Fundamental Researches of Fluid and Combustion for the Hypersonic Flight

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Abstract

The wind tunnel tests by using sub-scaled models play important roles for the development of the air-breathing propulsion system for a hypersonic transporter. However, in some cases, the flow of the wind tunnel is "vitiated" due to the heating process and/or the complex flow-path of the facility. To raise the total temperature to produce the high enthalpy flow, a combustion heating is usually applied, introducing the water vaper to the air stream. The complex flow-path of the facility would increase turbulence. Both the phenomena might affect the supersonic combustion process. To clarify the effects of the flow vitiation and ultimately, to establish the adjustment methodology that can deduce the data of real flight from the wind tunnel data, JAXA has initiated the 5-years study. The final goal is conducting the flight experiment to obtain the data on the supersonic combustion in an actual flight condition and verify the methodology by using both the flight data and the corresponding wind tunnel data.

Ref. URL: https://www.kenkai.jaxa.jp/research/supersonic/supersonic.html

Reasons and benefits of using JAXA Supercomputer System

Recently, hydrocarbon fuels become more promising fuels for a supersonic combustor than hydrogen because the combustion energy per volume is higher, enabling smaller demonstrators to be realized. A gaseous ethylene is selected as the fuel for the present flight experiment. Ethylene is rather simple hydrocarbon, but much more chemical species contributes to the combustion process than hydrogen. In addition, the flow conditions in the supersonic combustor and those around the hypersonic flight test vehicle are quire severe. As a result, the CFD for the present design evaluation requires large computation time. Furthermore, many cases of the CFD must be executed for aerodynamic design of the flight test vehicle and the combustor model within the scheduled period. Therefore, the use of the JSS system is essential for the success of the present research program.

Achievements of the Year

(1) Development of a tool for predicting facility dependence on supersonic combustion:

The CFD tool based on a RANS method that was constructed last fiscal year, was applied to the prediction of the performance of an ethylene-fueled supersonic combustor for the flight test "S-520-RD1". The CFD results were compared to the wall pressure data obtained from the flight test using the CFD parameters that were adjusted through ground tests conducted before the flight test. As a result, for the airflow conditions around at a dynamic pressure of 110 kPa, the difference between the CFD and measured data was 16.2% in terms of the pressure thrust calculated by the integration of wall pressure on thrust surface. Thus, the target that the difference was less than 5% was not achieved. To improve the prediction accuracy, the CFD parameters were readjusted through ground tests conducted after the flight test. As for the ground tests, the airflow conditions at the combustor entrance were corresponded to the those for the actual flight as much as possible. Eventually, the reaction mechanism, turbulence model and turbulent Schmidt number were changed from the previous ones. The second comparison between the CFD and flight test results showed that for the airflow conditions around at a dynamic pressure of 110 kPa, the difference was reduced to 0.1% within the targeted accuracy in terms of the pressure thrust (Fig. 1).

(2) Thermal and aerodynamic analysis for RD1 flight experiment vehicle

As RD1 flight experiment vehicle detailed design progressed, the fuselage shape was often reviewed in order to eliminate interference with a launcher fairing and to enlarge mount space for onboard instruments. CFD aerodynamic analysis for RD1 vehicle was performed each time at the flight Mach number ranges from 2 to 7, and the aerodynamic DB was updated. Figure 2 shows the pressure coefficient on the surface of RD1 vehicle and the Mach number distribution around the fuselage at the Flight Mach number of 6 and the angle of attack of 5 degrees. In addition, the flight analysis was performed using the aerodynamics DB to confirm the stability and safety of the flight experiment. It was confirmed that the flight plan would be feasible and there would be no safety issues for the RD1 vehicle flight. The CFD results was also used to determine formulas to calculate the flight dynamic pressure and flight attitude from the outputs of ADS pressure sensors. In addition, the risks of erosion and significant local temperature rise of RD1 flight experiment vehicle due to aerodynamic heating were also evaluated by thermal analysis using commercial software Abaqus, in which, the aerodynamic heating to the RD1 vehicle surface predicted by CFD was used for heat load input to the thermal analysis. Predicted surface temperature on the RD1 vehicle is shown in Fig. 3. The result shows that the surface temperature would not rise high enough to cause melting damage.

It is noted that S-520-RD1 sounding rocket was successfully launched in July 2022, RD1 flight experiment vehicle flew almost as planned, and supersonic combustion data was obtained under actual flight conditions.

(3) Stress analysis for the vibration test of the flight experiment vehicle:

Vibration analysis was performed on the analysis model of the flight experiment vehicle scheduled for launch by S-520-RD1 to confirm that the structure would not be overloaded. Accelerometers were mounted to the flight experiment vehicle, PSD evaluation was performed, and the measured results and the analysis results were compared for validation. Although the analysis results and the measured results showed some discrepancies, the frequency characteristics and the order of magnitude fairly agreed at the frequency range between 100Hz and 1000Hz in general. Since the validity of the analysis was confirmed, the stress analysis in the vibration test was performed. Figure 4 shows the analysis results. It was judged that there was no structural overload due to the vibration test, even at locations where no accelerometer was installed.

(4) CFD evaluation of the aerodynamic design of an RD1 test model for ground test in RJTF

Post-flight combustion tests using a RD1 combustor model were conducted using Ramjet engine Test Facility (RJTF) under the test flow conditions, which match airflow conditions at representative times of the RD1 flight experiment on supersonic combustion. By replacing with a smaller compression ratio inlet, the Mach number at the entrance of the combustor was adjust to the flight conditon as well as the kinetic energy. The shape of this new inlet was determined by CFD evaluation. Comparison of the combustion test results with both the inlets showed that flow condition at the combustor entrance strongly affected the combustion characteristics in the combustor although the test flow condition is the same.

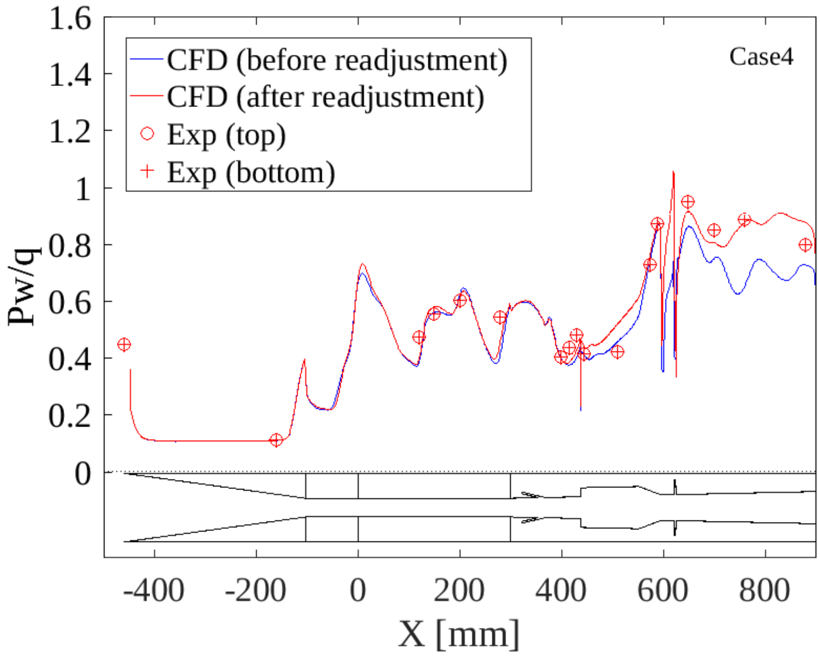

Fig. 1: Comparison between CFD results and flight test data (wall pressure distributions on combustor top wall)

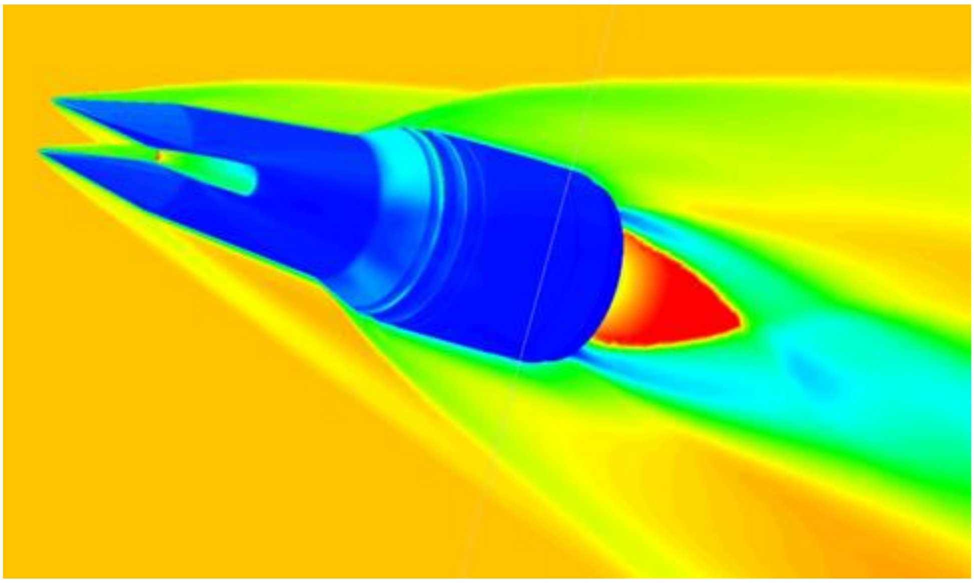

Fig. 2: Pressure coefficients on body surface of RD1 flight experiment vehicle and Mach number contours around the fuselage at Flight Mach 6 and angle-of-attack of 5 degrees.

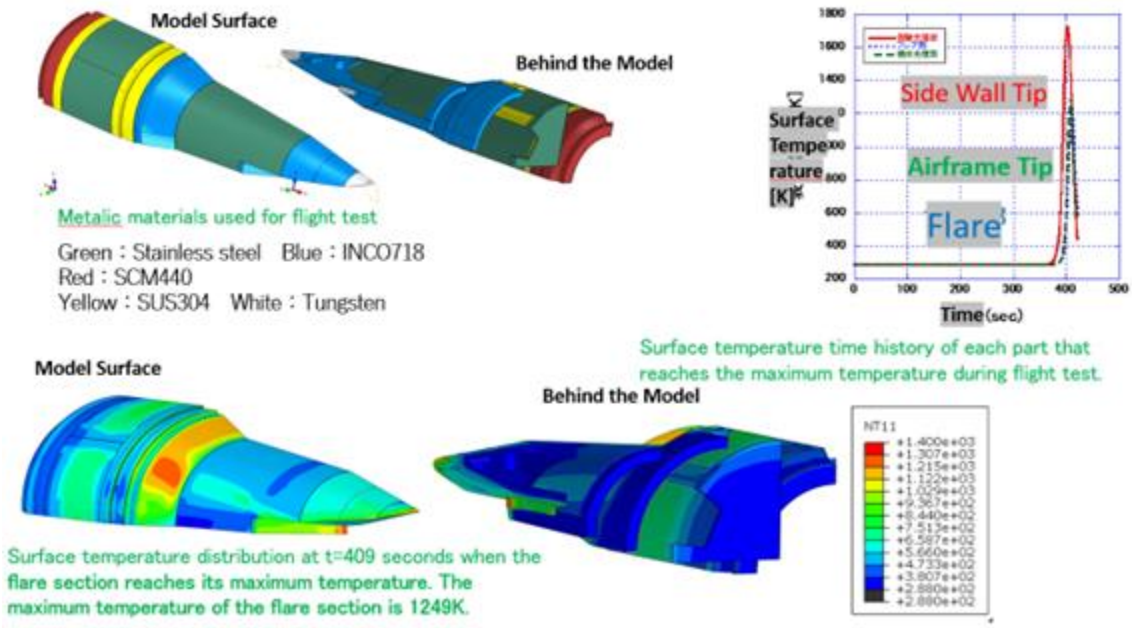

Fig. 3: Prediction results of surface temperature on RD1 flight experiment vehicle

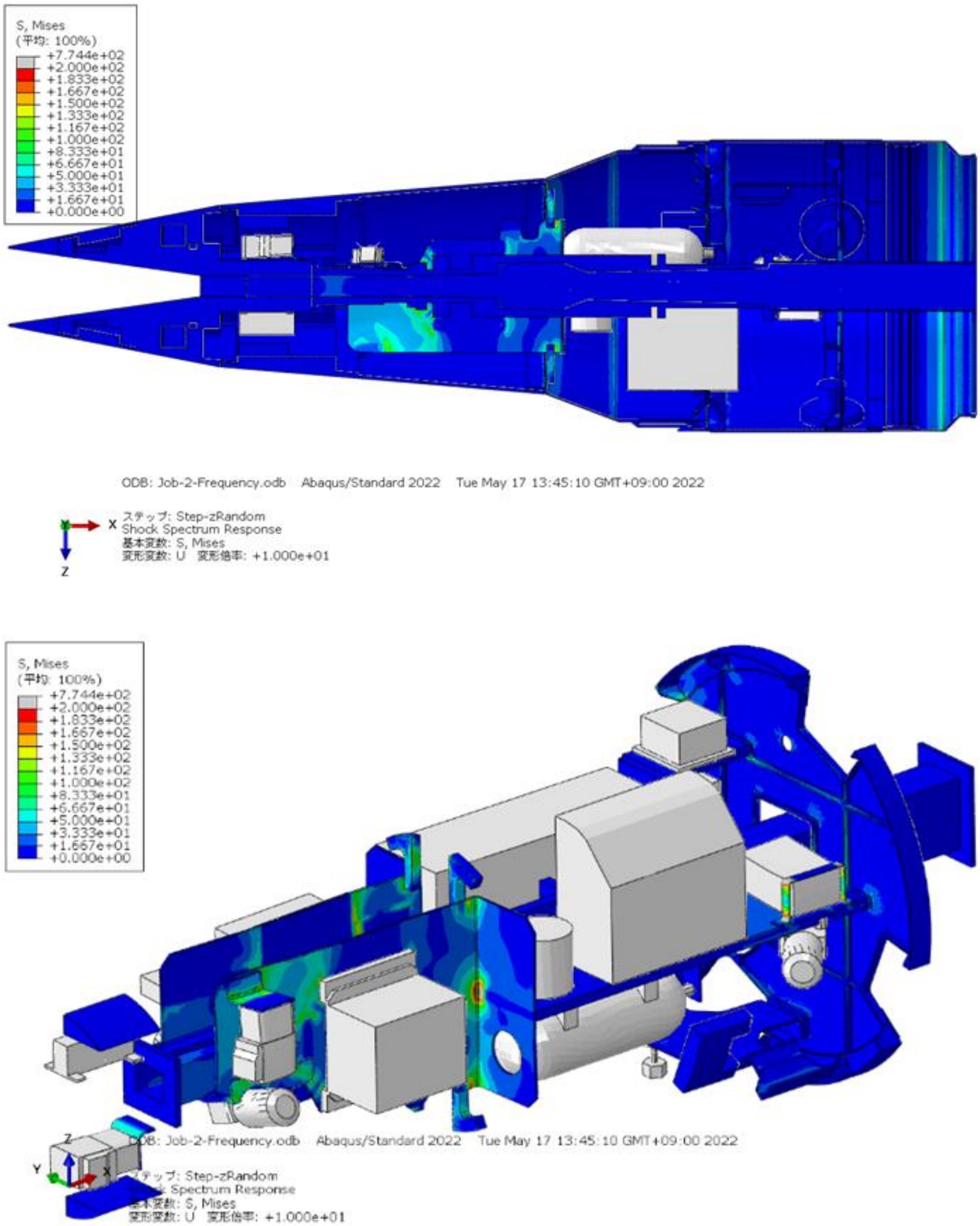

Fig. 4: Predicted stress for RD1 flight experiment vehicle during the vibration test

Publications

- Peer-reviewed papers

1) Kobayashi, K., Tomioka, S., Takahashi, M., Kodera, M., "Reaction mechanism reduction for ethylene-fueled supersonic combustion CFD, " CEAS Space Journal, https://doi.org/10.1007/s12567-023-00484-1, 2023.

2) Takahashi, H., Hasegawa, S., Tani, K., Journal of Spacecraft and Rockets (submitted).

- Non peer-reviewed papers

1) Tani, K., Supersonic Combustion Flight Test Team, "Flight Experiment of Supersonic Combustion with S-520-RD1 Sounding Rocket," JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, Keynote speech, 2023.

2) Takegoshi, M., Supersonic Combustion Flight Test Team, "Development and Functional Testing for Flight Experiment Vehicle using S-520-RD1" JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, 2023.

3) Takahashi, M., Takegoshi, M., Saito, T., Kato, K., Kodera, M., Isono, T., Onodera, T., Kobayashi, K., Tomioka, S., "Ground Test Results Corresponding to S-520-RD1 Flight Experiment on Supersonic Combustion," JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, 2023.

4) Kobayashi, K., Tomioka, S., Takahashi, M., Kodera, M., "Reaction mechanism reduction for ethylene-fueled supersonic combustion CFD, " HiSST-2022-0187, 2022.

- Invited Presentations

1) Tani, K., "Flight Experiment of Supersonic Combustion with S-520-RD1," FY2022 Space Transportation Symposium, Special Lecture, 2023.

- Oral Presentations

1) Kodera, M., Takahashi, M., Kobayashi, K., and Tomioka, S., "Flight Experiment of S-520-RD1: Comparison between Results of CFD, Flight and Ground Experiments," FY2022 Space Transportation Symposium, 2023.

2) Tani, K., Supersonic Combustion Flight Test Team, "Flight Experiment of Supersonic Combustion with S-520-RD1 Sounding Rocket," JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, Keynote speech, 2023.

3) Takegoshi, M., Supersonic Combustion Flight Test Team, "Development and Functional Testing for Flight Experiment Vehicle using S-520-RD1" JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, 2023.

4) Takahashi, M., Takegoshi, M., Saito, T., Kato, K., Kodera, M., Isono, T., Onodera, T., Kobayashi, K., Tomioka, S., "Ground Test Results Corresponding to S-520-RD1 Flight Experiment on Supersonic Combustion," JSASS northern branch 2023 conference and 4th Reusable Space Transportation Symposium, 2023.

5) Kobayashi, K., Tomioka, S., Takahashi, M., Kodera, M., "Reaction mechanism reduction for ethylene-fueled supersonic combustion CFD, " HiSST-2022-0187, 2022.

- Other

1) Hasegawa, S., Tani, K., Patent application in process

Usage of JSS

- **Computational Information**

Process Parallelization Methods	MPI
Thread Parallelization Methods	OpenMP/Automatic Parallelization
Number of Processes	960 - 2000
Elapsed Time per Case	120 Hour(s)

- **JSS3 Resources Used**

Fraction of Usage in Total Resources*1(%): 4.00

Details

Computational Resources		
System Name	CPU Resources Used (core x hours)	Fraction of Usage*2(%)
TOKI-SORA	108,025,672.73	4.71
TOKI-ST	211,955.68	0.21
TOKI-GP	0.00	0.00
TOKI-XM	0.00	0.00
TOKI-LM	1,944.02	0.13
TOKI-TST	0.46	0.00
TOKI-TGP	0.00	0.00
TOKI-TLM	0.00	0.00

File System Resources		
File System Name	Storage Assigned (GiB)	Fraction of Usage[*2] (%)
/home	778.12	0.70
/data and /data2	53,342.57	0.41
/ssd	5,735.62	0.79

Archiver Resources		
Archiver Name	Storage Used (TiB)	Fraction of Usage[*2] (%)
J-SPACE	6.96	0.03

[*1]: Fraction of Usage in Total Resources: Weighted average of three resource types (Computing, File System, and Archiver).

[*2]: Fraction of Usage：Percentage of usage relative to each resource used in one year.

- **ISV Software Licenses Used**

ISV Software Licenses Resources		
	ISV Software Licenses Used (Hours)	Fraction of Usage[*2] (%)
ISV Software Licenses (Total)	1,797.08	1.25

[*2]: Fraction of Usage：Percentage of usage relative to each resource used in one year.