Rocket engine high-enthalpy flow simulation using heated CO₂ gas to verify the development of a rocket nozzle and combustion tests

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Abstract. The LE-7A engine is the first-stage engine of the Japanese-made H-IIA launch vehicle. This engine has been developed by improving and reducing the price of the LE-7 engine used in the H-II launch vehicle. In the qualification combustion tests, the original designed LE-7A (LE-7A-OR) engine experienced two major problems, a large side load in the transient state of engine start and stop and melt on nozzle generative cooling tubes. The reason for the troubles of the LE-7A-OR engine was investigated by conducting experimental and numerical studies. In actual engine conditions, the main hot gas stream is a heated steam. Furthermore, the main stream temperature in the nozzle changes from approximately 3500 K at the throat to 500 K at the exit. In such a case, the specific heat ratio changes depending on the temperature. A similarity of the Mach number should be considered when conducting a model flow test with a similar flow condition of the Mach number between an actual engine combustion test and a model flow test. High-speed flow tests were conducted using CO₂ gas heated up to 673 K as a working fluid and a 1:12 sub-scaled model nozzle of the LE-7A-OR engine configuration. The problems of the side force and the conducted form of the shock waves generated in the nozzle of the LE-7A-OR engine during engine start and stop were reproduced by the model tests of experimental and numerical investigations. This study presented that the model flow test using heated CO₂ gas is useful and effective in verifying the numerical analysis and the design verification before actual engine combustion tests.

1. Introduction

The H-IIA launch vehicle was developed based on an H-II launch vehicle while planning for the improvement of reliability and attaining a cost reduction of approximately 50% to acquire international competitiveness [1]. Table 1 shows the specifications of the LE-7A engine used for the H-IIA launch vehicle in comparison with that of the LE-7 engine for the H-II launch vehicle. The nozzle skirt of the LE-7A-OR engine comprised the upper regenerative tubes cooled by liquid hydrogen and the lower sheet metal made by a forging process. A step was established between the lower- and upper-part skirts. In addition, film cooling with hydrogen gas was adopted on the lower-part nozzle’s inner surface to keep the metal temperature of the lower-part nozzle under the allowable metal temperature. However, an unexpected high side force of more than the permission level of the actuator was obtained when the qualification combustion tests of the LE-7A-OR engine were conducted using the ground facilities at the liquid engine examination test stand of the Tanegashima Space Center. The side force value was...
over 300 kN. The improvement of the LE-7A-OR engine should be forced to reduce the side force within the actuator’s permission level [2, 3].

**Table 1** Comparison of the engine specifications of LE-7 and LE-7A

|                      | LE-7A | LE-7 |
|----------------------|-------|------|
| **Thrust [kN]**      | 1098  | 1078 |
| **Specific Impulse [s]** | 440   | 446  |
| **Combustion Chamber Pressure [MPa]** | 12.2  | 12.7 |
| **Total Length [mm]** | 3680  | 3243 |
| **Maximum Diameter [mm]** | 1965  | 2570 |
| **Expansion Ratio**   | 51.7  | 51.4 |
| **Weight [kg]**       | 1830  | 1720 |
| **Burn Time [s]**    | Max 400 | 350  |

Experiments were conducted to investigate the reason of the LE-7A-OR troubles by using dried pure nitrogen gas as a working fluid. However, the tests could not reproduce the troubles. Accordingly, we determined that the reason why the high-speed flow test of the LE-7A-OR engine by using dry nitrogen gas could not reproduce the trouble is the specific heat ratio of the working fluid. The specific heat ratio of the combustion gas (mainly steam) changed from 1.16 at the combustion chamber to 1.28 at the nozzle exit. The use of pure dried nitrogen gas, which is a well-known and established high-speed experimental method, keeps the constant specific heat ratio of 1.4 and could not simulate the actual LE-7A-OR engine states. We examined the specific heat ratio of three atomic gases to fit with steam under a rocket engine combustion state. Consequently, we found that CO₂ is the best.

As part of the development of an improved LE-7A(LE-7A-IM) engine nozzle, we experimentally conducted an evaluation of the influence of the nozzle shape on the heat flux distribution on the nozzle wall surfaces and thrusts using 1/12 sub-scaled nozzle models of the LE-7 and the LE-7A-OR engine with heated CO₂ gas. Furthermore, we conducted experiments by using a 1/12 sub-scaled nozzle of the LE-7A-IM engine. We also performed an analysis to verify the re-designed improved nozzle within a permitted small thrust.

This study describes the novel experimental technique to simulate the real rocket engine combustion flow by using heated CO₂ gas. The test results were obtained for the purpose mentioned above and compared with the CFD analysis results.

### 2. Phenomenon with the original LE-7A engine

The LE-7 engine nozzle had a truncated perfect (TP) shape. The LE-7A-OR engine nozzle shape chose a compressed truncated perfect (CTP) nozzle shape dissimilar to the LE-7 engine. The CTP nozzle shape is the design method used to axially shorten the nozzle head by compressing a TP nozzle. The CTP nozzle was adopted as the design technique for the LE-7A-OR nozzle because the CTP nozzle had splendid characteristics of freely selecting the expansion ratio depending on the compression of TP nozzle and generating a small performance loss with shape compression [4]. The initial expansion angle of the LE-7A-OR engine is approximately 3° bigger than that of the LE-7 engine. Figure 1 shows the comparison of the nozzle contour of the LE-7A-OR engine with that of the LE-7 engine.

Two deficient phenomena on the nozzle skirt of the LE-7A-OR engine were generated in the combustion tests in the initial stage of the LE-7A engine development. One phenomenon is the large side thrust in the transient state of engine start and stop. The other is the damage of the nozzle generative cooling tubes of the upper-part nozzle skirt.

The side load origin was estimated because of the transition of the separation pattern from shock
separation to restricted shock separation (RSS)\textsuperscript{[5, 6]}. Figure 2 is referred from reference \textsuperscript{[6]}, in which M. Frey and G. Hagemann described the detailed flow structure of the FSS and the RSS. The RSS is attributed to a reattachment of the separated flow to the nozzle wall, which induces shocks and expansion waves. The shocks generated high pressure on the wall, and the reattached flow caused a high heat flux region.

![Fig. 1 Nozzle contour comparison of the LE-7A and LE-7 engines](image1)

![Fig. 2 Phenomenological sketch of the FSS and the RSS \textsuperscript{[6]}](image2)

3. Experimental test facility and measuring techniques

The combustion temperature of the LE-7A engine under the actual engine operating conditions was approximately 3500 K. It was thought and created to simulate the high-temperature steam flow of the rocket engine nozzle by using the heated CO\textsubscript{2} gas as working fluid to obtain the flow resemblance at a laboratory level. Figure 3 clearly shows that the steady-state specific heat ratio of the original LE-7A engine in the actual engine operating conditions can be almost simulated if CO\textsubscript{2} is used as the actuating experimentally working fluid and the stagnation temperature of the CO\textsubscript{2} gas can be heated up to 1200 K.

The Takasago R&D Center of Mitsubishi Heavy Industries, Ltd. has an experimental test facility, including the pebble heater heating arrangement that can increase gas by possibly up to a maximum of 400 °C (673 K). A rocket engine nozzle flow test can be simulated and the resemblance between the combustion gases of 3500 K flow through the nozzle and CO\textsubscript{2} gas in the experiment is possible by performing the experimental test utilizing CO\textsubscript{2} heated up to 673 K as the working fluid using this device. We revised the contour of the sub-scaled model nozzle to fit 673 K, instead of heating up the CO\textsubscript{2} gas to 1200 K as mentioned earlier. We re-designed the sub-scaled test nozzle contour to agree with the Mach number distribution of the actual LE-7A-OR engine operation of 3500 K flowing through the test nozzle contour in a stagnation point temperature of 673 K. The design was implemented by re-designing the original nozzle shape with a throat radius of 0.398 times of the throat curvature with the non-viscosity method. The nozzle length/throat diameter was fixed at the same value with the actual engine configuration. Furthermore, the correction of the boundary layer thickness by the difference of the Reynolds number between the CO\textsubscript{2} test and the actual engine operation was not revised. The maximum expansion corner was designed such that the position where the internal shock intersected at the sub-
scaled model nozzle center agreed with that of the LE-7A-OR engine. Furthermore, the scaled test nozzle contour was revised such that the Mach number distribution of the radial direction at the nozzle exit agreed with that of the LE-7A-OR nozzle.

![Fig. 3 Comparison of the specific heat ratio between the combustion gas and the heated CO₂](image)

The 1/12 sub-scaled nozzle models were manufactured with the abovementioned concepts. High-speed flow tests were also performed. Figure 4 shows a comparison of the numerical results of the CO₂ high-speed flow test of the LE-7A-OR sub-scaled model with the actual combustion condition.

![Fig. 4 Computed characteristic curve contours of the LE-7A-OR nozzle](image)

![Fig. 5 Scaling nozzle model and static pressure taps](image)
The test facilities comprised a pebble heater cumber, a heated gas reservoir tank, a high-speed opening and shutting valve, a 20 MPa reservoir tank with a high pressure, an ejector, and a silencer. The sub-scaled test nozzle is mounted downstream of the high-speed opening and shutting valve.

The test nozzles represent the LE-7, LE-7A-OR, and LE-7A-IM nozzles. Figure 5 shows the LE-7A-IM model nozzle shape, dimensions, and static pressure tap-mounting locations. Pressure monitoring in the nozzle wall surface of 1.2 mm was performed by piercing the nozzle wall with a stainless steel pipe having a 1.2 mm outside diameter and approximately 30 mm length. Pressure gauges of Kulite XT-190-15G and Kulite XT-190-25G were also attached to the pipe ends. The pressure gauges had an accuracy of ±0.5% of full scale. The pressure gauge was a semiconductor gauge type having a response frequency of 100 kHz and approximately 2 kHz, including a 30 mm-long pressure pipe.

4. Experimental results and discussion

The experiments on the sub-scaled nozzle models of the LE-7, LE-7A-OR, and LE-7A-IM engines were conducted by processing with the test section of the ramjet test facility. Accordingly, CO₂ gas was heated using a pebble heater up to 673 K and 2 MPa. The carbon dioxide concentration was examined and confirmed by measuring the oxygen concentration before and after the examinations.

Two test cases were considered. In case A, the high-speed opening and shutting valve was opened, and the nozzle upper stagnation pressure was maintained at approximately 2 MPa. Furthermore, the transient test was started by operating an ejector and changing the pressure back from atmospheric pressure to 0.01 MPa or from 0.01 MPa to atmospheric pressure. The pressure-changing time of the back pressure was approximately 10 s in the start and stop simulation tests.

Figure 6 shows the test result at the time of shut down and start-up of the LE-7 sub-scaled nozzle test. Figure 6 also plots each pressure ratio \( P_o/P_e \) in a transverse axis versus each wall pressure/back pressure \( P_w/P_e \) in a vertical axis. \( P_o \) is the chamber pressure; \( P_e \) is the nozzle exit pressure; and \( P_w \) is the pressure at number i static pressure taps. Figures 7 and 8 show the test result of the LE-7A-OR and LE-7A-IM sub-scaled nozzles, respectively, in the same manner as that of the LE-7 sub-scaled nozzle. The \( P_w/P_e \) of shutdown in Figure 7 clearly shows that the RSS\(^7\) was estimated to occur on the LE-7A-OR sub-scaled nozzle surface because of \( P_w/P_e > 1 \). Meanwhile, the pressure ratio \( P_w/P_e \) is less than 1.0 in the case of the LE-7 and the LE-7A-IM. Moreover, no big pressure change in \( P_w/P_e \) of the LE-7 and the LE-7A-IM occurred (Figures 6 and 7). The test results of the LE-7 and the LE-7A-OR sub-scaled nozzles clearly simulated the results of the actual LE-7 and the LE-7A-OR engine combustion tests.

![Fig. 6 Static pressure change of the LE-7 model nozzle at transient conditions in 10 s](image-url)
In case B, an ejector to control the back pressure was operated to maintain the back pressure \( P_e \) at 0.01 MPa. The high speed opening and shutting valve was then opened or closed to raise or reduce the nozzle entrance pressure \( P_o \) to 2 MPa or 0.01 MPa in 0.2 s. Figure 9 shows the test result of case B using the sub-scale model nozzle of the LE-7 engine.

The RSS for the LE-7 sub-scale model test in case B is estimated to occur at a period where the wall surface pressure \( P_w \) was higher than the nozzle back pressure \( P_e \) \((P_w/P_e > 1)\) at the shut down tests shown in Figure 9. In other words, the wall surface pressure of the LE-7 sub-scaled nozzle showed an unstable flow condition in the transient test of case B at a very rapid shut down in 0.2 s.

The facts obtained in this experiment meant that the RSS occurred even with the LE-7 sub-scaled nozzle by the short shut down time of 0.2 s. However, the RSS did not occur in the actual combustion examination of the LE-7 engine by the shut down time of 4.0 s.

**Fig. 7** Static pressure change of the LE-7A-OR model nozzle at transient conditions in 10 s

**Fig. 8** Static pressure change of the LE-7A-IM model nozzle at transient conditions in 10 s

In case B, an ejector to control the back pressure was operated to maintain the back pressure \( P_e \) at 0.01 MPa. The high speed opening and shutting valve was then opened or closed to raise or reduce the nozzle entrance pressure \( P_o \) to 2 MPa or 0.01 MPa in 0.2 s. Figure 9 shows the test result of case B using the sub-scale model nozzle of the LE-7 engine.

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**Fig. 9** Static pressure change of the LE-7 model nozzle at transient conditions in 0.2 s
In contrast to the test results of the LE-7A-OR sub-scaled nozzle, the wall surface pressure ratio did not exceed the nozzle back pressure \((P_{w}/P_{e} < 1)\) in all the examinations in the LE-7A-IM sub-scaled nozzle, even with the hard simulation test of shutdown in 0.2 s in case B.

The test results show that the LE-7A-OR nozzle shape causes a more unstable flow than the LE-7 nozzle shape. The case B tests clearly illustrate that the LE-7A-IM is stable with the same level of the LE-7 nozzle. The simulation test clearly demonstrates that using the heated CO\(_2\) gas is very useful in verifying the development of a rocket nozzle and combustion tests. In addition, the severe shut down test operated in 0.2 s is useful in checking and assuring the stability of the flow of the newly designed nozzle in transient conditions.

5. Analytical method and results

The analysis was conducted using the second-order upwind method, the positive elucidation at a two-dimensional axis symmetry analysis, and the second space precision with a TVD scheme. In addition, a two-equation turbulence model (i.e., \(k-\varepsilon\) model) is used. The numerical analysis was conducted according to the transient CO\(_2\) sub-scaled model tests under the boundary conditions that the circumference side and the nozzle upper-reach circumference are assumed as isolated walls. The number of grid points was 401 (axial direction) \(\times\) 71 (radial direction) in the nozzle section. The total number of grids was about \(8 \times 10^4\). Meanwhile, the minimum grid spacing in the \(r\) direction satisfies \(y^+ < 1\) at a grid point adjacent to the nozzle wall. The thermal properties of the CO\(_2\) were modeled in the simulations by the models published by McBride et al.\([11]\).

Figures 9–11 illustrate the Mach number distributions and the characteristic curves in the nozzle at the steady-state actual engine conditions of the LE-7, LE-7A-OR, and LE-7A-IM nozzles, respectively.
Figures 13–15 show the numerical results of the simulation of the shutdown tests in 0.2 s by using CO₂ as a working fluid of the LE-7, LE-7A-OR, and LE-7A-IM sub-scaled nozzles, respectively. The strong side force tends to occur in shutdown at a pressure ratio $P_o/P_e$ around 40 and 80 at the actual LE-7A-OR engine combustion tests. The notes of Figures 13–15 show the flow patterns estimated from the Mach number distribution [8–10]. The CFD results of the LE-7 and the LE-7A-OR sub-scaled nozzles shown in Figures 13 and 14 clearly reproduce the RSS outbreak at around $P_o/P_e = 40$. The CFD can estimate the wall surface pressure decreases just before the RSS outbreak. The RSS outbreak in Figure 15 suggests that $P_o/P_e = 40$ is the critical pressure ratio.
phenomenon is clearly captured by the CFD analysis. The CFD analysis in Figure 15 shows that the RSS does not occur at the shutdown test in 0.2 s by using the LE-7A-IM sub-scaled nozzle at a pressure ratio \( \frac{P_0}{P_e} \) around 40. This result guarantees the CFD analysis accuracy that can be used for the rocket nozzle design.

![Mach contour plots of the LE-7A-IM nozzle at shut down in 0.2 s](image)

**Fig. 15** Mach contour plots of the LE-7A-IM nozzle at shut down in 0.2 s

Figure 16 shows the comparison between the experimental measurement of the LE-7A-OR sub-scaled nozzle test at the shutdown test in 0.2 s and the numerical analysis results just under the same conditions with the experiments. Figure 16 illustrates that the CFD analysis can estimate the RSS outbreak even though it occurs at a little lower pressure ratio of \( \frac{P_0}{P_e} \).

![Comparison of the static pressure change between the numerical analysis and the experimental measurement of the LE-7A-OR nozzle at the shut down condition](image)

**Fig. 16** Comparison of the static pressure change between the numerical analysis and the experimental measurement of the LE-7A-OR nozzle at the shut down condition

6. **Conclusion**

This study presented a novel experimental technique to simulate the real rocket engine combustion flow by using heated CO2 gas. The experiments and the numerical analysis of the sub-scaled nozzle model tests using CO2 gas of the LE-7 engine, original LE-7A engine, and re-designed LE-7A engine lead to the following conclusions:
1. The new verification method of a rocket nozzle design and a rocket engine combustion test is presented by using the heated CO\textsubscript{2} gas instead of the high-enthalpy flow of a rocket engine combustion gas.

2. The specific heat ratio \( \gamma \) depending on the temperature can be exactly adjusted between the CO\textsubscript{2} gas and the rocket engine combustion gas.

3. The flow visualization and detailed flow measurement can be conducted by utilizing the heated CO\textsubscript{2} gas to simulate the real rocket engine combustion gas flow. The model flow test using the heated CO\textsubscript{2} gas is useful and effective for the accuracy verification of the numerical analysis and the design verification before the actual engine combustion tests.

4. The rapid shut down test in 0.2 s made the LE-7 sub-scale nozzle flow into the RSS. This severe CO\textsubscript{2} test condition can be used to confirm the nozzle flow stability and is useful for the design criteria of the rocket engine operation and nozzle contour.

Nomenclature

FSS: free shock separation
\( k \): turbulent kinetic energy
\( P_e \): back pressure at a nozzle exit
\( P_w \): static wall pressure
\( P_o \): stagnation pressure
RSS: restricted shock separation
\( r \): \( r \) coordinate
\( t \): time
\( z \): \( z \) coordinate
\( \varepsilon \): turbulent dissipation rate

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