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Performance Evaluation of LE-7 High Pressure Pumps

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Performance Evaluation of LE-7 High Pressure Pumps*

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ABSTRACT

The LOX and LH_2 pumps of the LE-7 rocket engine are characterized by high delivery pressure and a large flow rate. The hydrodynamic performance of these pumps was thermodynamically evaluated. The performance of the LOX pump was expressed by the adiabatic head and efficiency, because LOX is not particularly compressible. However, the efficiency directly determined using the measured pressures and temperatures was corrected to approximate the true efficiency because there was internal leakage from the split pump to the main pump. For evaluation of the LH_2 pump performance, the polytropic head and efficiency were used, because LH_2 shows much greater compressibility than LOX. Comparison of the calculations and test results confirmed that they better approximated the true head and efficiency than the adiabatic head and efficiency. The efficiency of both pumps was fairly high compared with that of large rocket pumps which have been developed to date.

Key Words: LE-7 LOX/LH_2 turbopump, pump performance, adiabatic efficiency, adiabatic head, polytropic efficiency, polytropic head

概　　要

LE−7の推進薬供給用液体酸素および液体水素ポンプは，大流量・高吐出圧である。これらのポンプの流体力学的な性能は熱力学的な評価がなされた。液体酸素ポンプの性能は，液体酸素があまり大きな圧縮性を示さないため，断熱揚程および断熱効率に基づいて評価した。しかしながら，スプリットポンプから主ポンプ側への内部漏れがあるため，計測された温度，圧力より直接計算した効率に対して，補正を施して真の効率を求めた。液体水素ポンプの性能評価に関しては，液体水素が液体酸素よりもかなり大きな圧縮性を示すため，ポリトロープ効率ならびに揚程を採用した。計算結果と試験結果との比較により，断熱効率および揚程よりもポリトロープ効率および揚程の方がより真の値に近いことが確認された。両ポンプは，今日までに開発された他のロケット用大型ポンプと比較して，かなり高い効率を示した。

1. Introduction

A large launch vehicle, the H-II, has been developed in Japan. The launch vehicle uses a LOX/LH_2 engine, the LE-7, the thrust of which is about 1,000 kN. The cryogenic propellant feed pumps of the LE-7 engine are characterized by high delivery pressure and large flow rate. The hydrodynamic performance of these pumps was thermodynamically evaluated mainly for the following reasons.

(a) With regard to compressible fluids, the ordinary pump performance evaluations, which are based on assumptions of incompressibility, do not necessarily show the true pump performance because a fair amount of energy input to a pump

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is spent on increasing the internal energy.

(b) With regard to pump efficiency measurement, a torquemeter could not be installed between the pump and the turbine of a turbopump. The installation of a torquemeter complicates turbopump assemblies to such a degree that they are not able to operate at the rated rotational speed.

The efficiency of the LOX pump was evaluated based on the adiabatic efficiency[1,2] because LOX is not so compressible. However, the efficiency directly determined from the measured pressures and temperatures was corrected in order to obtain the true efficiency because there is internal leakage from the split pump to the main pump.

With regard to the LH_2 pump performance, the polytropic head and the polytropic efficiency which has been used as the true aerodynamic efficiency[3] were examined if they showed the true pump performance, because LH_2 is much more compressible than LOX. Since it was impossible to know the detailed compression process in a pump, a simplified calculation[4] was carried out to determine the polytropic head and efficiency.

2. Polytropic Head and Efficiency

A typical compression process of cryogenic fluids is presented in Fig. 1 using an enthalpy (h) – entropy (s) diagram. p_1 and p_2 represent the pump inlet and outlet pressure, respectively. The isentropic and actual compression processes are indicated by dotted lines. The adiabatic efficiency is presented by the following equation in which both the kinetic and geodetic heads are neglected.

$$\eta_a = \frac{\Delta h_{is}}{\Delta h_{act}} \tag{1}$$

where Δh_{is} and Δh_{act} are the increase of enthalpy in the isentropic compression process and the energy input to the pump, respectively. Since it was impossible to know the detailed compression process in a pump, the polytropic head and efficiency are calculated by the following expedient procedures. An isentropic compression process with fixed efficiency is assumed between all the adjacent isobaric lines which are drawn between the two isobaric lines of pressures p_1 and p_2 as shown in Fig. 1. The polytropic head Δh_{tr} is obtained as the sum total of all isentropic enthalpy increments between the adjacent isobaric lines.

$$\Delta h_{tr} = \Sigma \delta_{is,i} \tag{2}$$

The polytropic efficiency is defined as follows.

$$\eta_{tr} = \frac{\Delta h_{tr}}{\Delta h_{act}} \tag{3}$$

As shown in Fig. 1 the enthalpy increment between the adjacent isobaric lines increases with the increase of entropy. So both the polytropic head and efficiency result in lager values than those of the adiabatic head and efficiency. Figs. 2, 3 and 4 show calculated differences between the polytropic and adiabatic efficiencies with LOX, LN_2 and LH_2,

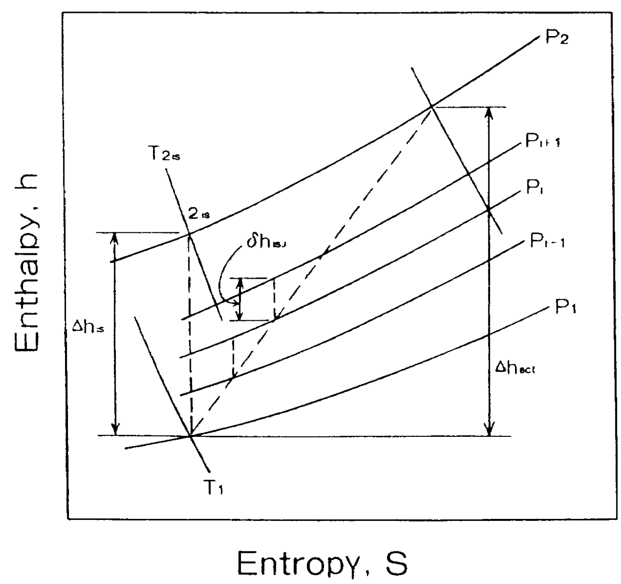

Fig. 1 Compression process of pump fluid

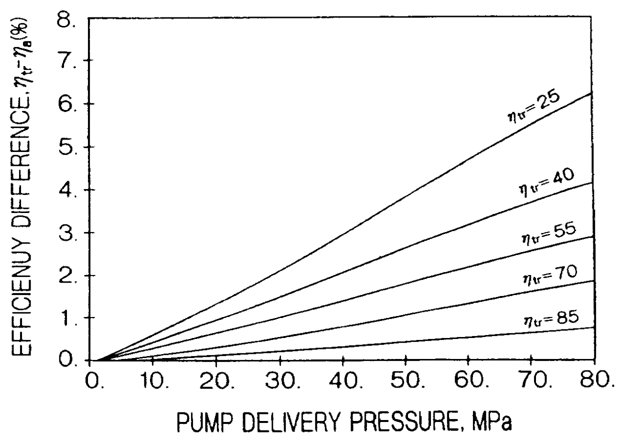

Fig. 2 Relationship between pump delivery pressure and efficiency difference (LOX)

respectively. The thermodynamic properties of LOX, LN_2, which were necessary to obtain the efficiency and head, were according to reference[4]. LH_2 shows a much larger efficiency difference than LOX or LN_2 because it has greater compressibility. In Figs. 2, 3 and 4, the efficiency differences tend to increase with the decrease of pump efficiency, due to the fact that the larger hydrodynamic loss in a pump causes a greater rise in the pump fluid temperature resulting in greater compressibility.

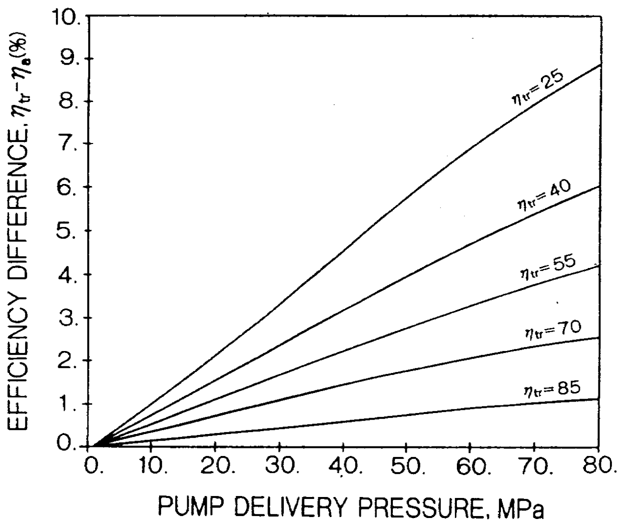

Fig. 3 Relationship between pump delivery pressure and efficiency difference (LN_2)

3. Test Pumps and Test Procedures

The LOX and LH_2 pumps of the LE-7 engine are shown in Figs. 5 and 6, respectively. The major design parameters of these pumps are presented in Table 1. The impellers of the main pump and the split pump are arranged on a common shaft with the

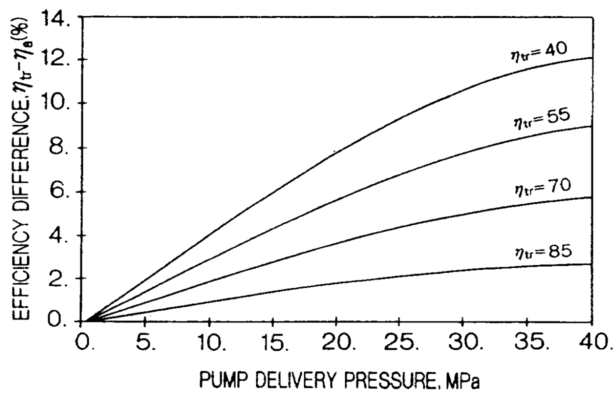

Fig. 4 Relationship between pump delivery pressure and efficiency difference (LH_2)

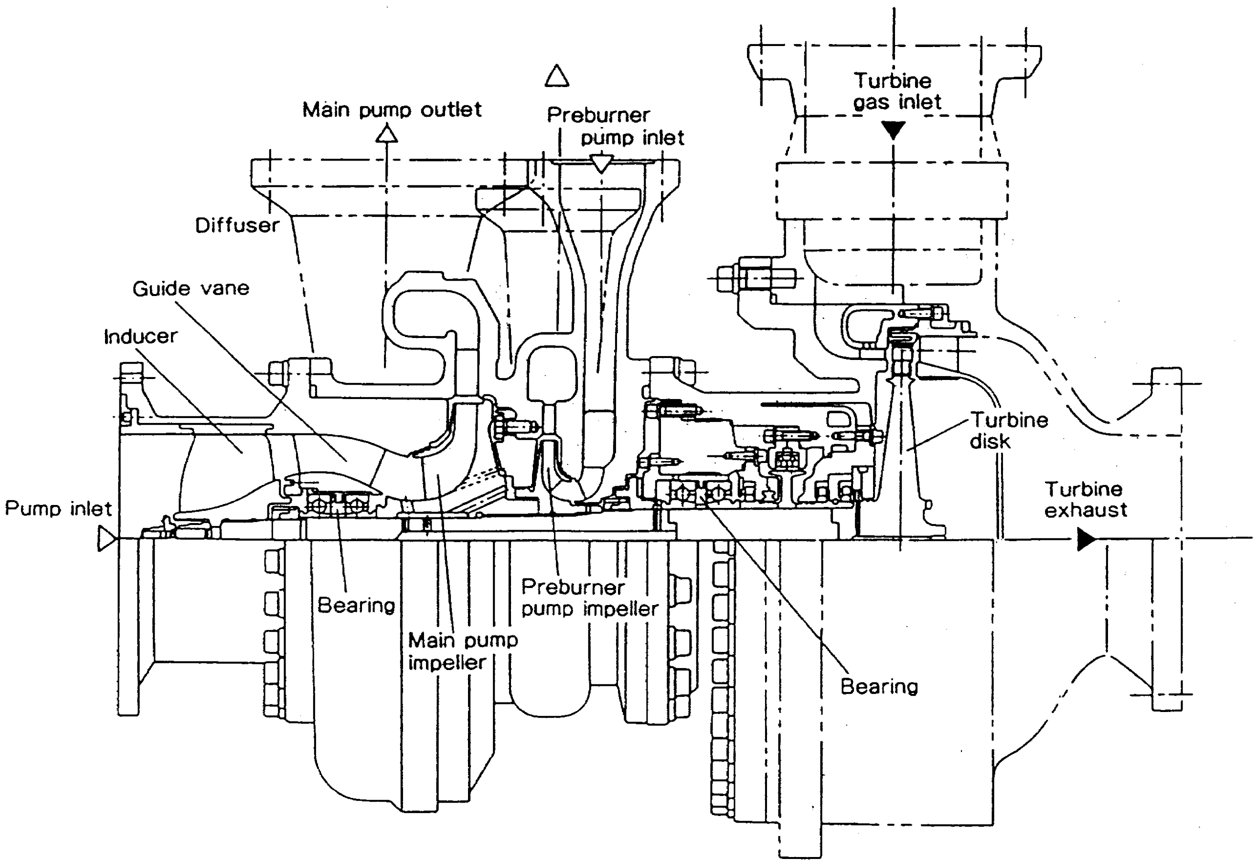

Fig. 5 LE-7 LOX turbopump

LOX pump. The main pump has an inducer with three swept-back blades. The split pump sucks in about 20 percent of the delivery of the main pump. There is internal leakage from the split pump to the main pump through the wearing ring seal. The LH_2 pump is a two-stage centrifugal pump with an inducer which is similar to that of the LOX pump. Each of the main impellers has 10 full vanes and 10 partial vanes.

Fig. 7 shows the LE-7 LOX turbopump test facility used to obtain the data of the LOX pump. The test facility of the LE-7 LH_2 turbopump is very

Table 1 Design parameters of LE-7 propellant feed pumps

	LOX Pump Main	LOX Pump Split	LH2 Pump
Rotational speed, rpm	20,000	20,000	46,130
Shaft power, kW	5,222	662	22,065
Stage specific speed, (m,m³/s,s⁻¹)	0.0947	0.0644	0.0562
Mass flow, kg/s	229.0	43.8	38.9
Volume flow, ℓ/s	201.0	38.4	563.0
Inlet pressure, MPa	0.40	20.1	0.32
Outlet pressure, MPa	21.3	32.7	31.5

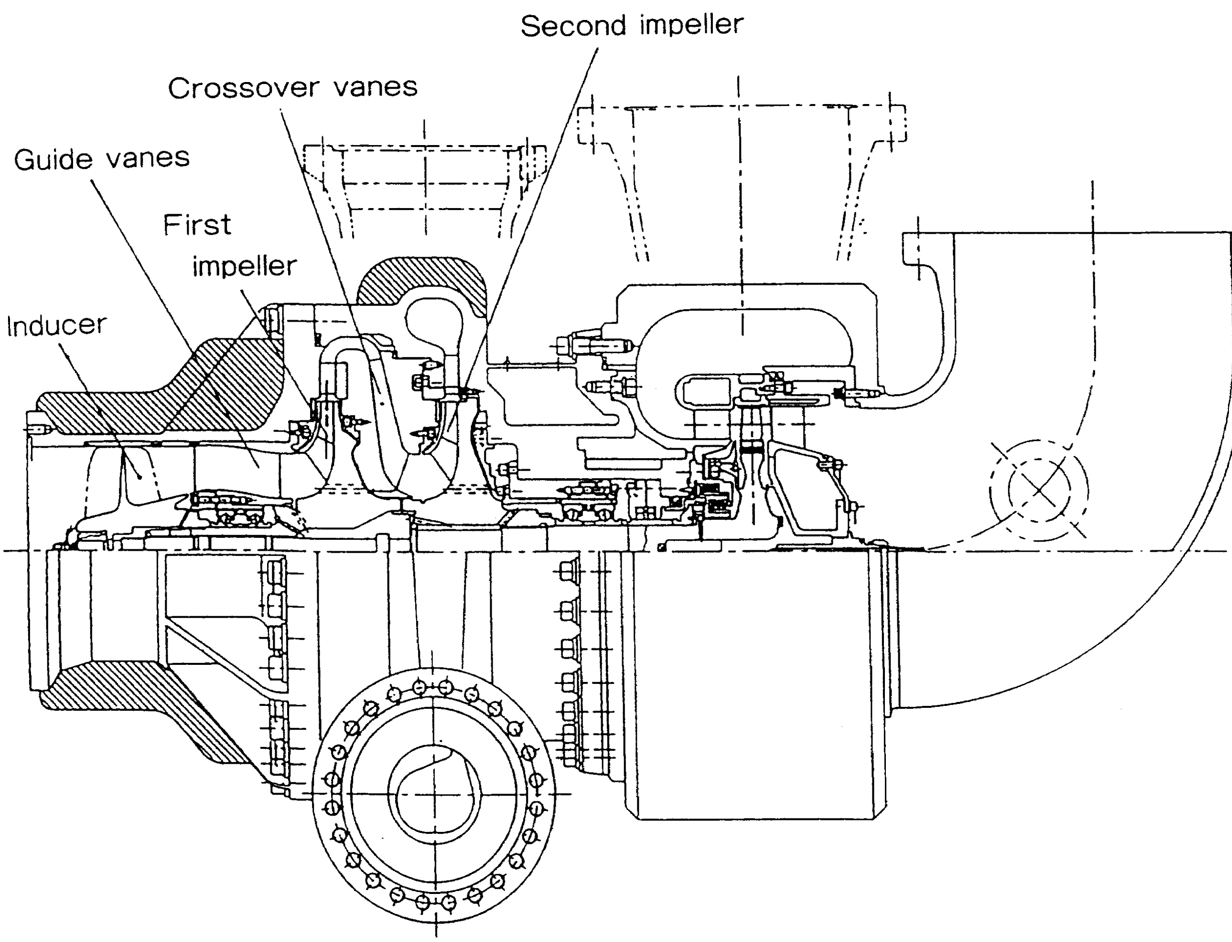

Fig. 6 LE-7 LH_2 turbopump

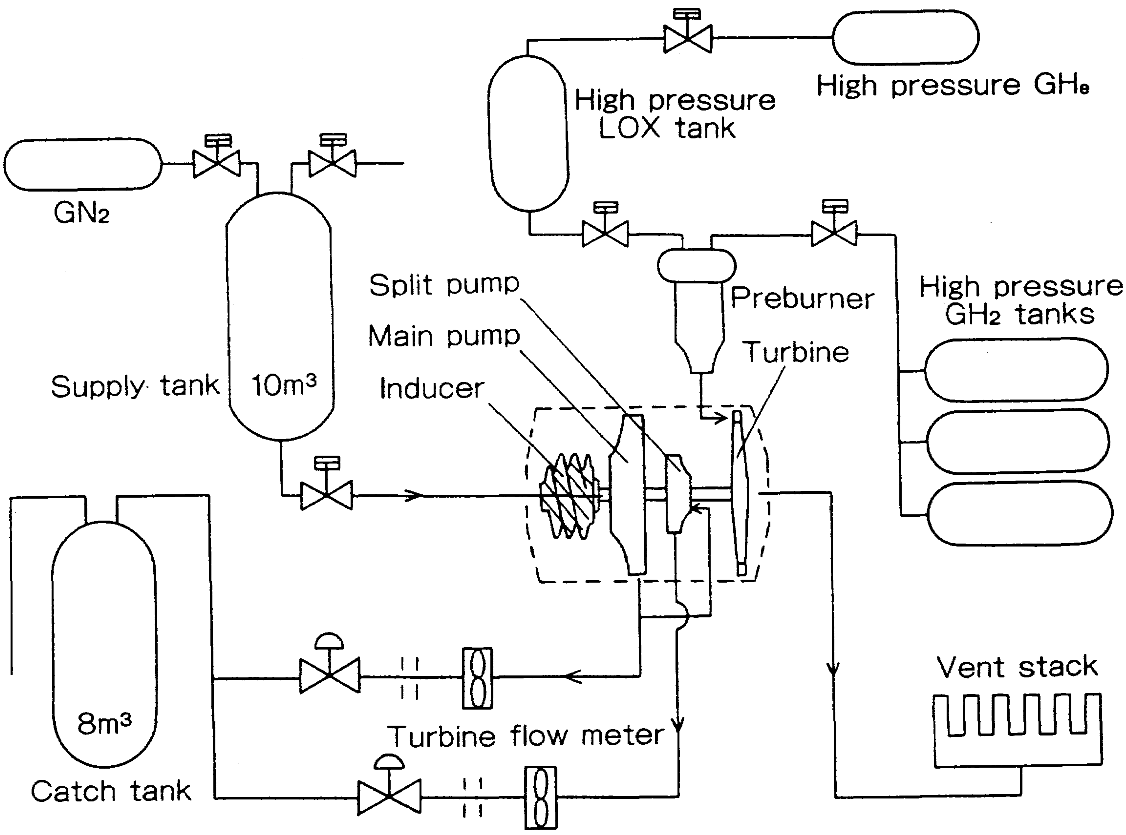

Fig. 7 LE-7 LOX turbopump test facility

similar to that of the LOX turbopump. The pressures and temperatures at the pump inlet and outlet were measured to obtain the enthalpies which are necessary to thermodynamically calculate the pump performance. All the pressures were measured by strain-gage type sensors. Temperature measurements of LOX and LN_2 were carried out with C-C thermocouples which were calibrated using LN_2. LH_2 temperatures were measured with platinum resistance thermometers. Fluid properties, which were necessary to obtain the pump performance, were according to reference[4]. All the flow rates were measured by turbine type flowmeters.

4. Performance of the LOX Pump

Since there is internal leakage from the split pump to the main pump as shown in Fig. 5, the influence of this leakage on the performance of both pumps must be considered. Fig. 8 schematically shows the internal flow of the pumps. The apparent adiabatic efficiencies of the main and the split pump were obtained utilizing the measured temperatures and pressures of both the pump inlet and outlet. These efficiencies are represented by the following

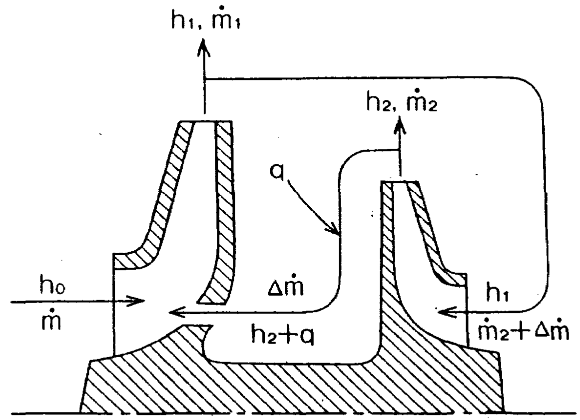

Fig. 8 Internal flow of main and split pump

equations.

$$\eta^*_{a,m} = \frac{h_{1is} - h_0}{h_1 - h_0} \tag{4}$$

$$\eta^*_{a,s} = \frac{h_{2is} - h_1}{h_2 - h_1} \tag{5}$$

The mass flow of the internal leakage from the split pump to the main pump through the wearing ring seal is designated as $\Delta\dot{m}$, which is determined by calculation utilizing the measured pressure distribution within both the pumps. q is the enthalpy increment of the leakage flow which is caused by the disc friction loss of the back shroud of the split pump impeller. The disc friction loss is also obtained by calculation using the following equation.

$$L_d = \frac{1}{2} C_m \rho \omega^2 \left(\frac{D_{s2}}{2}\right)^5 \left(1 + \frac{5e}{D_{s2}}\right) \qquad (6)$$

where D_{s2} and e are the diameter of the split pump impeller and the sum total of the front and back shroud thickness, and C_m, ρ and ω are the moment coefficient, fluid density and angular velocity, respectively. The enthalpy increment q was determined by the following equation.

$$q \cong \left(\frac{L_d}{2}\right) \Big/ \Delta\dot{m} = \frac{1}{2}\frac{L_d}{\Delta\dot{m}} \qquad (7)$$

The apparent efficiencies ($\eta^*_{a,m}$, $\eta^*_{a,s}$) are corrected by the following equations using the symbols in Fig. 8 to obtain the true efficiencies of both pumps.

$$\eta_{a,m} = \frac{\eta^*_{a,m}}{1 - \dfrac{\Delta\dot{m}}{\dot{m}_1}\dfrac{h_2 - h_1 + q}{h_1 - h_0}} \qquad (8)$$

$$\eta_{a,s} = \frac{\eta^*_{a,s}}{1 + \dfrac{\Delta\dot{m}}{\dot{m}_2}\dfrac{h_2 - h_1 + q}{h_2 - h_1}} \qquad (9)$$

Figs. 9 and 10 show the performances of the main pump and the split pump which were obtained using LN_2 as the pump working fluid. The pump pressure rises in these tests were less than 10 MPa, indicating that the influence of compressibility on the pump efficiencies or heads ought to be less than 0.5 percent according to Fig. 3. In Figs. 9 and 10, the adiabatic head is compared with the ordinary pump head which was obtained on the assumption of incompressibility. With both pumps, the two kinds of heads fairly well agreed, which verified that the pressures and temperatures were measured with high accuracy in the present tests. The apparent adiabatic efficiency of both pumps is shown by dotted lines and the corrected efficiency using equations (8) and (9) is shown by solid lines. The influence of the internal leakage ($\Delta\dot{m}$ in equations (8) and (9)) on the split pump efficiency was much greater than that on the main pump, because the mass flow of the split pump ($\dot{m}_2$ in equation (9)) is about one fifth of that of the main pump ($\dot{m}_1$ in equation (8)).

The data mentioned above were obtained in a test characterized by comparatively low rotational speed. The performances of the main pump at rated rotational speeds are shown in Fig. 11. Since the main pump was modified mainly with regard to the balance hole diameter of the impeller, the performance is a bit worse than that shown in Fig. 9. The scattering of the efficiency in Fig. 11 falls within a range of few percent, which also verified the usefulness of thermodynamic evaluation of pump performance, even with LOX and LN_2 which show

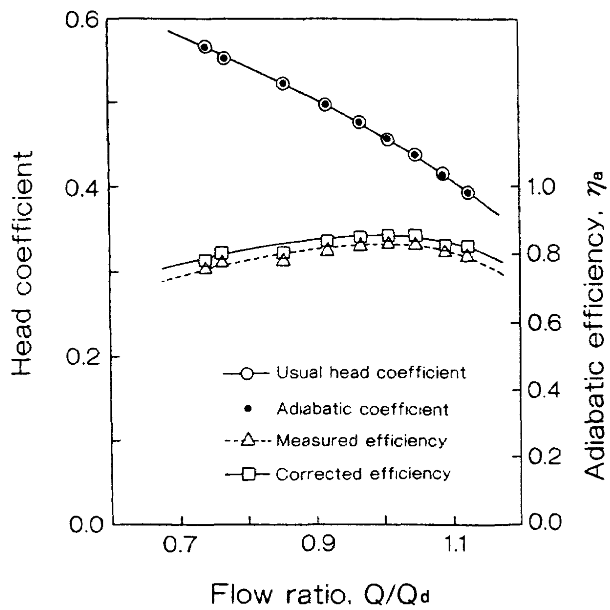

Fig. 9 Performance of LOX main pump at low rotational speeds and comparison of adiabatic and ordinary head

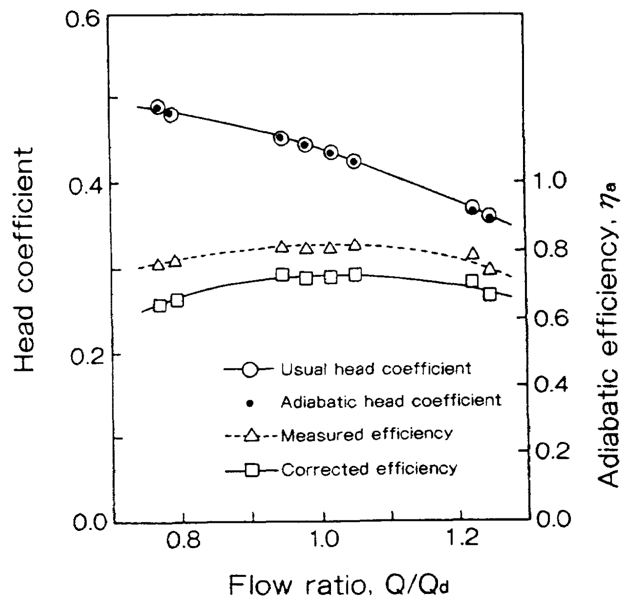

Fig. 10 Performance of LOX split pump at low rotational speeds and comparison of adiabatic and ordinary head

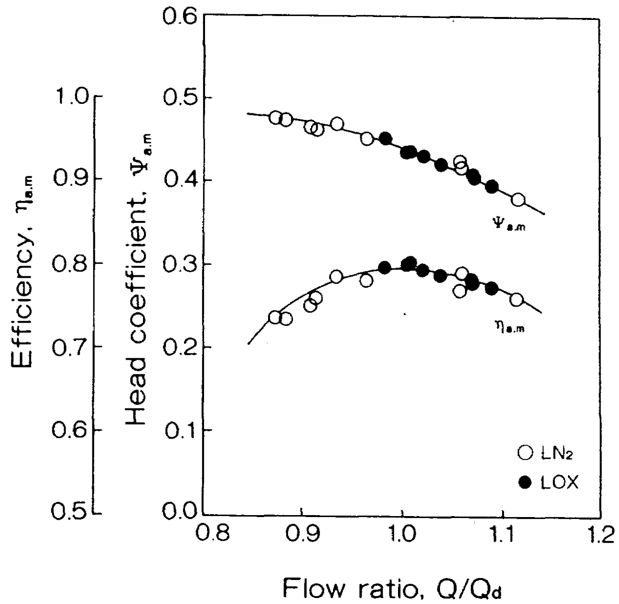

Fig. 11 Performance of LOX main pump at rated rotational speeds

comparatively small compressibility. However, the efficiency of about 80 percent at the designed flow rate ($Q/Q_d = 1.0$) is considered to be fairly high compared with those of the previously developed rocket pumps as shown in Fig. 14[5]. The detailed performance of the LOX pump has previously been reported[6]. Fig. 14 shows the stage efficiency of the rocket pumps with the main impeller, the diameter of which was more than 195 mm.

5. Performance of the LH_2 Pump

Test results of the LE-7 LH_2 pump are presented in Figs. 12 and 13. With regard to LN_2, the performance was represented by the adiabatic head and efficiency which are considered to closely approximate the true performance because the delivery pressure in the LN_2 tests was less than 16 MPa.

With regard to LH_2, not only the adiabatic head and efficiency but also the polytropic head and efficiency are presented in Figs. 12 and 13. The polytropic head and efficiency fairly well agreed with the head and efficiency obtained in the LN_2 test. Based on the above mentioned fact, the polytropic head and efficiency can be considered to show nealy true pump head and efficiency. Consequently, the adiabatic head and efficiency must be corrected using Figs. 2, 3, 4, etc., if the true pump performance is required.

The efficiency of about 75 percent obtained with

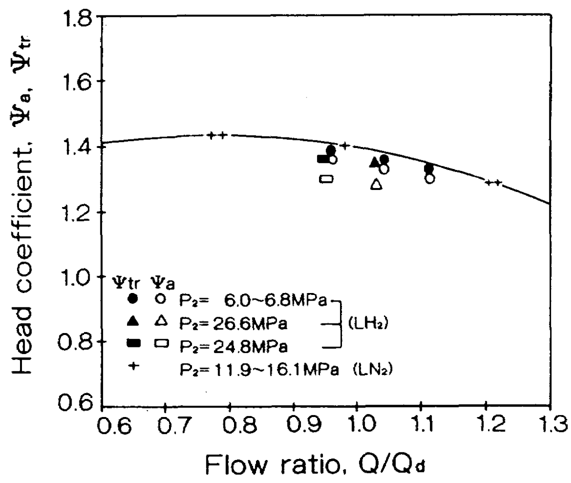

Fig. 12 LH_2 pump head and comparison of adiabatic and polytropic head

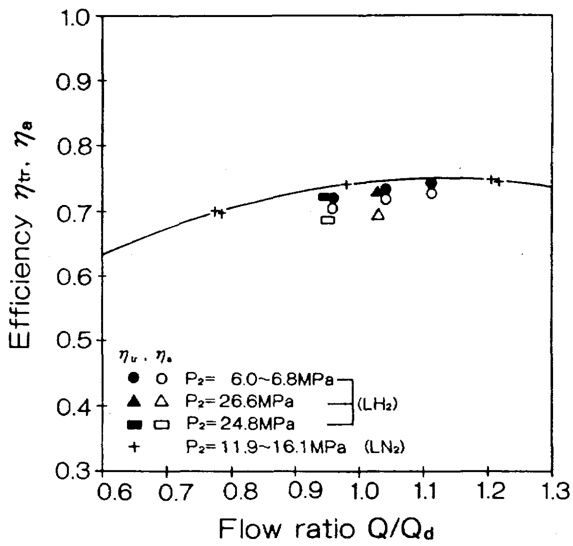

Fig. 13 LH_2 pump efficiency and comparison of adiabatic and polytropic efficiency

the present LH_2 pump can also be considered as reasonable as shown in Fig. 14.

6. Concluding Remarks

The LOX and LH_2 pumps of the LE-7 rocket engine are characterized by high delivery pressure and large flow rate. The hydrodynamic performance of these pumps was thermodynamically evaluated.

The performance of the LOX pump was expressed by the adiabatic head and efficiency because LOX is not so compressible. However, the efficiency directly determined using the measured pressures and temperatures was corrected to approximate the true efficiency because there was internal leakage from the split pump to the main pump.

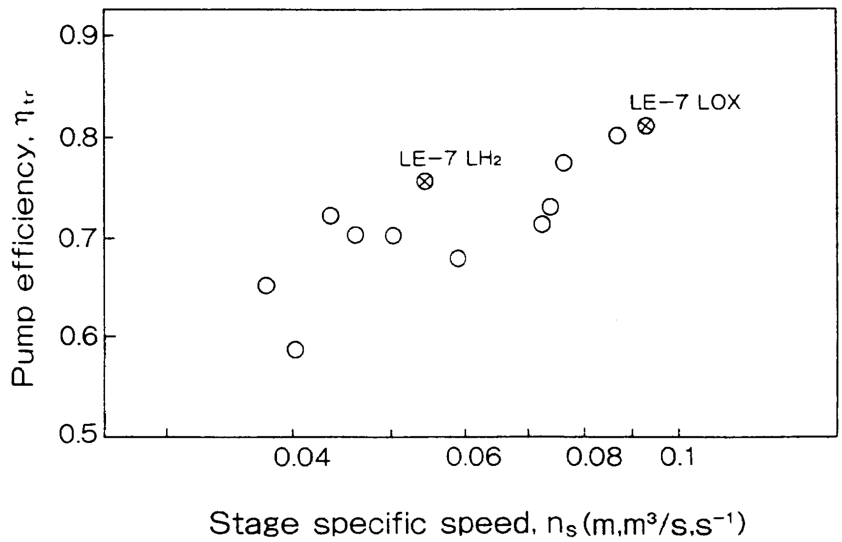

Fig. 14 Efficiency of large rocket pumps

With the evaluation of the LH_2 pump performance, the usefulness of polytropic head and efficiency were examined, because LH_2 shows much greater compressibility than LOX. It was confirmed by comparison of calculation and test results that the polytropic head and efficiency better approximated the true head and efficiency than did the adiabatic head and efficiency.

The efficiencies of the LE-7 LOX and LH_2 pumps were fairly high compared with the large rocket pumps which have been developed to date.

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