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Tackling the Challenge of ‘Combustion Instability’ in Rocket Engine Development with Full-Scale Simulation

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Development of the engine for Japan’s next-generation large-scale flagship rocket, the H3, has been underway since 2014. Alongside engine firing tests, numerical simulations have played a crucial role in this development process. Notably, Dr. Haga successfully conducted full-scale simulations of the combustor using the supercomputer Fugaku. His work paved the way for elucidating the mechanism behind “combustion instability”—a phenomenon that can potentially cause damage to rocket engines—and is expected to contribute to the development of safer, higher-performance rockets.

A Note on This Article

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Combustion is utilized in a wide range of industrial equipment, including various energy conversion and propulsion systems. Consequently, elucidating combustion mechanisms and accurately predicting and controlling combustion behavior are crucial for the efficient development, optimal design, and selection of operating conditions for such equipment. In recent years, the use of numerical simulation has become essential to achieving these goals while reducing development time and costs. Numerical simulation of combustion involves the simultaneous computer-based solution of the continuity equation for fluid dynamics, momentum equations, energy equation, chemical species conservation equations, and the equation of state for the system in question. However, when combustion is involved, the computational load is extremely high compared to cases where combustion is not considered; this is due to the large number of chemical species conservation equations that must be solved and the fact that the temporal and spatial scales of combustion phenomena are smaller than those of turbulence.

Among combustion-related research topics, the prediction and control of combustion instabilities are indisputably one of the most challenging. Combustion instabilities remain among the most challenging phenomena that can lead to issues such as flashback, damage to combustor walls, and combustion noise. To advance numerical analysis technologies—such as those for predicting combustion instabilities—the project representative (Kurose) established the “Research Workshop on Advanced Numerical Analysis Technologies for Combustion and Gasification” in 2011. In 2018, this initiative was reorganized as the “Consortium for Next Generation Combustion System CAE (CNGC)” within RIKEN; it currently operates with a membership comprising 13 industrial organizations and 13 academic or national research institutions (https://www.riken.jp/en/collab/research/consortium/cngc/).

This research project aimed to predict the combustion instability characteristics of turbulent combustion fields within actual liquid rocket engine combustors through ultra-large-scale simulations. Because the pressure inside a rocket engine combustor is extremely high, the temporal and spatial scales of combustion phenomena become very small; furthermore, the coexistence of supercritical and subcritical states renders the ideal gas approximation inapplicable. Consequently, performing these simulations is far more challenging than conventional combustion simulations. Addressing this challenge requires not only enhancing the accuracy, speed, and stability of combustion models and flow solvers but also advancing computational performance. The results presented here were achieved only after significant advances had been made in addressing these issues. Even so, generating the results required a full month of computation on the supercomputer Fugaku. From an engineering perspective, the goal is to complete a single simulation case within one or two days at most. Viewed in this light, combustion simulation still has a long way to go, necessitating further improvements in speed and accuracy. There are high hopes that the use of recent advances in AI technology might contribute to achieving these ambitious goals—but will they truly deliver? Particularly in Japan, where the consequences of failure in rocket development can be severe, the ability to accumulate experience through trial and error—and even failure—within a virtual environment holds immense significance. Such advancements in numerical simulation have the potential to be a game-changer that fundamentally transforms the nature of rocket development.

While the project representative would ordinarily be the interviewee for this article, the subject of rocket technology is both technically sophisticated and sensitive from the standpoint of national security. Accordingly, I have asked Dr. Takanori Haga at JAXA, Deputy Project Representative of this research project, to provide background information and technical explanations.

What Happens inside a Rocket Engine?

The H3 is a rocket currently being operated by the Japan Aerospace Exploration Agency (JAXA) in collaboration with private companies. It measures 63 meters in length—equivalent to the height of a 20-story building. The thrust required for this massive rocket to lift off is generated by the LE-9 engine, a liquid-fuel engine. The specific component Dr. Haga focused on for the simulation was the combustor of the LE-X engine, which was developed over approximately ten years starting in 2005 to demonstrate technologies later adopted in the LE-9 (Fig. 1).

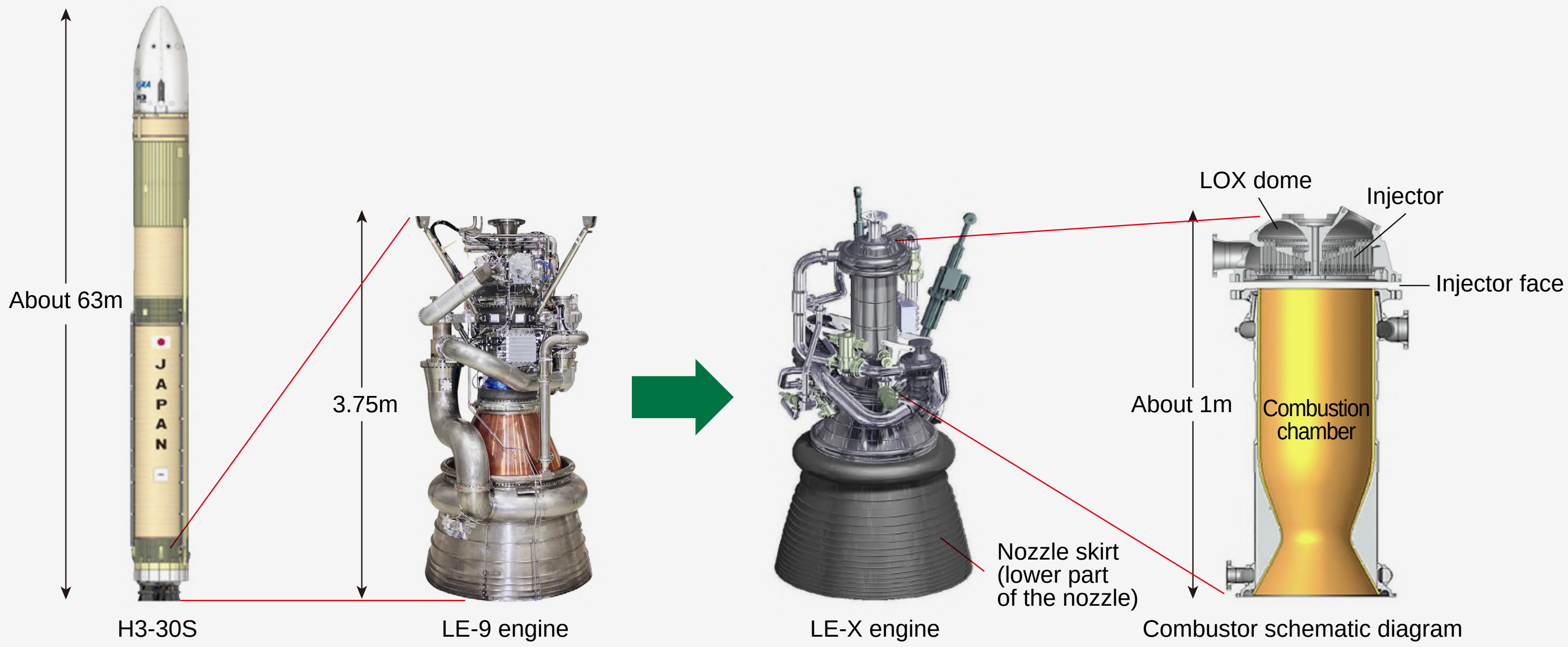

Fig. 1 : Relationship between the H3 rocket and the combustor simulated by Dr. Haga

The H3-30S (the smallest configuration of the H3 rocket, without solid rocket boosters) is equipped with three LE-9 engines. The LE-X engine was developed to demonstrate the technology used in the LE-9—the world's first high-thrust expander-bleed cycle engine—and was used in firing tests. Dr. Haga is conducting simulations of the combustor based on data from these tests. The injectors are approximately as thick as a large pencil (available in three lengths), and there are over 500 of them in the actual engine (see also Fig. 3). "LOX" in "LOX dome" stands for Liquid Oxygen.
Images of the H3-30S (https://www.rocket.jaxa.jp/rocket/h3/outline.html#01), LE-X engine (https://stage.tksc.jaxa.jp/jedi/event/pdf/JEDISymposium2011/20111124/[1-3].pdf) are provided by JAXA, and LE-9 engine is provided by MHI.
The schematic diagram of the combustor is a modified version—used with permission—of the LE-9 engine combustor schematic found in Mitsubishi Heavy Industries Technical Review Vol. 53, No. 4 (2016), pp. 37–43.

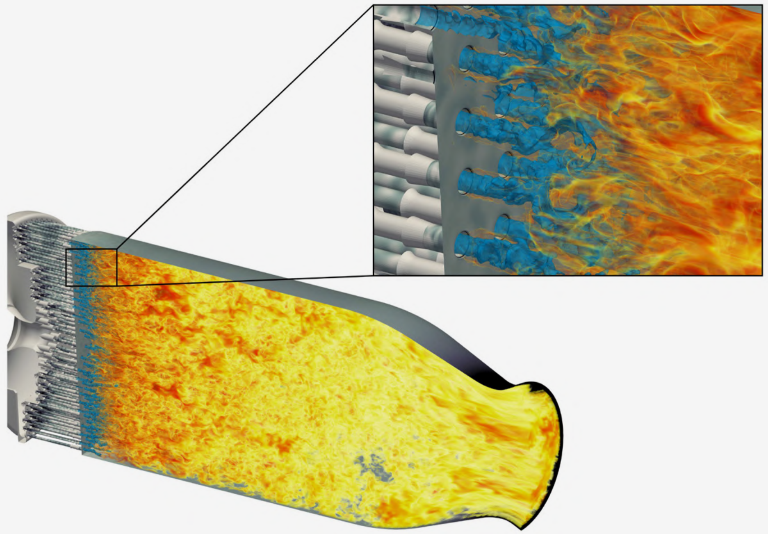

Fig. 2 : Reactions occurring within the combustion chamber

This figure visualizes the results of a simulation conducted by Dr. Haga (details provided later) to facilitate understanding of the processes taking place inside the combustion chamber. Regions of high density are colored blue, representing the flow of liquid oxygen exiting the injector. Although gaseous hydrogen is not depicted in this figure, the flame originates where hydrogen and oxygen mix—near the surface of the liquid oxygen stream—and spreads toward the lower part of the combustion chamber (to the right in this figure). The figure illustrates the nature of the flame by using orange to represent regions where the hydrogen-oxygen mixture ratio is close to the stoichiometric ratio (where the reaction proceeds with optimal balance and the flame is intense) and yellow for regions that deviate slightly from this ratio (where the flame is somewhat weaker).

"In the LE-X, liquid oxygen and gaseous hydrogen—derived from vaporized liquid hydrogen—are fed into the combustor by turbopumps. The injector has a coaxial design: liquid oxygen is injected from the center while gaseous hydrogen is injected from the surrounding area. A flame forms where the two mix due to their velocity difference and subsequently grows (Fig. 2). Although the liquid oxygen is at approximately 100 K (-173°C), the flame formed at the tip of each injector reaches temperatures as high as 3,300 K (approx. 3,000°C); as the flow proceeds toward the lower region of the combustion chamber, chemical reactions progress and the volume of combustion gas—consisting of water*[1] and dissociated chemical species—increases. This combustion gas is accelerated and expelled through the nozzle (the section extending downward from the combustor's constriction), thereby generating rocket thrust," Dr. Haga says.

A phenomenon known as "combustion instability" can occur within the combustion chamber. "In combustion instability, the flame and sound (pressure fluctuations) reinforce each other. Flame fluctuations generate sound waves. When these sound waves reflect off the combustion chamber walls and return to disturb the flame, further sound waves are generated. As this interaction intensifies, the sound grows louder and the flame instabilizes violently. While the pressure inside the combustion chamber is around 100 atm during stable combustion, the peak pressure fluctuation during combustion instability can reach double that value, potentially leading to engine damage," Dr. Haga explains. Consequently, suppressing combustion instability is a critical challenge in rocket engine development. However, conducting a firing test every time a design change is made entails significant time and cost. To address this challenge, Dr. Haga aims to reproduce combustion instability through high-fidelity simulations of the fluid dynamics inside the combustion chamber—including both the combustion gases and the propellants—with the ultimate goal of helping to suppress these combustion instabilities.

Incorporating Combustion Reactions and the Equation of State of Gas into Fluid Simulations

The simulations were performed using LS-FLOW-HO, software developed by the Research Unit III, to which Dr. Haga belongs, long before the team began using Fugaku. Dr. Haga recalls that the development process was quite arduous, because simulating the flow inside the combustion chamber requires not only solving equations of fluid motion but also formulating and simultaneously solving equations that account for the various changes accompanying combustion reactions.

First, let us examine how the motion of fluids is calculated. Unlike water and other incompressible fluids, the fluid inside a combustion chamber is compressible, meaning that its density changes significantly as it is compressed. To determine values such as flow velocity, temperature, and pressure in the motion of such compressible fluids, three fundamental equations must be solved: conservations of mass, momentum and energy. The flow within the combustion chamber is turbulent, characterized by the appearance of vortices of various sizes. A technique commonly used to simulate such turbulence is Large-Eddy Simulation (LES)*[2], which involves dividing the computational domain into a fine grid to perform calculations.

To apply this method to the flow inside the combustor, Dr. Haga created a computational model of the combustor with the assistance of Mr. Hiroyuki Ito of Ryoyu Systems, a participant in the project (Fig. 3). Due to the combustor's complex geometry, the LOX dome, injector, and combustion chamber were meshed separately and then joined using the overset grid method*[3]. The individual grid cells were unstructured hexahedrons; with approximately 380 million cells—and eight computational points per cell—the total number of points reached a massive figure exceeding 3 billion.

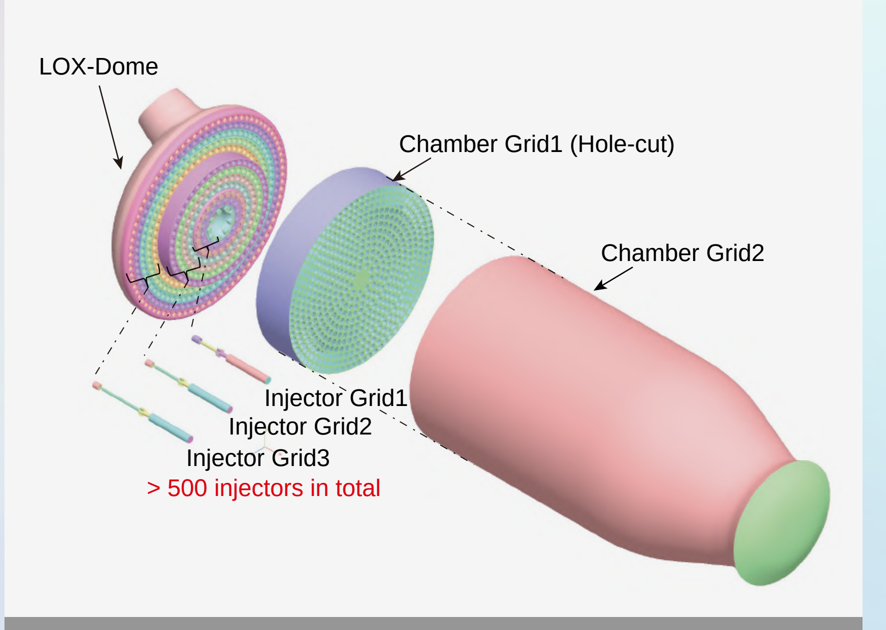

Fig. 3 : Computational model used for the simulation
More than 500 injectors are arranged in 12 concentric rows. They come in three different lengths, with the shorter ones located closer to the center (Injector Grid 1 is the shortest, followed by Grids 2 and 3 in increasing order of length). Unnecessary sections of the combustion chamber mesh have been hollowed out to reduce the number of grid cells.

The greatest challenge Dr. Haga faced was how to incorporate combustion reactions into the fluid dynamics calculations. The combustor operates at a high pressure of 100 atm; furthermore, combustion reactions generate various chemical species, the distributions of which shift rapidly over both time and space. To calculate fluid motion with high accuracy, these conditions had to be accounted for in the LES calculations.

“To address this problem, I cooperated with the project representative, Prof. Kurose. Specifically, he helped introduce a combustion model known as the ‘Flamelet method’ and developed a ‘Flamelet table.’ This table was generated by pre-calculating chemical species distributions under a wide range of conditions for ‘diffusion flames’—where hydrogen and oxygen mix and burn. By inputting two parameters from this table—the hydrogen-oxygen mixture fraction and the water[*1] mass fraction (an indicator of reaction progress)—into individual calculation points during the LES process, we were able to accurately represent the combustion state within the flow,” Dr. Haga explained.

An equation of state is used to derive temperature and pressure from the chemical species composition, density, and energy obtained in this manner. When liquid oxygen is injected at 100 atm, it enters a supercritical[*4] state and can be treated as a gas; however, due to its high density, it behaves very differently from an ideal gas, necessitating the use of a real-gas equation of state. “Real-gas equations of state are complex and include coefficients determined by the chemical species composition. Since the composition varies at each calculation point, data from the Flamelet table also had to be incorporated, and Prof. Kurose helped us with this as well,” Dr. Haga said.

With these steps completed, the stage was finally set for LES calculations of the flow in the full-scale combustor.

Differences of Just a Few Millimeters in Combustor Shape Stabilize Combustion

Dr. Haga utilized Fugaku to conduct simulations using LS-FLOW-HO as part of Industrial Access Projects spanning the 2024 and 2025 fiscal years. “Initially, large pressure fluctuations occurred after the simulation had been running for some time, causing it to become unstable; we therefore stabilized the calculation by employing a technique known as an ‘absorbing sponge’ to artificially dampen these early-stage pressure fluctuations (Fig. 4),” he says.

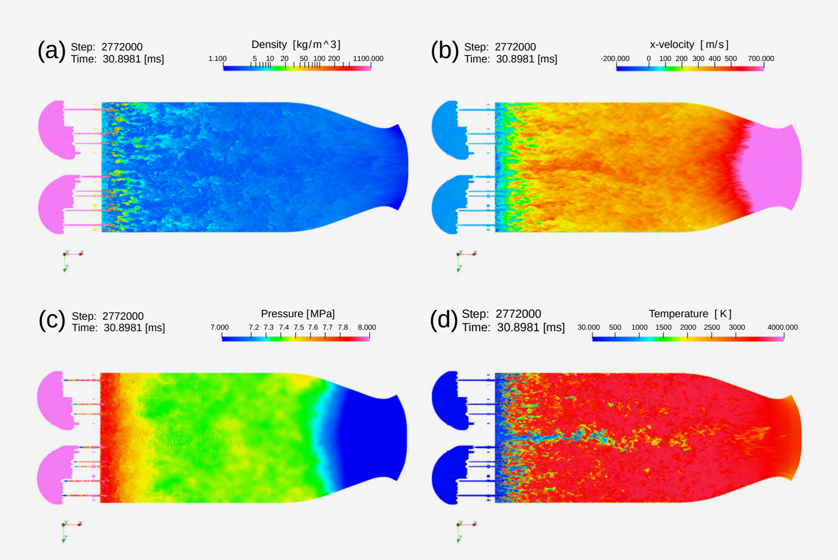

Fig. 4 : Simulation of physical property changes within the combustor

(a) Density, (b) flow velocity, (c) pressure, and (d) temperature. The images are frames extracted from videos showing changes over approximately 4 ms of real time. After artificially stabilizing the calculation, a stable combustion state was observed prior to the onset of large pressure fluctuations. Fig. 2 also shows a snapshot from this simulation (using a different visualization method). Since firing tests allow for pressure and temperature measurements within the combustion chamber using only a limited number of sensors, the shapes and fluctuation patterns of the flames—produced by more than 500 injectors—could only be visualized through simulation. In-situ visualization software called Kombyne was used to visualize the large-scale data and create the videos for Figs. 4 and 5. “We received assistance from Dr. Jorji Nonaka of RIKEN in setting up the visualization environment,” Dr. Haga says.

"For the 2025 fiscal year, calculations were performed by first establishing a stable state using an absorbing sponge and then removing it. While a stable combustion state was maintained for over 15 ms during this simulation, continuing the calculation led to the generation of "rotating pressure waves" immediately below the injector face (Fig. 5), subsequently causing the calculation to become unstable. Calculations were conducted under three different sets of conditions, such as varying the injection parameters, leading to the similar results," Dr. Haga says.

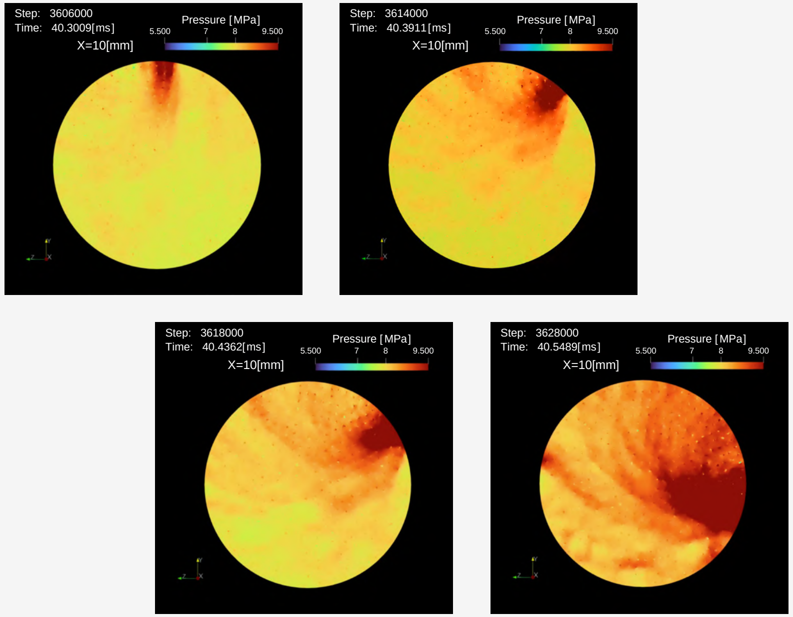

Fig. 5 : Rotating pressure wave generated in the simulation

These circles represent a cross-section of the combustion chamber 10 mm below the injector face (see Fig. 1). They are stills from a video showing how the pressure wave develops while rotating along the wall surface (clockwise).

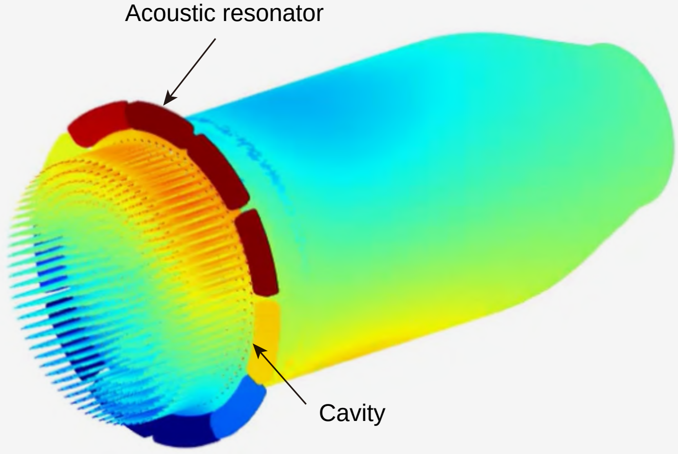

Fig. 6 : Newly added acoustic resonator

The acoustic resonator is a hollow, box-like structure that encircles the outer perimeter of the injector face. At the interface between the acoustic resonator and the combustor, the combustor wall protrudes outward by a few millimeters, forming a circumferential groove. This figure illustrates the geometry of the computational model created for simulation purposes; the shape differs from that of the actual hardware.

The rotating pressure wave observed within the combustor cross-section shown in Fig. 5 is considered one of the various modes of combustion instability, and it appears that the simulation successfully reproduced this phenomenon. However, this specific mode of combustion instability did not occur during actual firing tests. Dr. Haga focused on the acoustic resonator (Fig. 6) as a potential reason for this discrepancy. "Actual combustors are equipped with acoustic resonators to suppress combustion instability, but we had omitted them from our computational model. We hypothesized that including a resonator would stabilize combustion, while omitting it would lead to instability, so we modified the model and ran the simulation again. Contrary to our expectations, however, no rotating pressure waves appeared in either case. We believe the reason for this is that we had newly incorporated a 'groove' (or cavity) at the junction between the acoustic resonator and the combustor in both scenarios, and this groove likely contributed to stabilizing the combustion," Dr. Haga explains.

Achieving High-Precision Simulation through a Unique Computational Scheme

While the goal of reproducing combustion instabilities has not yet been fully achieved, performing a simulation of a rocket engine combustor at full scale is believed to be a world first. "We utilized thousands of nodes on Fugaku for a full month just to run the simulation for a single set of conditions. The scale of this simulation would have been impossible to achieve without Fugaku," reflects Dr. Haga.

How will the research proceed from here? Dr. Haga explains: "Building on the results of the past two years, I aim to reproduce the combustion instabilities observed in firing tests and to simulate the effects of acoustic resonators. If we can predict combustion instabilities, I hope the technology can be used for final checks prior to actual engine firing tests. Furthermore, LS-FLOW-HO employs a unique computational scheme known as the Flux Reconstruction (FR) method, which I have researched for many years. This scheme is well-suited for parallel processing and offers the advantage of achieving high accuracy with a relatively low number of grid cells; however, its numerical stability still needs improvement, and there is still work to be done to fully realize that high accuracy. Completing this scheme is another important goal for the future."

Dr. Haga is also looking ahead to the use of FugakuNEXT, the next-generation successor system to Fugaku, and is experimenting with running LS-FLOW-HO on GPUs. Additionally, he is collaborating with a group led by Prof. Hiroshi Gotoda of the Tokyo University of Science on big-data analysis to extract meaningful insights from the vast amounts of data generated by these simulations. It seems there is no stopping Dr. Haga's drive for new challenges.

*1 Because the combustion gases are at extremely high temperatures and pressures, the water (H_2O) in this case exists as water vapor rather than as liquid water.
*2 A method that directly calculates vortices larger than the grid cell size and models vortices smaller than the grid cell size.
*3 A method of calculation that combines multiple individually created grids. Effective for complex shapes and many parts. The correct answer cannot be obtained without deleting cells in the overlapping grid areas, but deleting too much will create gaps in space, so pre-processing is necessary to trim the grid boundaries appropriately.
*4 A state in which a substance possesses the properties of both a liquid and a gas. It appears when a substance exceeds its critical point (temperature and pressure specific to each substance) in terms of temperature and pressure.

About the Researcher

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As an undergraduate majoring in aerospace engineering, Dr. Haga read a paper on a computational scheme and wrote his own program to implement it; when he obtained the same results as the paper, he found it fascinating. After earning his doctorate, he spent three years as a postdoctoral researcher at Iowa State University in the U.S., working under Prof. Z.J. Wang who developed the FR method. Upon returning to Japan, he was invited to join JAXA, where he has continued researching the FR method for over 17 years. His research motto is to verify ideas through his own investigation, rather than simply accepting what is written in academic papers. He describes himself as a "tenacious researcher" who refuses to give up until every conceivable method has been tried. He developed a taste for bourbon whiskey during his time in the U.S., and says that "spending time chatting leisurely with the bartender at my favorite whiskey bar" is the best way for him to unwind and recharge.

Interview date: June 19, 2026

Associated Research Projects:

Very large-scale simulations of turbulent combusting flows in realistic liquid rocket engine combustors: Investigation of combustion instability mechanism (hp240016)
Very large-scale simulations of turbulent combusting flows in realistic liquid rocket engine combustors: Toward combustion instability prediction by big-data and AI analysis (hp250023)
Project Representative: Ryoichi Kurose, Kyoto University
Deputy Project Representative: Takanori Haga, Japan Aerospace Exploration Agency (JAXA)

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