combustion gas mixture and turbulent advection properties is used to account for the effect of partial pressure and reaction specific empirical constants. The heterogenous reaction rate of the nozzle surface with the combustion gas is defined by a single equation, meaning that the combustion gas mixture is treated as a single oxidizing agent. This is possible because a Gamma (distribution-type) function of equivalence ratio is used to replicate the effect of individual oxidizing species concentration on the empirical constants of the Arrhenius-type equation, and the Sherwood number is used to incorporate the effect of turbulence on the delivery of oxidizing species to the nozzle surface.

Chapter 3 explains the experimental data reduction concept and algorithms for determining the data necessary for the empirical model introduced in Chapter 2. This methodology, referred to as Comprehensive Data Reduction, is a multi-tiered iterative algorithm based on characteristic exhaust velocity, thrust, chemical equilibrium, and heat flux in the nozzle. Chapter 4 introduces the numerous experimental apparatus that were used in the course of this research. One benefit of the Comprehensive Data Reduction methodology introduced in Chapter 3 is that tests that were not originally conducted for investigating nozzle erosion may still be used to do so, so long as the requisite measurements were taken. As a result, a wide range of tests and related test procedures were available for analysis. In summary, four distinguishable test motors and their test stands are introduced in detail, as well as the data acquisition procedures and associated experimental uncertainties.

Chapter 5 presents the results of experimentation, and empirical correlation of results on the model of Chapter 2. Direct measurement histories are examined along with the results of Comprehensive Data Reduction. The validity of assumptions of the Comprehensive Data Reduction methodology are verified, and general trends of equivalence ratio shift and decrease in chamber pressure due to nozzle erosion are highlighted. Nozzle surface temperature, pressure and equivalence ratio of combustion gas at the onset of nozzle erosion are used to determine the empirical constants of a newly defined term referred to as the Erosion Onset Factor. The remaining empirical constants are determined through the least-squares method of the nozzle erosion rate data. Nozzle erosion rates are taken as linear approximations of the nozzle throat erosion histories of each test at 0.5 s intervals.

Chapter 6 discusses the results in the context of hybrid rocket design and research impact. First, the results of Chapter 5 are interpreted to show how the empirical model holds up in practice. Second, the reduction of nozzle erosion through oxidizer selection and cooling is proposed. Lastly, a framework for the incorporation of the Comprehensive Data Reduction methodology and nozzle erosion investigation in ongoing research is suggested to permit continuous analysis and improvement of nozzle erosion prediction and prevention.