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PARTIAL BLEED EXPANDER CYCLE FOR LOW THRUST LOX/LH_2 ROCKET ENGINE

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ABSTRACT

The expander cycle or the coolant bleed cycle LOX/LH2 engine is considered suitable for use with the orbit transfer vehicle and the upper stage of a conventional rocket because of their simplicity of engine system. However, these engine cycles generally require a thrust chamber with a high expansion area ratio in order to obtain a high performance and necessarily require a High Altitude Test Facility even in the initial phase of development.

Here, the authors propose a new engine cycle called the "Partial Bleed Expander (PBE) cycle". In the PBE cycle, only the turbopump of one propellant (usually LH2) is driven in the expander cycle and a portion of fuel is bled to drive the turbopump of the other propellant (usually LOX). The bled fuel may be utilized for dump cooling or film cooling. From the calculation of the PBE cycle, it was made clear that the PBE cycle can perform at a level close to that of the expander cycle with the bleeding rate resulting in minimum Isp loss.

概　　要

上段用小形液酸／液水ロケットエンジンには，エキスパンダーサイクルやクーラントブリードサイクルが推奨されている。これはシステムの高性能化と単純化を計るためであるが，両サイクル共に長短を有する。本研究では，LH_2 ポンプをエキスパンダータービンで，LOXポンプをブリードタービンで駆動し，かつブリードによる比推力の損失を最小におさえ得る新しいエンジンサイクル，PBE（Partial Bleed Expander）サイクルについて検討を行った。この結果，本サイクルではシステム開発の容易性とエキスパンダーサイクルに非常に近い高性能とを合わせ持つことを期待できることが明らかとなった。

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1. Introduction

A low thrust LOX/LH_2 rocket engine[1] is useful for the orbit transfer vehicle and the upper stage of a conventional rocket. In order to satisfy the requirements for this kind of engine, such as reliability and light weight, a simple configuration is required. Among existing engine cycles, the expander cycle* (Fig. 1) and the coolant bleed cycle**(Fig. 2) are most suitable. In both cycles, the energy for driving turbopumps depends on heat absorption by regenerative cooling.

In general, those engine cycles having a fully regeneratively cooled thrust chamber with a high expansion area ratio require a high altitude test facility during the development, even in the component test of the thrust chamber. This may cause a higher development cost. The thrust

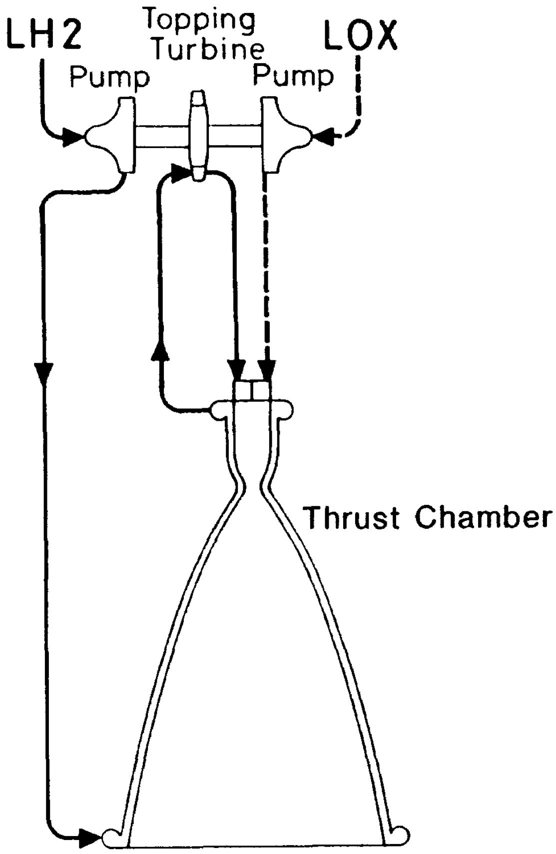

Fig. 1 Fully Regeneratively Cooled (FRC) Expander Cycle.

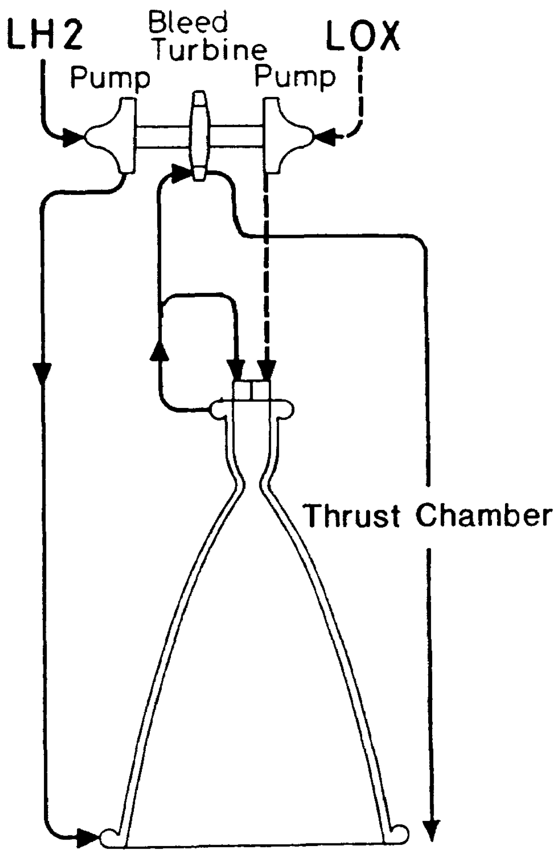

Fig. 2 Coolant Bleed Cycle.

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* The expander cycle is one of the liquid rocket engine cycles in which the engine coolant (usually hydrogen fuel) picks up the energy while cooling the thrust chamber in the super critical condition, drives the turbopump system and is injected into the thrust chamber (see Fig. 1).

** The coolant bleed cycle is one of the liquid rocket engine cycles in which one propellant (usually hydrogen fuel) cools the thrust chamber in the super critical condition before it is injected into the thrust chamber and a part of the heated coolant is bled into the atmosphere after driving the turbopump system (see Fig. 2).

chamber is often divided into the regeneratively cooled combustion chamber and the nozzle extension in order to avoid the use of a high altitude test facility. In this case the expander cycle entails such disadvantages as low performance due to the decreased achievable chamber pressure[2] and an increase of pump weight due to increased pump discharge pressure. On the other hand, the coolant bleed cycle entails increased performance loss due to the increased bleeding rate when the thrust chamber is divided into two parts.

In this study, the Partial Bleed Expander (PBE) cycle is proposed and discussed. In the PBE cycle, the fuel is partially bled from the original expander cycle to drive the oxidizer turbopump. This cycle has the advantages of producing high performance close to that of the expander cycle and of making the development of the engine system convenient.

2. Engine Cycle Concept

The expander cycle as shown in Fig. 1 has no theoretical performance loss from the viewpoint of the engine cycle because all the propellant is burned in the combustion chamber at high temperature and is sufficiently expanded in the nozzle. Fig. 3 is a flow schematic of the expander cycle composed of a regeneratively cooled truncated thrust chamber and a dump cooled nozzle extension. This type of engine doesn't need a high altitude test facility except for a test of high altitude performance during the development.

The qualitative relation of power per unit fuel (LH_2) flow rate for the turbine and the pumps of the expander cycle (see Table 1 for definition) versus fuel pump discharge pressure, $P_{p,fu}$, is shown in Fig. 4 for various chamber pressures, P_c. The

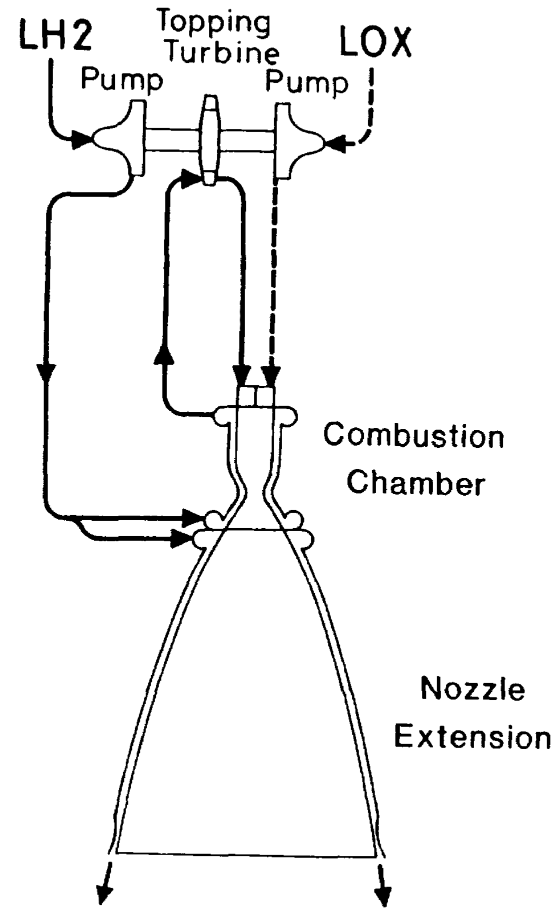

Fig. 3 Partially Regeneratively Cooled (PRC) Expander Cycle.

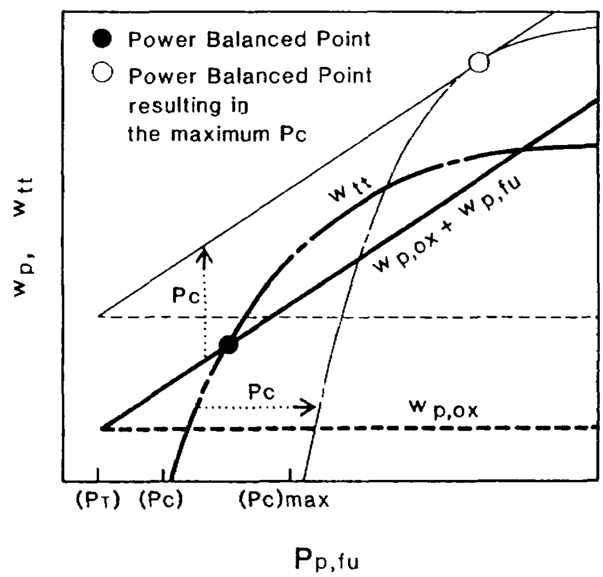

Fig. 4 Power Balance between Turbine and Pumps for Expander Cycle.

engine cycle balances at the intersection of the curve for the summation of the required power of both pumps, $w_{p,ox}$ + $w_{p,fu}$, and the curve for the power generated by the turbine, w_{tt}. The higher P_c requires a higher $P_{p,fu}$ for cycle realization. $P_{p,fu}$ increases remarkably with increased P_c and at last both curves, $w_{p,ox}$ + $w_{p,fu}$ and w_{tt}, touch at one point resulting in a maximum chamber pressure. Beyond the maximum P_c, the curves never intersect and the cycle isn't realized.

Since the maximum w_{tt} is nearly proportional to the heat absorption by regenerative cooling, the use of a truncated chamber results in a decrease of maximum chamber pressure and a higher $P_{p,fu}$. In this case, as understood from Fig. 3, such undesirable features can be avoided by the removal of the LOX turbopump from the original expander cycle.

The PBE cycle is proposed because of the above considerations. In the PBE cycle, the LOX turbopump is removed from the expander cycle, and is driven by the bled gas as shown in Fig. 5. Although the theoretical I_{sp} efficiency of this cycle depends on the bleeding ratio B (see Table 1), it is possible to minimize the I_{sp} loss of the engine system by effective utilization of exhaust gas from the bleed turbine for oxidizer pump, such as dump cooling* or film cooling** of the nozzle. When the PBE cycle is compared with the coolant bleed cycle, it can be seen that the bleeding flow rate remains at a small value in the PBE cycle because the bled gas drives only a single turbopump. This is useful for raising the hydrogen temperature after dump cooling and improves the specific

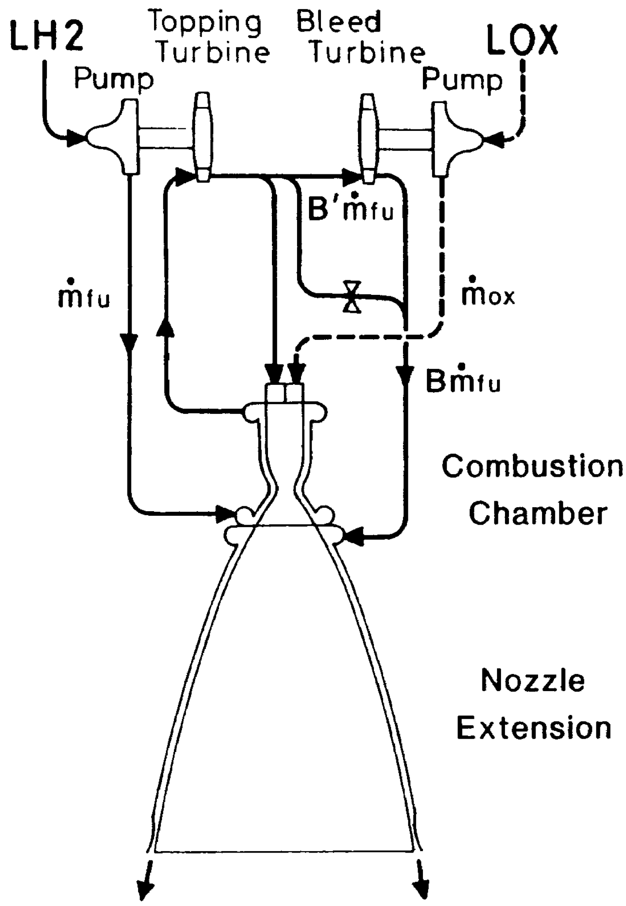

Fig. 5 Partially Regeneratively Cooled (PRC) Partial Bleed Expander (PBE) Cycle.

* The dump cooling is one of the cooling methods of the thrust chamber in which the heated coolant is dumped through the super sonic nozzle to recover the specific impulse after it cooled the chamber jacket. A low molecular coolant (hydrogen or ammonia) is suitable to raise the specific impulse.

** The film cooling is one of the cooling methods of the thrust chamber in which the fuel is injected along the chamber wall to cool the wall. The heat absorption by the coolant and the low combustion temperature of the fuel rich mixture are utilized to lower the wall temperature.

impulse.

Four basic flow variations for the PBE cycle can be considered. They correspond to which turbopump is removed from the expander cycle, the LOX turbopump or the LH_2 turbopump, and where the turbine gas is bled from, before the topping turbine or after. However, the removal of the LH_2 turbopump from the expander cycle results in an excessive bleeding ratio. In this study, the PBE cycle shown in Fig. 5 is chosen to be analyzed in detail.

3. Calculation Method

In order to obtain a power balance of turbopumps, the iterative method is used. Fundamental relations used in the calculation are listed in Table 1. Engine performance is evaluated by using the theoretical efficiency of specific impulse, $\eta_{I,cycle}$, in which the actual I_{sp} losses occured in the thrust chamber are neglected and it is assumed that the theoretical I_{sp} efficiency of the expander cycle with a fully regener-

Table 1 Fundamental Equations for Analysis.

1.	Pressure Drop Coefficient $k_j = (P_{p,fu} - P_{tt,i})/P_c$ $k_{fu} = (P_{tt,e} - P_c)/P_c$ $k_{ox} = (P_{p,ox} - P_c)/P_c$
2.	Engine Mixture Ratio $r_{eg} = \dot{m}_{ox}/\dot{m}_{fu}$
3.	Power per Unit Fuel (LH_2) Flow Rate $w_{p,fu} = (P_{p,fu} - P_{T,fu})/(\rho_{fu}\eta_{p,fu})$ $w_{p,ox} = r_{eg}(P_{p,ox} - P_{T,ox})/(\rho_{ox}\eta_{p,ox})$ $w_{tt} = \eta_{tt}C_pT_{tt,i}(1 - (P_{tt,e}/P_{tt,i})^{\frac{\gamma-1}{\gamma}})$ $w_{bt} = \eta_{bt}C_pT_{bt,i}(1 - (P_{bt,e}/P_{bt,i})^{\frac{\gamma-1}{\gamma}})$
4.	Bled Gas Flow Ratio $B' = \dot{m}_{bt}/\dot{m}_{fu}$ $(= w_{p,ox}/w_{bt})$ for bleed turbine $B = \dot{m}_d/\dot{m}_{fu}$ for dump cooling where $B \geqq B'$
5.	Chamber Mixture Ratio $r_c = r_{eg}/(1 - B)$
6.	Theoretical Cycle Efficiency of Specific Impulse $\eta_{I,cycle} = \dfrac{(1 + r_{eg} - B)(I_{sp,r_c} - \Delta I) + BI_{sp,d}}{(1 + r_{eg})I_{sp,r_{eg}}}$ where ΔI is the specific impulse loss due to the heat loss into the dump cooled nozzle wall.

atively cooled thrust chamber is 100% because the heat loss through the nozzle is recovered by the fully regenerative cooling. It involves an I_{sp} loss caused by bleeding and a loss of theoretical I_{sp}, ΔI caused by a heat loss into the dump cooled nozzle wall. A part of the performance loss is recovered as $I_{sp,d}$ by dump cooling.

Table 2 Engine Operating Parameters.

Mixture Ratio : 5.0

Thrust (kN)	2.5	10	100
Contraction Area Ratio	6	4	3
Expansion Area Ratio	400	200	150
Characteristic Chamber Length (m)	0.8	0.75	0.8

Table 3 Assumed Values of Parameter.

Turbopump Efficiency

Thrust (kN)	Case	$\eta_{p,fu}$	η_{tt}	$\eta_{p,ox}$	η_{bt}
2.5	η_M	0.38	0.52	0.29	0.31
10	η_H	0.46	0.65	0.50	0.40
	η_M	0.42	0.60	0.43	0.35
	η_L	0.38	0.53	0.35	0.28
100	η_M	0.60	0.75	0.65	0.30

Pressure Drop Coefficient

Thrust (kN)	Case	k_j (PRC)	k_j (FRC)	k_{fu}	k_{ox}
2.5	k_M	0.30	0.45	0.22	0.44
10	k_L	0.13	0.20	0.16	0.22
	k_M	0.22	0.34	0.22	0.33
	k_H	0.32	0.49	0.27	0.44
100	k_M	0.22	0.34	0.22	0.42

The three engine cycles shown in Fig. 1, 3 and 5 will now be discussed. Assumed engine operating parameters are listed in Table 2. Nozzle contour is determined by Rao's method.[3] In the calculation of gas side heat transfer to the thrust chamber, Bartz's simple equation[4] is applied to the combustion chamber region, and the turbulent boundary layer method[5] is applied to the nozzle divergent region. The computer programs of reference 6 and 7 for rocket performance and thermodynamic properties are used. In this study, the location of the division of the thrust chamber is determined so that the nozzle flow doesn't separate at sea level.[8]

Parameters such as the turbopump efficiency, η_{tp}, defined as a product of pump efficiency, η_p, and adiabatic turbine efficiency, η_t, and the pressure coefficient, k, assumed in the calculation are summarized in Table 3. Each parameter is assumed based on data for existing engines and on data for other studies. The case of $\eta_{tp} = \eta_M$ and $k = k_M$ for 10 kN thrust is used as the reference point. As for a 10 kN thrust, two cases of overall turbopump efficiency other than the reference case have a 5% deviation from the reference case.

4. Results

(1) Thrust of 10 kN

(i) Influence of Regenerative Cooling Area

The relation between the chamber pressure and the fuel pump discharge pressure under the reference condition is shown in

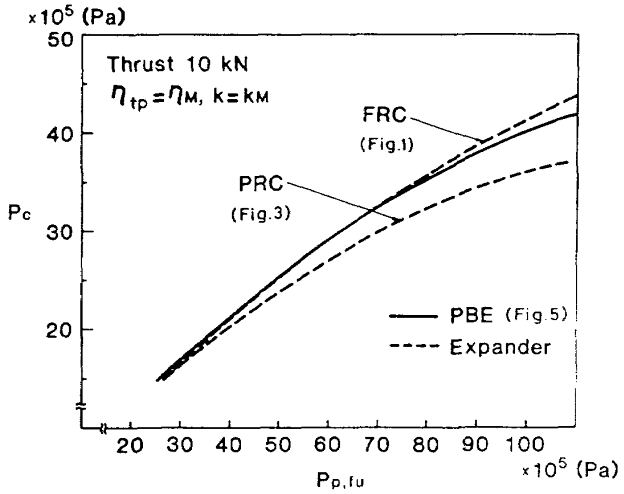

Fig. 6 Available Chamber Pressure versus Hydrogen Pump Discharge Pressure for Various Engine Cycles at 10 kN Thrust.

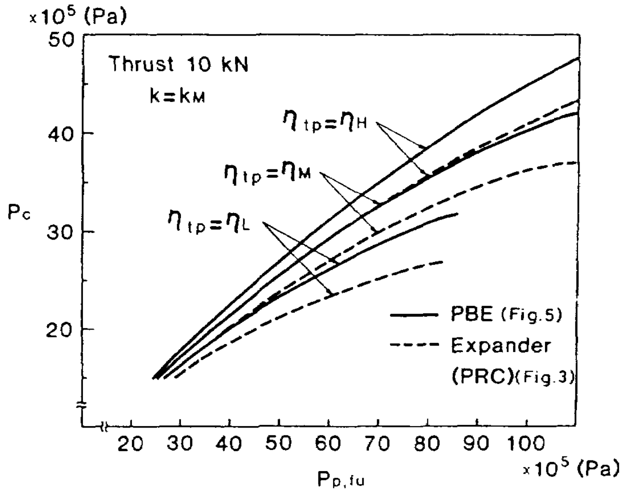

Fig. 7 Effect of Turbopump Efficiency upon Available Chamber Pressure versus Hydrogen Pump Discharge Pressure for Various Engine Cycles at 10 kN Thrust.

Fig. 6. This figure suggests that the partially regeneratively cooled (PRC) expander cycle requires higher LH_2 pump discharge pressure especially at higher chamber pressure compared with that of the fully regeneratively cooled (FRC) expander cycle and can attain only lower maximum chamber pressure. In the partially regeneratively cooled (PRC) PBE cycle, the chamber pressure versus the LH_2 pump discharge pressure curve is almost identical to the curve for the fully regeneratively cooled expander cycle.

(ii) Influence of Turbopump Efficiency

The influence of turbopump efficiency on the chamber pressure versus LH_2 pump discharge pressure curve when the reference pressure drop coefficients are used is presented in Fig. 7. It is known that the employment of the PBE cycle is equivalent to a 5% improvement of the overall turbopump efficiency in the PRC expander cycle since the difference of overall turbopump efficiency in each case is 5%.

(iii) Influence of Pressure Drop Coefficient

The influence of the pressure drop coefficient on the chamber pressure versus LH_2 pump discharge pressure when the reference turbopump efficiencies are used is presented in Fig. 8. The PBE cycle results in a wider margin for the pressure drop limitation compared with the PRC expander cycle as was the case with turbopump efficiency.

(iv) Cycle Efficiency of Specific Impulse

The bleeding ratio of the PBE cycle with the reference value of pressure drop is shown in Fig. 9. In this figure, *B* is the bleeding ratio required for dump cooling necessary to get the assigned exit temperature of the dump coolant, and *B'* is the bleeding ratio required for driving the LOX turbopump. Therefore, the range of bleeding ratio actually required for this system is the upper region of the *B* curve

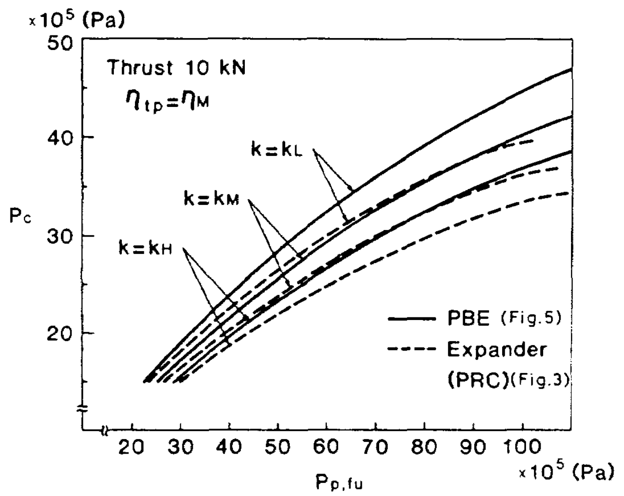

Fig. 8 Effect of Pressure Drop Coefficients upon Available Chamber Pressure versus Hydrogen Pump Discharge Pressure for Various Engine Cycles at 10 kN Thrust.

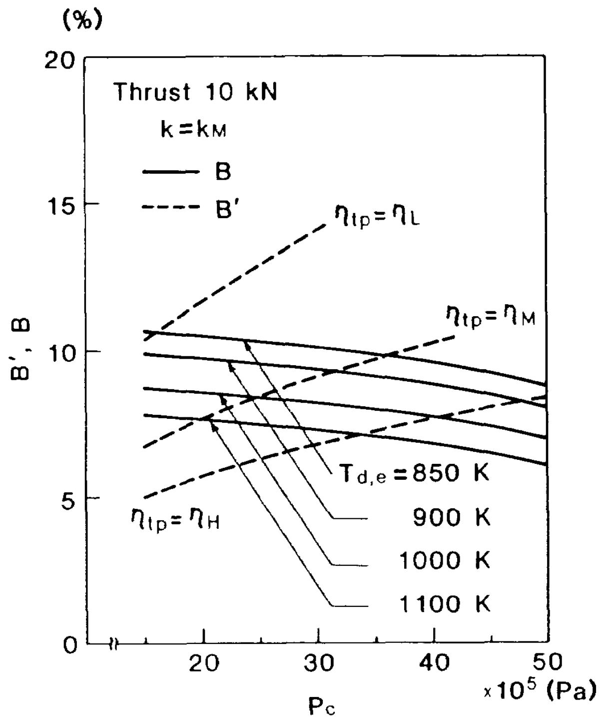

Fig. 9 Bleeding Fuel Flow Ratio Required for Dump Cooling and Driving LOX Turbopump for PBE Cycle at 10 kN Thrust.

and the B' curve. The exit temperature of 1100 K for dump cooling assumes the allowable temperature for the nozzle material and that of 850 K assumes the allowable temperature for brazing. It can be seen from Fig. 9 that the bleeding ratio for the LOX turbopump, B', remains within the range of bleeding for dump cooling, B, and that the I_{sp} loss is minimized in the case of reference turbopump efficiency. It can also be seen that the bleeding ratio required for dump cooling is about 10 − 15% of the fuel flow rate. The specific impulse, $I_{sp,d}$, is obtained under the assumption that the hydrogen gas is ejected through a $\epsilon = 5.7$ supersonic nozzle after dump cooling. The value of $\epsilon = 5.7$ is selected with reference to the HM-7 engine. The theoretical I_{sp} efficiency of the cycle, $\eta_{I,cycle}$, is shown in Fig. 10. In this figure, $\eta_{I,cycle}$ based on the turbopump efficiency, η_{tp} (broken line) and $\eta_{I,cycle}$ based on the dump coolant exit temperature, $T_{d,e}$ (solid line) are shown. The actual operating range is selected from the lower region of both lines. Even if the lowest exit temperature of dump coolant is selected, the loss of

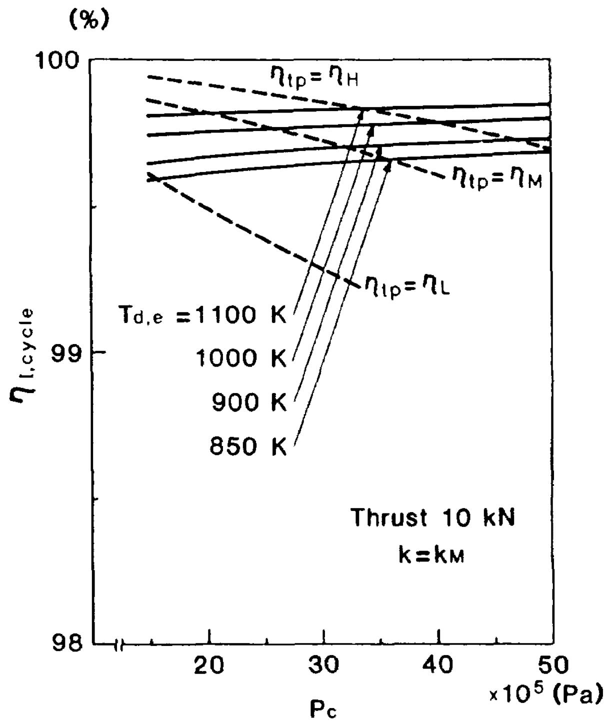

Fig. 10 Theoretical I_{sp} Efficiency for PBE Cycle at 10 kN Thrust.

I_{sp} remains within about 0.5% under the reference condition ($T_{d,e}$ = 850 K, η_{tp} = η_M).

(2) Thrust of 100 kN and 2.5 kN

Two cases of different thrusts are also studied. The chamber pressure versus LH_2 pump discharge pressure curves is shown in Fig. 11 for a 100 kN thrust and in Fig. 12 for a 2.5 kN thrust. In both cases, the PBE cycle gives a higher chamber pressure than that of the partially regeneratively cooled expander cycle under the same LH_2 pump discharge pressure as in the case of a 10 kN thrust.

The theoretical *Isp* efficiency is shown in Fig. 13 for a 100 kN thrust and in Fig.

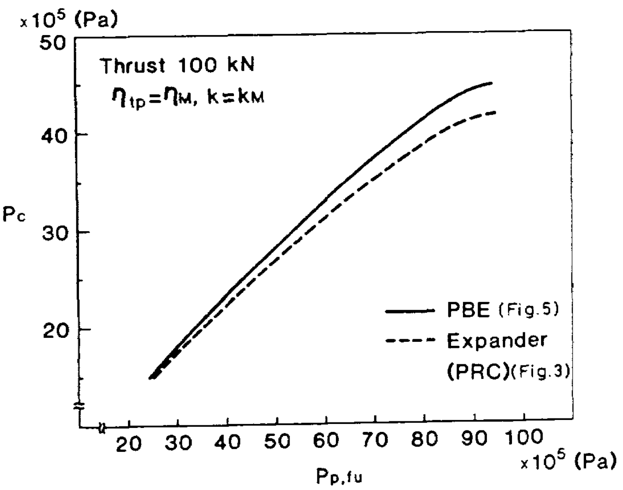

Fig. 11 Available Chamber Pressure versus Hydrogen Pump Discharge Pressure for Various Engine Cycles at 100 kN Thrust.

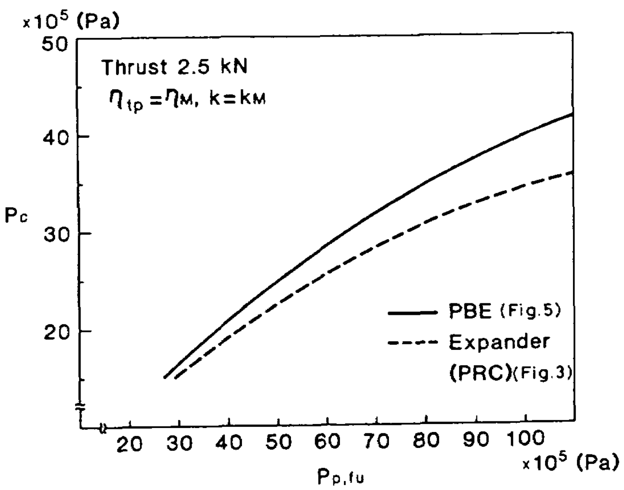

Fig. 12 Available Chamber Pressure versus Hydrogen Pump Discharge Pressure for Various Engine Cycles at 2.5 kN Thrust.

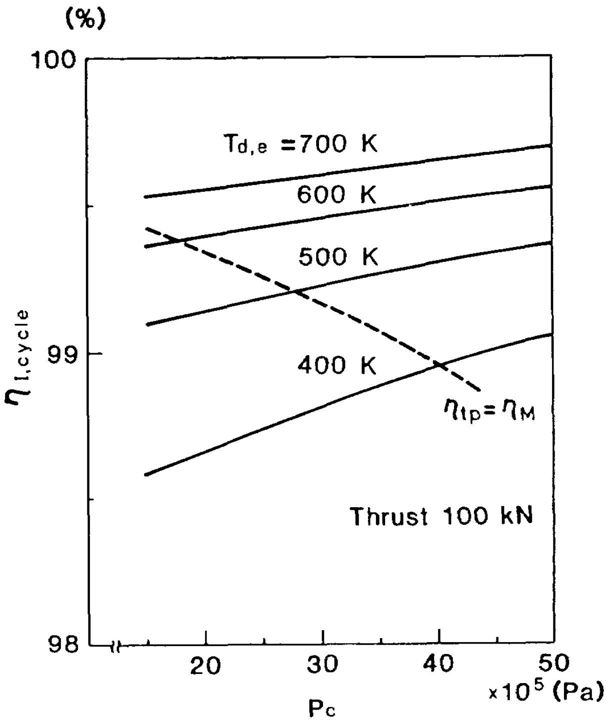

Fig. 13 Theoretical I_{sp} Efficiency for PBE Cycle at 100 kN Thrust.

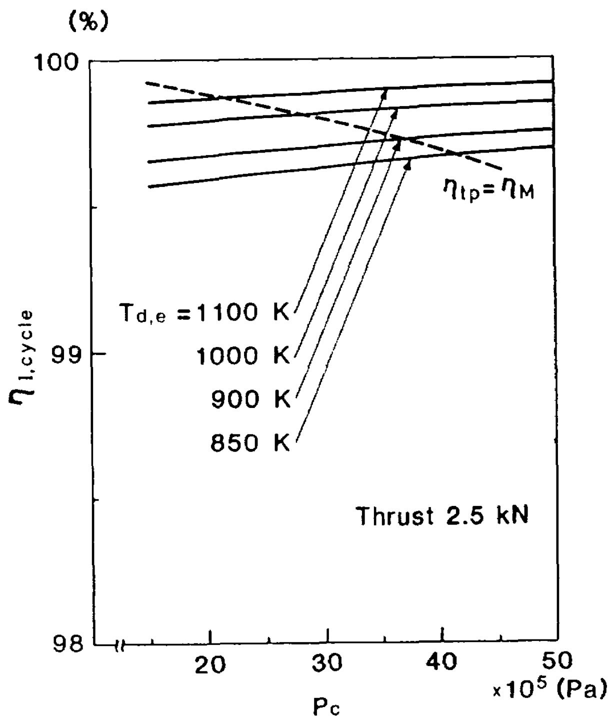

Fig. 14 Theoretical I_{sp} Efficiency for PBE Cycle at 2.5 kN Thrust.

14 for a 2.5 kN thrust. Fig. 13 shows that, in a high thrust, operating range is not restricted by the dump cooling exit temperature but by the bleeding rate required for the LOX turbopump. The *Isp* loss is within 1% for the case of a 100 kN thrust and within 0.5% for the case of a 2.5 kN thrust for the selected value of parameters and the safe side of the exit temperature of dump cooling.

Both figures shows that the PBE cycle is effective for a wide range of thrust.

5. Conclusions

The results presented above indicated the following.

(i) The PBE cycle has a wider margin of turbopump design and pressure drop limitation compared with the partially regeneratively cooled expander cycle.

(ii) The theoretical I_{sp} efficiency of the PBE cycle is more than 99% under the conditions used in the analysis.

These findings indicate that the PBE cycle facilitates the development of a high performance LOX/LH_2 engine having a high expansion area ratio nozzle. It has the advantage of not causing a raise in fuel pump discharge pressure as well as eliminating at most stages of development the need to use a high altitude test facility.

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Nomenclature

B : Bleeding ratio required for dump cooling
B' : Bleeding ratio required for bleed turbine
C_p : Specific heat at constant pressure
I_{sp} : Specific impulse
k : Pressure drop coefficient
$\dot{m}$: Flow rate
P : Pressure
r : Mixture ratio
T : Temperature
w : Power per unit fuel flow rate
γ : Specific heat ratio
ϵ : Expansion ratio
η : Efficiency
ρ : Density
ΔI : I_{sp} loss caused by a heat loss in the nozzle

Suffix

bt : Bleed turbine
c : Chamber
$cycle$: Engine cycle
d : Dump cooling
e : Exit
eg : Engine
fu : Fuel
H : High value case
I : Specific impulse
i : Inlet
j : Jacket
L : Low value case
M : Medium value case
ox : Oxidizer
p : Pump
T : Tank
t : Turbine
tp : Turbopump
tt : Topping turbine

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