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Bipropellant Performance of N_2H_4/MMH Mixed Fuel in a Regeneratively Cooled Engine

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Experimental regeneratively cooled bipropellant engines, with a vacuum thrust of 2000 N at a chamber pressure of 0.98 MPa and an area ratio of 240:1, were fired with hydrazine-monomethyl hydrazine (MMH) mixed fuels to evaluate potential performance and cooling improvement. Regeneratively cooled engine tests were conducted with 80% hydrazine-20% MMH mixed fuels, as well as with MMH single fuel, utilizing optimized injectors for each fuel. The chamber pressure was varied in a range from 0.6 to 0.9 MPa. Long-duration firing tests of 160 s were conducted to evaluate heat soak-back level and to demonstrate safe shutdowns of a mixed fuel regeneratively cooled engine. The peak specific impulse of the mixed fuel was more than 322 s, while that of MMH fuel was 308 s. Regenerative cooling with the mixed fuel seemed to be particularly advantageous in that the temperature increase through the cooling channels was smaller than that of MMH fuel; this reduced performance degradation due to reactive stream separation ("blow apart") at higher chamber pressures. No indication of explosion in the coolant channels or manifolds at engine shutdown was observed.

Nomenclature

A_{th} = geometrical throat area
BLL = boundary-layer loss
c = a constant in Eq. (6)
c^* = characteristic velocity
c^*_{ODE} = theoretical characteristic velocity for one-dimensional equilibrium flow
d_f = fuel orifice diameter
d_o = oxidizer orifice diameter
f_{dis} = discharge coefficient
f_p = correction coefficient to convert P_c to nozzle stagnation pressure
I_{ODE} = theoretical vacuum specific impulse for one-dimensional equilibrium flow
I_{spv} = vacuum specific impulse
$I_{spv,ff}$ = film coolant vacuum specific impulse
$I_{spv,MRc}$ = core propellant vacuum specific impulse
KL = kinetic loss
MR = overall mixture ratio, including film coolant
MRc = core mixture ratio
$\dot{m}_c$ = core propellant flow rate
$\dot{m}_{ff}$ = film cooling fuel flow rate
$\dot{m}_t$ = total propellant flow rate
n = a constant in Eq. (6)
P_c = chamber pressure at the injector face
$\dot{Q}_c$ = total heat transferred to regenerative cooling fuel
$\dot{q}_{ul}$ = heat flux at the upper limit of nucleate boiling
Re_F = fuel Reynolds number
R_N = Rupe number
T_{co} = fuel outlet temperature
TDL = two-dimensional loss
T_W = chamber wall temperature
u_f = velocity through fuel orifice
u_o = velocity through oxidizer orifice
V = velocity of coolant through cooling channels
α_f = fuel impingement angle
α_o = oxidizer impingement angle
ΔT_c = fuel temperature increase through regenerative cooling channels
ΔT_{sub} = subcooling, saturation temperature minus coolant temperature
ε = nozzle area ratio
η_{c^*} = c^* efficiency
η_{ER} = energy release efficiency
ρ_f = density of fuel
ρ_o = density of oxidizer

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Introduction

THERE is a strong demand for higher performance bipropellant liquid apogee propulsion systems for future Japanese large satellites. One possible near-term solution to this demand would be to replace the commonly used fuel, monomethyl hydrazine (MMH), with hydrazine. For pressure fed engines with a high-area ratio nozzle, the peak-delivered vacuum specific impulse of a nitrogen tetroxide (NTO)/hydrazine propellant system was calculated and verified by experiment to be more than 2% higher than that of a NTO/MMH system.[1] To realize this specific impulse advantage, it is necessary to overcome or avert possible problems associated with combustion chamber cooling with hydrazine. In general, the primary physical properties that enhance film cooling capability are, higher heat of vaporization, higher boiling point, and higher surface tension.[2] Furthermore, those that enhance regenerative cooling capability in the subcooled boiling region are, higher boiling point (higher saturation temperature), higher thermal conductivity, and higher heat capacity.[3] It can then be deduced from the physical properties of the fuels under consideration that the film and regenerative cooling capabilities of hydrazine would be superior to those of MMH, even without regard to the fact that the optimum mixture ratio of the NTO/hydrazine propellant system is much lower than that of the NTO/MMH system. However, it is known that the film cooling capability of hydrazine is markedly degraded under certain conditions due to the formation of a decomposition flame on the liquid film.[4] It has also been observed from our preliminary regenerative cooling experiment that an explosion in the cooling channels can occur after firing when a gas purge is applied.

To overcome these difficulties, an approach was employed to modify the thermal stability of hydrazine by adding a relatively small amount of MMH.[5] Miyajima et al.[5] selected a blend of 80% hydrazine-20% MMH (denoted by 80-20) for regenerative cooling tests. Their tests at a 450-N thrust level have shown that employing the 80-20 mixed fuel is a viable option for improving the performance and cooling capability of a small storable engine. However, their performance comparison of 80-20 mixed fuel and MMH single fuel was somewhat compromised for two reasons: 1) their reliance on an existing injector that was optimized for NTO/MMH propellants; and 2) their experiment was conducted at sea level using a low-area ratio nozzle, in comparison to a real space engine where regenerative cooling may be extended further into the nozzle expansion region. The present experimental study was undertaken to rectify those problems. An engine with a vacuum thrust of 2000 N at a chamber pressure of 0.98 MPa and area ratio 240:1 was used. Two injectors were employed; one was optimized for the NTO/80-20 mixed fuel and the other optimized for NTO/MMH. The engine was regeneratively cooled up to an area ratio of 7:1. Instead of extrapolating sea level results, specific impulse for the high-area ratio engine was measured directly in a high-altitude test facility.

Comparisons of specific impulses and thermal environments for MMH and 80-20 mixed fuels were made. Long duration firing tests of 160 s were conducted to evaluate heat soakback level and to demonstrate safe shutdowns of a mixed fuel regeneratively cooled engine. We concluded that, in comparison to MMH fuel, 80-20 mixed fuel is a promising fuel for obtaining a higher specific impulse performance and a better cooling capability.

Test Facility and Test Article

Test Facility

In order to test a low chamber pressure, high-area ratio engine, a very low environmental pressure level is required to obtain nozzle full flow. All firing tests were conducted at the High Altitude Test Facility of the National Aerospace Laboratory at Kakuda.[6] This facility is capable of obtaining an environmental pressure of about 0.1 KPa with a maximum test time of 170 s. One of the most important parameters for engine performance is I_{spv}, which depends on measured thrust, mass flow rate of propellants, and environmental pressure. The axial thrust was measured by a load cell in a compression mode. The estimated precision of the thrust measurement was $\pm 0.3\%$. The propellant flow rates were measured with two turbine flow meters in series. The flow meters were calibrated "in-place," "end-to-end" with NTO and 80-20 fuel before each test series. For MMH fuel, calibration data accumulated in the past were used. The estimated precision of the mass flow rate measurement was $\pm 0.25\%$. Capsule pressure was important for converting measured specific impulse to vacuum specific impulse. The estimated precision of the capsule pressure was about ± 0.01 KPa. The overall precision of the measured I_{spv}, taking the dual measurement effect into account, was calculated to be within $\pm 0.5\%$.

Regeneratively Cooled Chamber

The thrust level of the experimental engine was 2000 N at a chamber pressure of 1.0 MPa with a 240:1 area ratio nozzle. Figure 1 shows the engine set in an altitude capsule. The fuel that regeneratively cooled the combustion chamber was routed by external piping to the injector. Figure 2 shows the two regeneratively cooled chambers used. The length of the chambers from the injector face to the throat was 104.5 mm, and the characteristic length L^* of the chamber was 0.303 m. The chamber had 45 slotted cooling channels. To increase coolant speed and pressure drop, the channel depth was held constant at 0.5 mm, whereas the width varied from 2.65 mm at the cylindrical section to 1.52 mm at the throat section. The pressure drop through the cooling channels was about 0.15 MPa at a chamber pressure of 1.0 MPa. To reduce the heat load to the coolant, the inner wall was constructed of 2.5-mm-thick stainless steel (304 CRES). The upper half of the chamber shown in Fig. 2, designated REG-I, was used for the first series of tests. The lower half of Fig. 2 shows an improved version of the chamber (REG-II). The major modifications of the chamber were that the REG-II chamber was cooled over an extended region up to the injector cavity and that its coolant inlet manifold volume at the nozzle extension flange was reduced. With such modifications, it was projected that the temperatures at the noncooled regions, i.e., at the injector and nozzle extension flange, would not rise too high after a long duration firing.

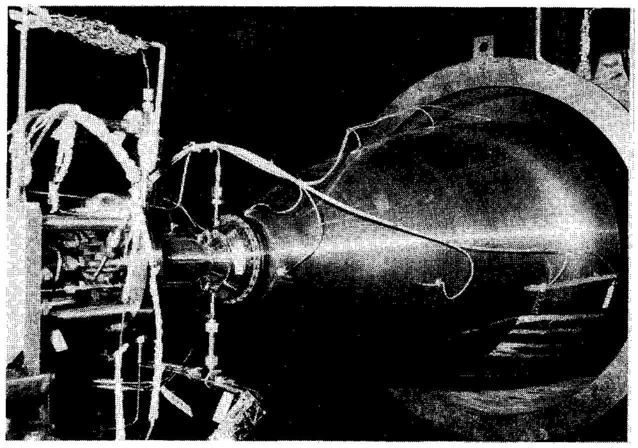

Fig. 1 Engine set in altitude capsule.

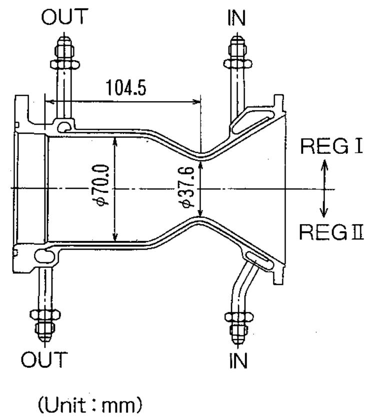

Fig. 2 Regeneratively cooled chambers.

Injectors

Two injectors were used, one for NTO/MMH (denoted by 27B) and the other for NTO/80-20 mixed fuel (36M). The design characteristics of the injectors are given in Table 1. The basic configuration of the injectors was a double concentric ring arrangement of unlike doublet elements, with film cooling orifices on the outermost third ring. Both of the injectors had quarterwave acoustic cavities at the side of injector body, the open area of the cavities being 7% of the chamber cross-sectional area. Figure 3 illustrates the 36M injector design. The injector 27B had 27 core elements and 26 film cooling orifices. The film cooling flow rate was determined from water flow tests to be 15% of the total fuel flow rate. It was originally designed for a film-cooled, carbon-carbon chamber.[7] Core elements were designed so that Rupe's optimum

Table 1 Design characteristics of injectors

	27B	36M
Propellants	NTO/MMH	NTO/80-20
Nominal mixture ratio	1.65	1.04
Film cooling ratio, % of fuel	15	15
Core mixture ratio	1.94	1.22
Nominal fuel temperature, K	353	333
Rupe number	0.520	0.494
Number of element	27(9/18)[a]	36(12/24)[a]
Oxidizer orifice diameter, mm	0.78	0.65
Fuel orifice diameter, mm	0.59	0.66
Impingement angle, deg	70(30/40)[b]	70(35/35)[b]
Injector pressure drop,[c] MPa	0.443/0.299	0.213/0.197
Number of film cooling orifices	26	24
Film cooling orifice diameter, mm	0.26	0.34

[a]Number of elements on (inner/outer) ring. [b](α_o/α_f), see Fig. 3. [c]Oxidizer/fuel at P_c = 0.698 MPa.

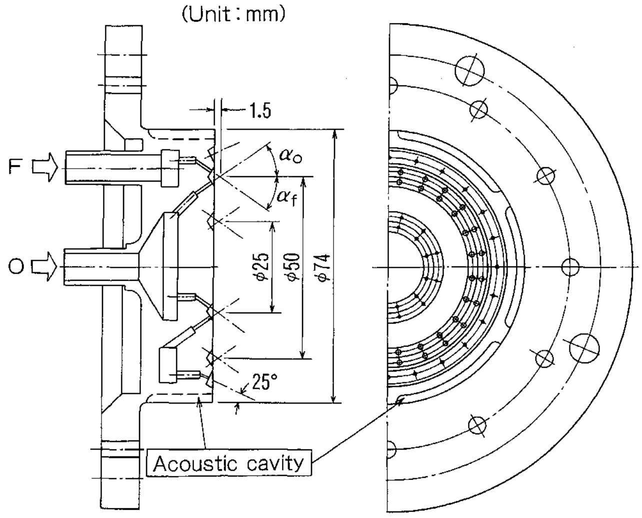

Fig. 3 Injector design (36M).

spray mixing condition[8] was obtained at an overall mixture ratio of 1:65 for the NTO/MMH propellant system. Optimum spray mixing occurs when R_N, defined by Eq. (1), equals 0.5:

$$R_N = 1/(1 + \rho_o u_o^2 d_o / \rho_f u_f^2 d_f) \tag{1}$$

Because of the increased fuel temperature in the present experiment, the Rupe number deviated from the optimum by 0.02 as shown in Table 1. However, this amount of deviation would not affect the spray mixing appreciably.

Reactive stream separation was examined using Lawver's correlation,[9] which states that the reactive stream separation of impinging coherent nitrogen tetroxide and amine streams occurs when

$$P_c > 3.03 \times 10^6/Re_F \tag{2}$$

where Re_F is based on the fuel orifice diameter of the injector element, and the unit of P_c is MPa. The injector orifice size and chamber pressure up to 1.2 MPa remained outside of the reactive stream separation region when fuel temperature at the injector was 293 K. Because of heat absorption from the chamber, the separation chamber pressure was expected to be reduced to 0.8 MPa for the present regeneratively cooled tests.

The injector 36M had 36 core elements and 24 film cooling orifices. The film cooling fraction was almost the same as that of injector 27B. Core injector elements were designed so that optimum spray mixing was obtained at an overall mixture ratio of 1.1 for the NTO/80-20 mixed fuel propellant system. The operating chamber pressure up to 1.0 MPa remained outside of the reactive stream separation region at a fuel injection temperature of 323 K. The number of core elements was increased mainly to avoid popping at higher chamber pressures. The performance comparison between MMH and 80-20 fuel is not affected significantly by a difference in the number of elements. Our experience with NTO/hydrazine indicates that an increase in core elements does not affect the performance significantly when the number of core elements is more than 24.

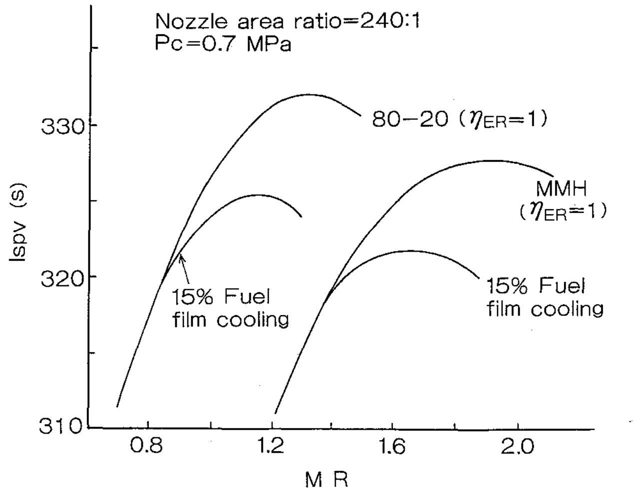

Fig. 4 Specific impulse comparison of NTO/80-20 and NTO/MMH.

Performance of Mixed Fuel

Figure 4 compares the theoretical specific impulses of 80-20, and MMH fuels at a nozzle area ratio of 240:1 and a chamber pressure of 0.7 MPa. The upper curves indicate specific impulses at perfect energy release, which is defined as

$$I_{spv}(\eta_{ER} = 1) = I_{ODE} - KL - TDL - BLL \tag{3}$$

This is the theoretical I_{spv} that assumes perfect energy release in the chamber at a uniform input mixture ratio. Nozzle expansion losses were calculated by a method[10] developed after the JANNAF methodology.[11] The boundary-layer loss was corrected for laminar flow.[12] The lower curves in Fig. 4 indicate a rough estimate of I_{spv} with 15% fuel film cooling, assuming perfect energy release in the core flow. Those curves were calculated by simple mass average as

$$I_{spv} = (I_{spv,MRc}\dot{m}_c + I_{spv,ff}\dot{m}_{ff})/\dot{m}_t \tag{4}$$

The mixing between core propellant and film coolant and the displacement effect of film coolant during nozzle expansion were neglected. Film coolant specific impulse was calculated assuming that decomposed film coolant expanded from the chamber pressure to the nozzle exit pressure using the frozen option of the one-dimensional equilibrium code. Sixty percent ammonia decomposition was assumed for hydrazine.

It can be seen from Fig. 4 that the peak I_{spv} between 80-20 fuel and MMH is about 4 s for the case of "perfect energy release" for uniform input mixture ratios. With 15% fuel film cooling, however, the difference is roughly estimated to be 3.5 s, and the mixture ratio of maximum I_{spv} shifts to the lower values, 1:15 for 80-20 fuel and 1:65 for MMH fuel.

In addition to the theoretical performance advantage, it is very easy to obtain high-energy release efficiency with the NTO/hydrazine propellant system.[13] However, as mentioned earlier, cooling by hydrazine involves inherent problems related to hot wall decomposition. The motivation for using mixed fuel is to obtain a specific impulse approaching that of hydrazine without the resultant cooling problems.

Test Results

In order to prevent a possible explosion at the instant of gas purge, such as occurred during the preliminary regenerative cooling tests with hydrazine, fuel delay shutdown was employed. Here, fuel delay shutdown means that the fuel valve is closed at a certain time after the oxidizer valve is closed. In the early tests, the fuel delay was set at 0.5 s, but in later stages of the test series a 0.2-s delay and no delay were employed without any explosion.

The primary performance parameter for the present tests is the vacuum specific impulse. However, c^* efficiency evaluated from chamber pressure measurement is also reported to indicate relative measure of combustion efficiency. It is defined as

$$\eta_{c^*} = c^*/c^*_{\mathrm{ODE}} \tag{5a}$$

$$c^* = (P_c f_p A_{\mathrm{th}} f_{\mathrm{dis}})/\dot{m}_t \tag{5b}$$

It should be noted that the nonuniformity of the flow due to film cooling was not accounted for in the evaluation of c^*. Figure 5 shows performance variation with firing time. The specific impulse and the coolant outlet temperature (Fig. 6) attained almost steady values after 15 s of firing in most of the tests. The difference of c^* and I_{spv} between the values at 15 and 160 s was within $\pm 0.5\%$. The coolant outlet temperature difference between 15 and 160 s was less than 3°C in an identical run. In the firing test using the REG-I chamber, chamber wall temperature near the injector rose to 600 K after 30 s and continued to increase rapidly. To preclude possible hydrazine decomposition, firing time to evaluate performance was set at 15 s. Maximum firing duration tested with the REG-I chamber was 30 s. As mentioned earlier, the REG-II chamber was improved by extending the cooling region so that the wall temperature near the injector would not rise too high. Firing time to evaluate performance was set at 30 s in the REG-II chamber. The maximum firing duration tested with the REG-II chamber was 160 s.

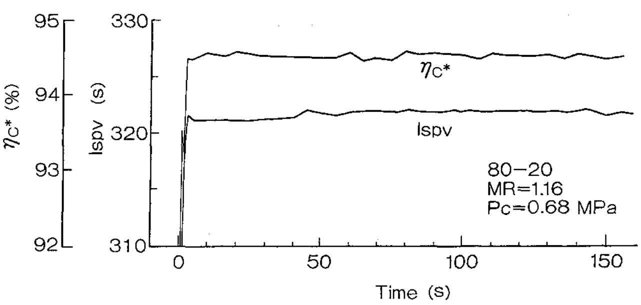

Fig. 5 Timewise variation of performance.

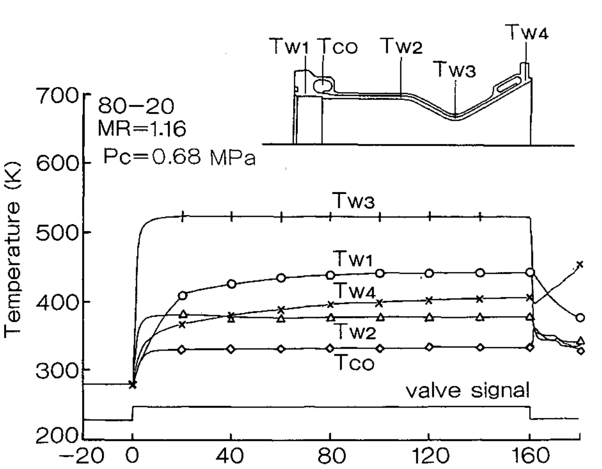

Fig. 6 Timewise variation of wall temperatures and coolant outlet temperature.

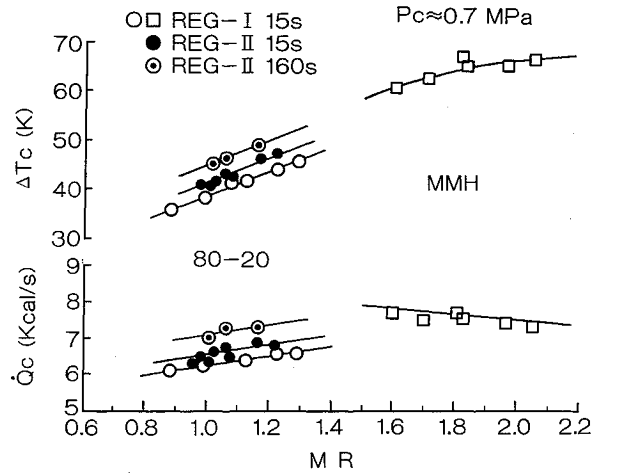

Fig. 7 Temperature increase through cooling channels and heat absorption.

Thermal Characteristics

Figure 6 shows the timewise variation of chamber wall temperatures and that of coolant outlet temperature measured in a long duration test using the REG-II chamber. Wall thermocouples were embedded at 1 mm from the inner wall. It is seen that the temperatures at the throat (TW3), and just upstream of the contraction (TW2), reached steady values in less than 10 s, whereas those at the cavity (TW1) and nozzle flange (TW4) increased slightly even after 140 s of firing. Heat conduction from these nonactively-cooled regions increased the coolant outlet temperature slightly after 15 s of firing.

Figure 7 summarizes the temperature increase through the cooling channels and the total heat load for 80-20 mixed fuel. The outlet temperature increased with mixture ratio. The difference of ΔT_c and $\dot{Q}_c$ between REG-I and REG-II may be attributed to the extended regenerative cooling region. The difference of the temperature increases at 15 and 160 s were generally within 3°C. A comparison of the thermal environment for 80-20 mixed fuel and MMH fuel is also shown in Fig. 7. It can be seen that the coolant temperature increases and that the total heat loads for 80-20 mixed fuel were smaller than those for MMH fuel. This is because of the larger total fuel flow and larger film cooling flow for the 80-20 mixed fuel (the film cooling fraction was the same at 15% for both MMH fuel and 80-20 mixed fuel). The smaller temperature increase is very important for prevention of possible fuel decomposition on hot walls, as well as to preclude reactive stream separation, resulting in a high injector performance. It may be seen that at the mixture ratios where the specific impulse was at a maximum (1.1 for 80-20 fuel and 1.8 for MMH fuel), the difference of the temperature increase was more than 20°C in favor of the 80-20 fuel.

Figure 8 compares measured wall temperatures at 1 mm from the inner surface for 80-20 fuel and MMH fuel. The wall temperatures at the throat were the same level for both 80-20 fuel and MMH fuel. The wall temperatures for 80-20 fuel just upstream of the contraction were very low, indicating that the liquid film cooling was effective at this station. For MMH fuel, however, wall temperatures at this station were about the same as those at the throat.

The agreement between the calculated and measured temperature increase of the coolant through regenerative cooling channels was reasonable as shown in Fig. 9. The heat transfer calculation for the gas-side was based on that of Stechman et al.,[14] and the calculation of regenerative heat transfer was based on that of Ohmori et al.[15]

In the absence of the data on the heat flux at the upper limit of nucleate boiling, the hydrazine data of Noel[16] was first recorrelated into the form

$$\dot{q}_{\mathrm{ul}} = c(V\Delta T_{\mathrm{sub}})^n \tag{6}$$

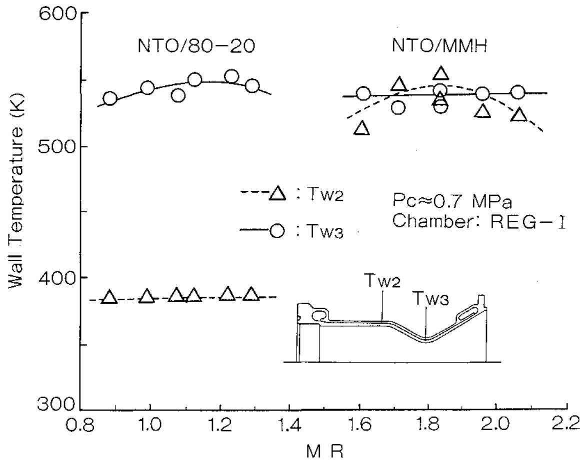

Fig. 8 Wall temperatures at 1 mm from the gas-side surface.

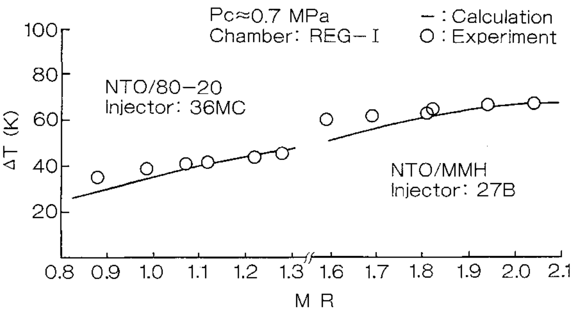

Fig. 9 Comparison of calculated and measured temperature increase through the cooling channels.

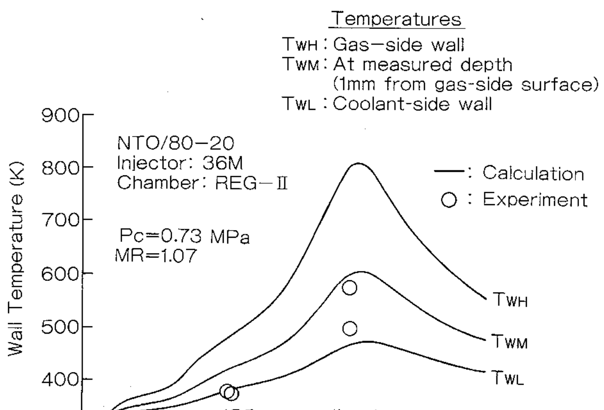

Fig. 10 Calculated and measured wall temperatures.

Then, it is assumed that Eq. (6) may be applied to 80-20 fuel. The single adjusting parameter in the calculation was the coolant efficiency factor, which was defined as the fraction of film coolant utilized for film cooling. Figure 10 compares calculated and measured wall temperatures for 80-20 fuel. The measured wall temperatures were generally lower than the calculated temperatures. Those temperatures were measured with sheathed thermocouples, 0.5 mm in diam, inserted radially and fitted in position by a seal. It may be inferred that temperatures somewhat lower than the actual temperature at the measured depth were indicated because of the contact resistance and radial heat conductance through the sheath. The important observation in Fig. 10 is that the coolant side wall temperatures seem to be sufficiently low (below 500 K) to preclude thermal decomposition of hydrazine, and that the gas side wall temperature is low enough to render use of common materials possible for construction of the combustion chamber.

Specific Impulse Performance

Figure 11 shows the effect of mixture ratio on performance at a chamber pressure of about 0.7 MPa for 80-20 mixed fuel and MMH fuel. The peak specific impulse of 80-20 mixed fuel was greater than 322 s at a mixture ratio of about 1.1, and that of MMH fuel was about 308 s at a mixture ratio of 1.8. It is seen that the mixture ratios of peak specific impulse did not coincide with those corresponding to the Rupe number of 0.5 (see Table 1). This may be attributed to the secondary mixing between adjacent sprays and the mixing of a portion of film coolant with the core flow. C^* efficiency of 80-20 fuel decreased rapidly with increasing mixture ratio, while that of MMH fuel decreased much more slowly. The difference of I_{spv} with 15% film cooling between 80-20 fuel at $MR = 1.1$ and MMH fuel at $MR = 1.8$ was about 4 s as shown in Fig. 4. However, as is seen in Fig. 11, a 3.3% difference in c^* efficiency (corresponding to 10 s in I_{spv}) between 80-20 fuel and MMH fuel was observed. If the difference of c^* efficiency approximately represents the difference of energy release efficiency, this and the above theoretical advantage for 80-20 fuel accounts for the large difference (14 s) of experimentally observed peak performance between 80-20 fuel and MMH fuel. It is not known exactly why the energy release efficiency for MMH is considerably lower than that of 80-20 fuel. However, we know from our previous experience that it is very easy to obtain a high-energy release efficiency with NTO/hydrazine propellants. One of the possible explanations of the high combustion efficiency of hydrazine is the higher burning rate of hydrazine droplets. It has been reported that the burning rate of hydrazine droplets is several times higher than that of MMH in combined decomposition and oxidation conditions.[17] The length of the combustor might not have been sufficient for obtained higher energy release in the present study. However, an increase in this combustion chamber length would entail problems because of increased heat load to the chamber. A more efficient injector design that would result in the production of finer droplets is required to obtain higher performance of the NTO/MMH propellant system.

Figure 12 shows the effect of chamber pressure on performance at a mixture ratio where the specific impulse peaked for each fuel. While the specific impulse of 80-20 mixed fuel did not vary appreciably up to a chamber pressure of about 0.9 MPa, a definite decrease for MMH fuel was observed at a chamber pressure as low as 0.8 MPa (as noted in an earlier study[7]). The chamber pressure at which stream separation occurs is calculated to be 0.8 MPa for MMH fuel and 10.0 MPa for 80-20 mixed fuel. These values are very close to the chamber pressures where performance decreases were observed, particularly for MMH fuel. The advantage of 80-20

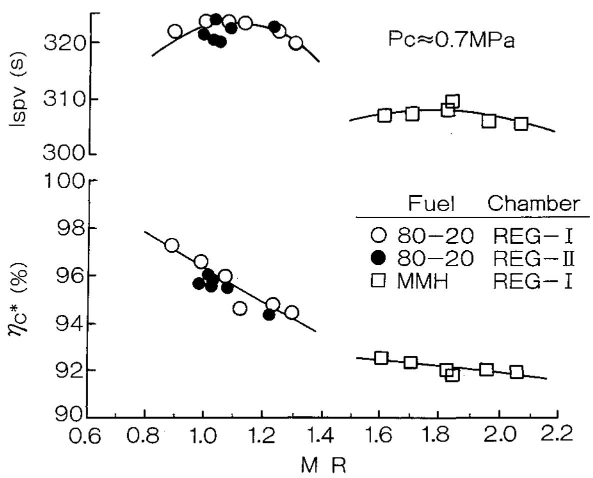

Fig. 11 Performances of 80-20 fuel and MMH.

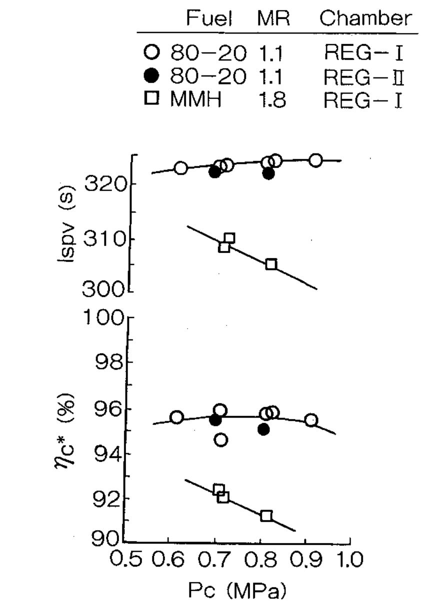

Fig. 12 Effect of chamber pressure on performance.

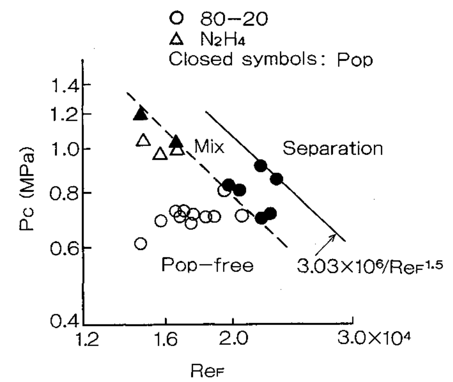

Fig. 13 Popping and reactive stream separation region.

mixed fuel over MMH fuel is that the onset of the energy release decrease due to reactive stream separation is at a higher pressure. This is because of a smaller Re_F, or a higher viscosity of 80-20 mixed fuel and a lower temperature increase through the regenerative cooling channels (Fig. 7).

Popping

Popping is irregular high-amplitude pressure pulsing in the combustion chamber. It is generally agreed that a pop is a liquid/gas two-phase explosion triggered by a local explosion near the jet impingement region. Pops were clearly indicated by the signals of an accelerometer mounted on the injector and of a load cell for thrust measurement. It should be noted that the 80-20 mixed fuel with the present film/regeneratively cooled configuration is particularly prone to popping. Popping was observed at a chamber pressure as low as 0.9 MPa in a 15-s duration test, at 0.8 MPa in a 30-s duration test, and at a pressure slightly higher than 0.7 MPa in a 160-s duration test. The popping region seems to be correlated by a function similar to Eq. (2), which correlates the separation region (Fig. 13). We speculate that the popping observed with the present injector design was triggered by reactive stream separation. Although popping occurred at lower chamber pressures for the 80-20 fuel for the present configuration compared with the hydrazine film cooled engine, this is mainly because of the increased Re_F due to the increased fuel injection temperature. From the hydrazine data for a fuel orifice with a comparable diameter plotted in Fig. 13, popping stability with 80-20 fuel seems to be about the same or slightly better than that of hydrazine in the P_c-Re_F plane.

Long Duration Tests

As described so far, it is possible to obtain a much higher I_{spv} performance in a moderate thermal environment with the 80-20 mixed fuel than with the MMH fuel. However, regarding potential application of the mixed fuel, e.g., apogee propulsion, it is necessary to demonstrate long duration capability. The typical firing duration for an apogee engine of a 2000-kg mass satellite is about 3000 s for the first burn, followed by shorter durations (400–100 s) for the second and third burns. Although the 160-s tests described below may not be sufficient to prove the full duration capability for a particular apogee mission, it is believed to provide information on long duration capability. Specific objectives of the long duration tests were as follows: 1) to evaluate timewise performance variation, if any; 2) to obtain the equilibrium temperature level at various stations of the chamber section; and 3) to evaluate the heat soak-back level and demonstrate shutdowns free from any explosions (such as those observed earlier with hydrazine fuel). Three 160-s duration tests at chamber pressures around 0.7 MPa were conducted. Objective 1 above was discussed already at the beginning of this section and will not be duplicated here.

As already shown in Fig. 6, full equilibrium temperatures at the various stations of the chamber section were not attained in a 160-s firing duration. However, even at stations where regenerative cooling was not effective, i.e., at the injector cavity and at the nozzle flange, nearly equilibrium temperatures were obtained at 160 s. These temperature levels were sufficiently low to provide a mild thermal environment, and therefore extended durability for an engine constructed from common materials. It is important to note that no drastic variation of the temperatures due to the movement of the liquid film cooled region was observed. The above-mentioned anomalous phenomenon was observed in some conditions with a hydrazine film-cooled engine.[17]

Figure 14 shows an example of heat soak-back level after engine shutdown. Soak-back is significant only at the nozzle flange. The thermal mass of the nozzle flange was responsible for this soak-back. In a practical engine, modifications in design may be necessary to reduce the heat conduction to the regeneratively cooled portion from the radiation cooled nozzle extension. A shutdown with a 0.2-s fuel delay followed by 2 cycles of 5-s nitrogen purge was employed for this particular case. Although T_{co} exhibited a peak following engine shutdown, it was too low to indicate decomposition of hydrazine. Also, no pressure spike in either the coolant inlet or the outlet manifold was observed during shutdowns in the three long duration tests. From the data analysis of a 30-s duration test without fuel delay, we believe that a fuel delay shutdown sequence is not a necessity.

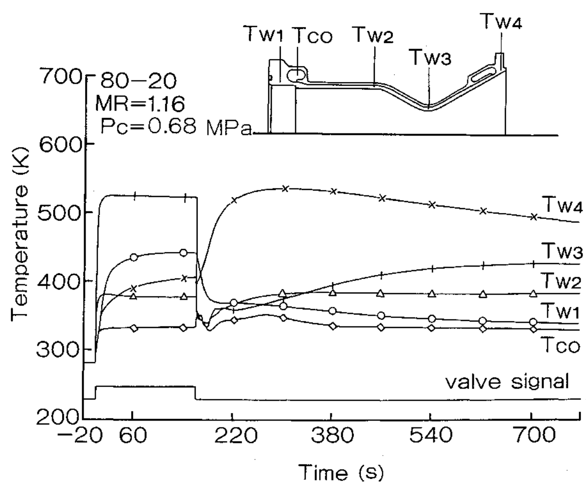

Fig. 14 Heat soak-back level after engine shutdown.

Possible Merits of Using 80-20 Fuel

Comparison of 80-20 fuel with MMH fuel is the main subject of this article. Regenerative cooling with hydrazine is dangerous in that an explosion in the cooling channels can occur after firing when a gas purge is applied, as mentioned earlier. Therefore, the merit of using 80-20 fuel in a film/regeneratively cooled mode instead of neat hydrazine fuel in a film cooled mode will be discussed in some detail. Major points of concern discussed are performance, cost of development tests, and thermal performance predictability.

Firstly, with hydrazine film cooled engines, it was difficult to reduce the film cooling fraction to less than 21% of the total fuel flow due to the excessive heating of the chamber. The I_{spv} of the qualified engine for the Japanese Engineering Test Satellite VI (ETS-VI) at P_c = 0.7 MPa is 317 s. It is very easy to obtain a high-core energy release efficiency with NTO/hydrazine propellants. But the performance in a film-cooled engine is very much compromised due to the large amount of film coolant necessary. Hydrazine is not a good film coolant on a very hot wall because of exothermic thermal decomposition. Secondly, with a hydrazine film-cooled engine, a firing test of very long duration (200–500 s minimum, depending on operating pressure) that simulates vacuum and thermal environment is usually required to obtain a thermal equilibrium at the chamber section. This is mainly because of the slow upstream movement of the liquid film-cooled region, and the anomalous behavior of gaseous film as indicated by an abrupt increase of wall temperature to a level of 1750 K upstream or at the contraction section of the combustion chamber. The latter, which was observed in some conditions well after 100 s of firing, was suspected to occur when a substantial amount of gaseous film began to decompose at those locations.[17] Contrary to the case of film-cooled engines, the time to thermal equilibrium at the chamber section is generally much shorter in a regeneratively cooled engine. The above discussion indicates that the cost of the development tests may be much less for a regeneratively cooled engine.

The remaining question is why we used combined film/regenerative cooling with 80-20 fuel instead of full regenerative cooling. First of all, the temperature of the cooling channel wall was designed to be less than 500 K so that no thermal decomposition of coolant would occur. Another requirement was that a decomposition flame adjacent to the wall be avoided so that the gas-side wall temperatures would not be higher than 800 K. This allowed more reliable calculation of film cooling since the effect of decomposition may be neglected. Also, a common material could be used for the construction of the chamber. Obviously, we did not determine the limit of the amount of film coolant necessary. Probably, 15% film cooling provided a substantial margin for a safe operation of the present 80-20 regeneratively cooled engine. The most important problem that remains unknown is under what conditions an explosive decomposition of hydrazine or 80-20 fuel occurs after engine shutdown.

Concluding Remarks

Regeneratively cooled experimental bipropellant engines with a vacuum thrust of 2000 N at a chamber pressure of 1.0 MPa and an area ratio of 240:1 were fired to evaluate the potential performance and cooling improvement of a hydrazine-MMH mixed fuel relative to MMH fuel. The results of regeneratively cooled thruster tests with 80% hydrazine-20% MMH (80-20) mixed fuel and MMH fuel can be summarized as follows:

1) The temperature increase of the mixed fuel was more than 20°C lower than that of MMH fuel, which is important in obtaining higher performance and in preventing possible fuel decomposition in the cooling channels.

2) The peak specific impulse of 80-20 mixed fuel was more than 322 s, which is at least 4% higher than that of MMH fuel, the difference being larger at higher pressures, presumably due to reactive stream separation.

3) Long duration (160 s) firing tests with 80-20 mixed fuel at a 0.7-MPa chamber pressure were conducted without any explosion due to heat soak-back. Equilibrium temperature levels were sufficiently low to provide extended durability to an engine constructed from common materials.

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