Study on Future Space Transportation System using Air-breathing Engines

Report Number: R23EG3205
Subject Category: Research and Development
URL: https://www.jss.jaxa.jp/en/ar/e2023/23733/

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Abstract

Recently, reusable rockets have been being studied to reduce the cost of space transportation systems significantly. However, in order to extend the structural lifetime, it is necessary to operate them with relatively low engine power, leading to a decrease in launch capability. Therefore, air-breathing engines such as scramjets and rocket/scram combined cycle engines are promising to compensate the drawback. By using air in the atmosphere as an oxidizer, it becomes highly efficient, and it can be expected to maintain and improve the launch capability even if it is reused. In this project, we will research and develop key technology for practical application of the engine.

Reasons and benefits of using JAXA Supercomputer System

The following points are raised as problems of engine design by ground experiments. 1) There are limits to reproducing various airflow conditions from takeoff to hypervelocity range. 2) Measured data is limited and complicated three-dimensional flow structure inside the engine can not be well identified. 3) Since the time and cost are limited, it is not easy to change the engine flow path configuration. Therefore, it is indispensable to utilize 3D CFD as a design tool, and a supercomputer is required for performing numerous CFD works efficiently.

Achievements of the Year

(1) Direct-connect combustor tests are often used for combustion testing of scramjet combustor components because they are relatively cost-effective and can be performed frequently. In this test method, the airflow compressed by an inlet of a real engine is simulated by the nozzle airflow of a combustion-heated supersonic wind tunnel, and a combustor model is attached to the nozzle exit. Since the entire nozzle airflow, including the boundary layer, flows into the combustor model, it is necessary to understand the airflow conditions at the nozzle exit accurately and in detail when examining the combustion test results and performing CFD corresponding to

the combustion test. Therefore, we have started the combustion CFD of the flow inside the whole combustion-heated supersonic wind tunnel, including the combustion air heater. (Fig. 1) CFD also determined the pitot tube installation spacing of the miniature pitot tube rake probe to be used for the nozzle flow calibration. We plan to verify the CFD results by comparing the measured distributions of pitot pressure and airflow composition at the nozzle exit plane and investigate the details of the nozzle flow characteristics.

(2) In order to develop a high-frequency space transportation system, engine research has been conducted at the Kakuda Space Center for many years. However, it has become important to integrate the engine and airframe and to study their interference effects. Therefore, aerodynamic characteristics of the airframe, which were optimized through trajectory analysis, etc., and engine were simulated separately by CFD. Also, CFD simulations of the airframe integrated with the engine were performed for comparative study. Figure 2 shows the results of numerical simulations of flight conditions at Mach 4.

(3) In a scramjet combustor, where turbulence, shock waves, and chemical reactions interact in a complex manner, a more detailed turbulent structure must be considered to accurately understand the internal structure. If the combustor interior is analyzed by DNS without model simplification in a numerical analysis, the computational cost is enormous. Therefore, the use of a hybrid LES/RANS model that combines LES, which models part of the turbulence, and RANS, which models all of the turbulence, can reduce the computational cost. In addition, to account for the turbulent structure upstream of the combustor, a further reduction in computational cost can be achieved by using the recycling/rescaling method, in which the inflow boundary is calculated as a time-varying boundary. Therefore, we have analyzed the upstream of the combustor while using these methods together for the analysis in the scramjet combustor. (Fig. 3) In the future, we plan to analyze the entire combustor after correcting the defects and modifying the code to speed up the calculation.

(4) We developed a tool for fast analysis of aerodynamic heating of the sharp leading edge and heat transfer to the inside of the material, and predicted the heating in a wind tunnel experiment and compared it with experimental values. (Fig. 4)

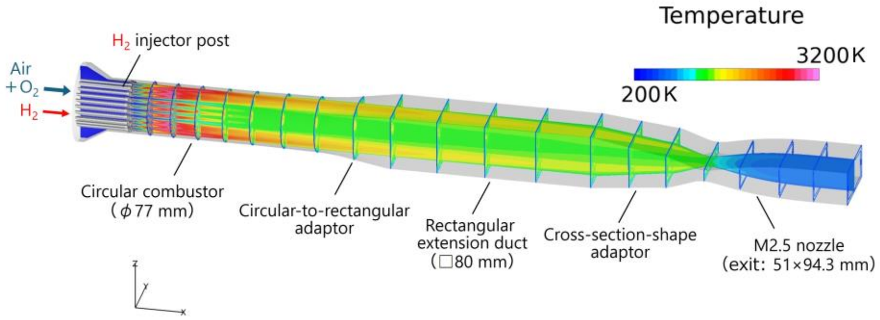

Fig. 1: Static temperature distribution on center cross-section and cross-sections at each flow direction in a combustion-heated supersonic wind tunnel, test airflow conditions: total temperature of 1500 K, total pressure of 1 MPa, designed Mach number of 2.5.

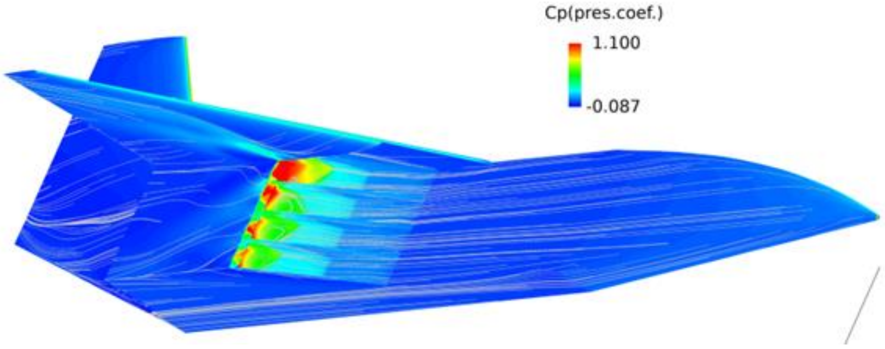

Fig. 2: Numerical simulation results of flight conditions at Mach 4 (distributions of pressure coefficient and oil flows on surface)

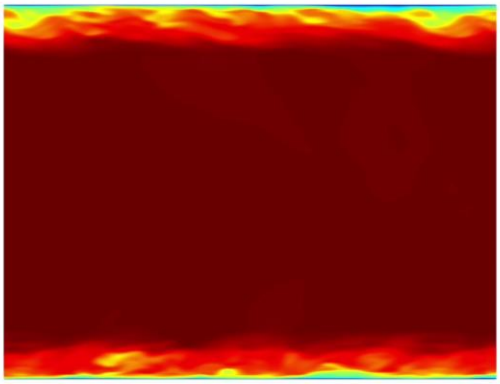

Fig. 3: Variation of unburned flows upstream of combustor: velocity distribution in center cross-section (inflow conditions: Mach number of 2.3, static temperature of 144.6 K, static pressure of 4.01 MPa) (Video. Video is available on the web.)

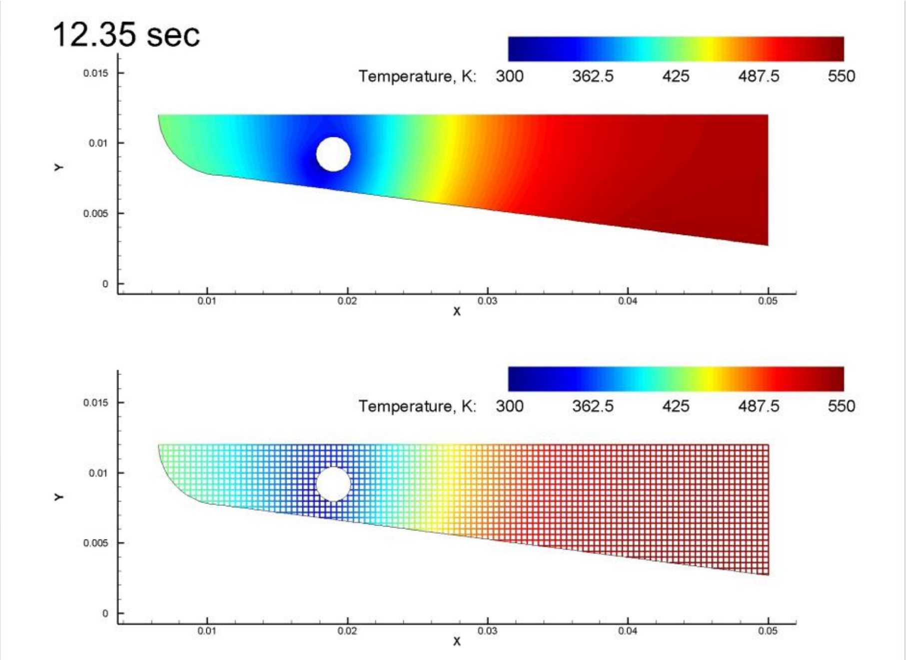

Fig. 4: Temperature distribution inside material and computational grid when near leading edge with cooling holes was heated by hypersonic flow (Video. Video is available on the web.)

Publications

- Non peer-reviewed papers

(1) Takahashi, M., "Evaluation of a prototype probe for measuring pitot pressure distribution in the boundary layer of a nozzle flow of a supersonic wind tunnel with a vitiated air heater," The proceedings of the 63rd Conference on Aerospace Propulsion and Power (domestic) / Northern Branch 2024 conference and the 5th symposium on reusable space transportation, JSASS-2024-0074, 2024.

- Oral Presentations

(1) Takahashi, M., "Evaluation of a prototype probe for measuring pitot pressure distribution in the boundary layer of a nozzle flow of a supersonic wind tunnel with a vitiated air heater," The 63rd Conference on Aerospace Propulsion and Power (domestic) / Northern Branch 2024 conference and the 5th symposium on reusable space transportation, 2B03, 2024.

Usage of JSS

Computational Information

Process Parallelization Methods	MPI
Thread Parallelization Methods	N/A
Number of Processes	256 - 4800
Elapsed Time per Case	200 Hour(s)

- **JSS3 Resources Used**

Fraction of Usage in Total Resources[*1](%): 0.82

Details

Computational Resources		
System Name	CPU Resources Used (core x hours)	Fraction of Usage[*2](%)
TOKI-SORA	20,185,428.68	0.91
TOKI-ST	209,614.28	0.23
TOKI-GP	0.00	0.00
TOKI-XM	0.00	0.00
TOKI-LM	1,236.11	0.09
TOKI-TST	0.00	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	232.02	0.19
/data and /data2	21,587.50	0.13
/ssd	2,565.50	0.24

Archiver Resources		
Archiver Name	Storage Used (TiB)	Fraction of Usage[*2] (%)
J-SPACE	10.12	0.04

[*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)	13,013.84	5.87

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