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# Development of Liquid Oxygen and Hydrogen Turbopumps for the LE-5 Rocket Engine

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**The National Space Development Agency of Japan (NASDA) started to develop the H-1 rocket, a future launch vehicle of Japan, in 1981. The second stage of the launch vehicle uses a 10-ton thrust (in vacuum) liquid oxygen and liquid hydrogen pump-fed propulsion system, which has a gas generator cycle engine (LE-5). Since 1977, NASDA and the National Aerospace Laboratory of Japan (NAL) have been developing an LOX and $LH_2$ turbopump system, which uses a dual-shaft turbopump arrangement with two turbines in series. Full power closed-loop operations of the turbopump system were successfully performed in 1980. Progress in the development of the turbopump system is presented in this paper.**

## Introduction

THE development of the H-1 rocket was started in 1981. The rocket will have the capability to place a 550-kg payload into a geostationary orbit. The second stage of the launch vehicle uses a 10-ton thrust (in vacuum) liquid oxygen (LOX) and liquid hydrogen ($LH_2$) pump-fed propulsion system, which has a gas generator cycle engine (LE-5). The engine system start is carried out with a hydrogen bleed cycle using gaseous hydrogen vaporized in combustion chamber tubes.

Since 1977, an LOX and $LH_2$ turbopump system, which uses a dual-shaft turbopump arrangement with turbines in series, has been developed. Both turbopumps consist of a single-stage centrifugal pump with an inducer powered by a two-row velocity compounded impulse turbine.

In the first step of the development, pumps, turbines and other major components were individually designed and tested in order to investigate hydraulic performance, mechanical integration, life and reliability, and so on. In the next step, the LOX and $LH_2$ turbopump assemblies were made and tested, and testing of the turbopump system was conducted in order to investigate the characteristics of the turbopump system.

Full power closed-loop operations of the turbopump system were successfully performed in 1980. Turbopump power control, which is necessary for keeping a fixed engine thrust and obtaining a given engine mixture ratio, was also completely accomplished.

## Turbopump System Features

The LE-5 engine and its characteristics are presented in Fig. 1 and Table 1, respectively. A schematic diagram of the turbopump system is presented in Fig. 2, and characteristics of the turbopump operations are summarized in Table 2. The two turbines are driven by hydrogen-rich hot gas produced by a LOX/$LH_2$ gas generator. The hot gas successively passes through the $LH_2$ and LOX turbopump turbines, a series turbine arrangement, development of which was considered to be easier than that of a single geared turbopump arrangement. Comparatively high turbopump system efficiency was attained with this series turbine arrangement. Another merit was that the LOX turbopump shaft seal conditions were improved compared with a parallel turbine arrangement. Turbopump power control is accomplished by using two valves, LOX turbine and $LH_2$ turbine bypass valves (LTBV and HTBV), shown in Fig. 2.

## Design and Integration

### LOX Turbopump

The mechanical configuration of the LOX turbopump is illustrated in Fig. 3. It consists of a single-stage centrifugal pump with a swept-back helical inducer and a two-row velocity compounded impulse turbine.

A tabulation of major inducer parameters is presented in Table 3. Geometric details of the inducer are presented in Fig. 4 The inducer blade profile consists of a straight line at the entrance and a circular arc. The inducer was machined from stainless steel. The inducer casing which was made from carbon filled Teflon was used in order to avoid metal to metal contact. With the impeller, an aluminum alloy backshroud with six vanes and a frontshroud were machined separately and joined by aluminum brazing. Anodic coatings were formed on the impeller wearing rings. The casing rings were also made from carbon filled Teflon, in which design the ill effect of the considerable plastic thermal contraction was alleviated. A double volute casing was used in order to decrease radial thrust variations in wide operating ranges.

The turbine blade profiles were designed using a previously reported method.[1] The blade profiles of the first rotor, the stator and the second rotor are illustrated in Fig. 5. The full admission nozzle consists of 37 blades. Both the unshrouded rotor and stator blades have blunt leading edges. The rotor blade, the disk, and the shaft were made from a solid material by machining and by an electro-sparking process.

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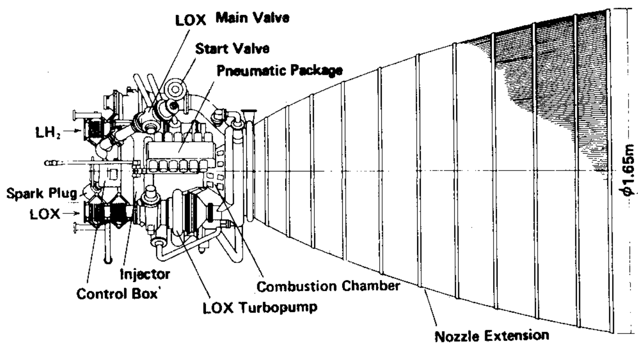


Fig. 1 External configuration of LE-5 engine.

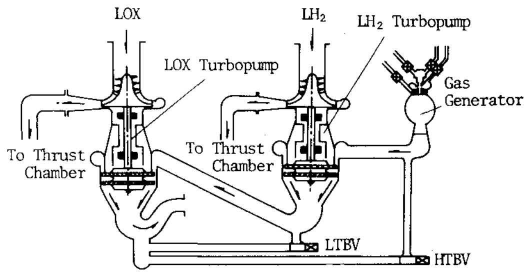


Fig. 2 Turbopump system schematic.

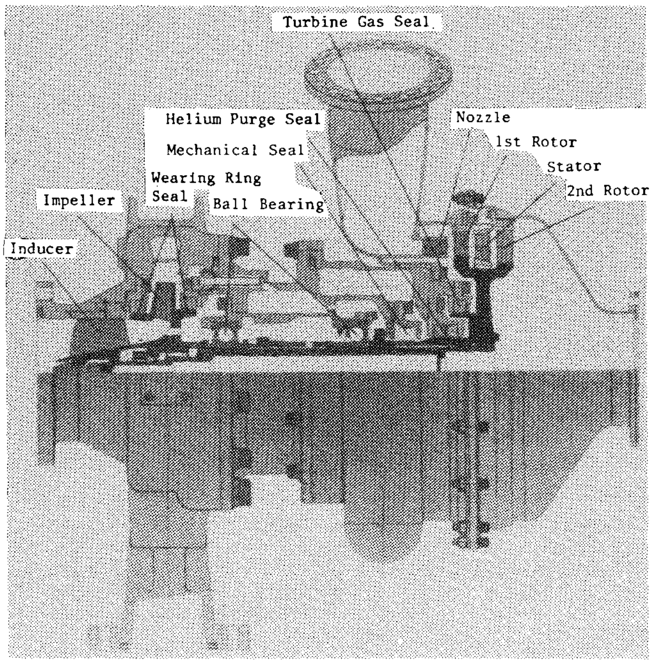


Fig. 3 Liquid oxygen turbopump.

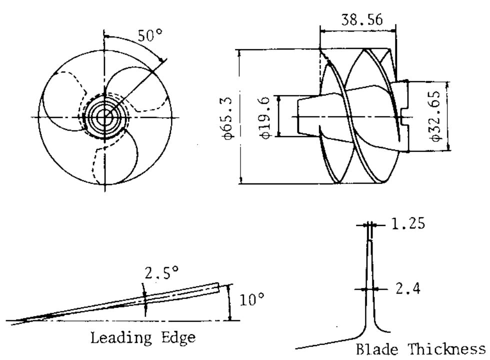


Fig. 4 LOX pump inducer.

**Table 1 LE-5 engine parameters**

| | |
|---|---|
| Thrust (vacuum), tons | 10 |
| Specific impulse (vacuum), s | 442 |
| Chamber pressure, ata | 35 |
| Engine mixture ratio | 5.5 |
| Length, m | 2.7 |
| Weight (dry), kg | 200 |

**Table 2 Turbopump design parameters**

| Parameter | LOX turbopump | $LH_2$ turbopump |
|---|---|---|
| Speed, rpm | 16,500 | 50,000 |
| Pump required NPSH, m | 7.5 | 56 |
| Pump delivery pressure, ata | 52.5 | 56 |
| Pump flow, kg/s | 19.4 | 3.52 |
| Pump efficiency, % | 65.8 | 58.9 |
| Turbine flow, kg/s | 0.390 | 0.423 |
| Turbine inlet pressure, ata | 4.87 | 24.0 |
| Turbine outlet pressure, ata | 2.61 | 4.98 |
| Turbine inlet temperature, K | 693 | 842 |
| Turbine efficiency, % | 39.2 | 47.6 |

**Table 3 Design parameters of LOX pump inducer**

| | |
|---|---|
| Required NPSH, m | 7.5 |
| Suction specific speed, m, $m^3$/min, rpm | 3964 |
| Inlet flow coefficient | 0.1 |
| Outlet flow coefficient | 0.121 |
| Head coefficient | 0.160 |
| Inlet hub-tip ratio | 0.3 |
| Outlet hub-tip ratio | 0.5 |
| Inlet blade angle at tip, deg | 10.0 |
| Outlet blade angle at tip, deg | 12.25 |
| Number of blades | 3 |
| Solidity at tip | 2.3 |

Figure 3 shows how the ball bearings are cooled by liquid oxygen, which passes through a filter set in the casing, through turbine-end and pump-end bearings and returns to the impeller eye through balance holes. The main shaft seal system presented in Fig. 6 consists of a face contact metal-bellows seal, a helium purged double circumferential intermediate seal and a circumferential hot gas seal. The intermediate and hot gas seals are a hydrodynamic type and have segmented seal rings with Rayleigh step pads.

Table 4 shows the materials of the major LOX turbopump components.

### $LH_2$ Turbopump

The mechanical configuration of the $LH_2$ turbopump is illustrated in Fig. 7. It also consists of a centrifugal pump with an inducer and a two-row velocity compounded impulse turbine.

The design of the inducer is almost the same as that of the LOX pump inducer. The constants of the three blade swept-back inducer are presented in Table 5. The inducer was machined from A-286 alloy. The inducer casing was coated with silver. The geometric features of the impeller are presented in Fig. 8. After a backshroud with six full vanes and six partial vanes and a frontshroud were separately machined, they were joined by diffusion bonding. A step labyrinth wearing ring seal was used in order to control the internal recirculation in the pump. Silver was also coated on the casing ring against the labyrinth. The double volute casing with a conical diffuser was cast from aluminum alloy.

The turbine blade profiles were designed using the method presented in Ref. 2. Blade profiles of the first rotor, the stator, and the second rotor are presented in Fig. 9. The

**Table 4 Materials of LOX turbopump components**

| Component | Material |
|---|---|
| Pump | |
| Inducer | SUS 304 |
| Impeller | Aluminum alloy (A6061) |
| Volute casing | Aluminum alloy (AC4C) |
| Shaft | INCO 718 |
| Turbine | |
| Nozzle | INCO 718 |
| Rotor blade | INCO 718 |
| Stator blade | INCO 718 |
| Manifold | INCO 718 |
| Mechanical seal | |
| Mating ring | WC |
| Seal ring | Carbon |
| Segmented seal | |
| Runner | INCO 718 (chromium plating) |
| Seal ring | Carbon |
| Bearing | |
| Retainer | Glass-fiber-filled Teflon |
| Ball and race | SUS 440C |

**Table 5 Design parameters of $LH_2$ pump inducer**

| | |
|---|---|
| Required NPSH, m | 56 |
| Suction specific speed, m, $m^3$/min, rpm | 4474 |
| Inlet flow coefficient | 0.1 |
| Outlet flow coefficient | 0.117 |
| Head coefficient | 0.092 |
| Inlet hub-tip ratio | 0.3 |
| Outlet hub-tip ratio | 0.5 |
| Inlet blade angle at tip, deg | 9.93 |
| Outlet blade angle at tip, deg | 11.4 |
| Number of blades | 3 |
| Solidity at tip | 2.6 |

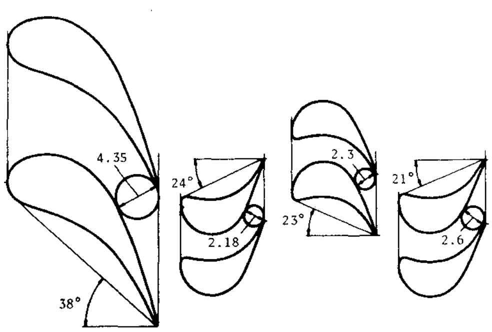


**Fig. 5 Blade profiles of LOX turbopump turbine.**

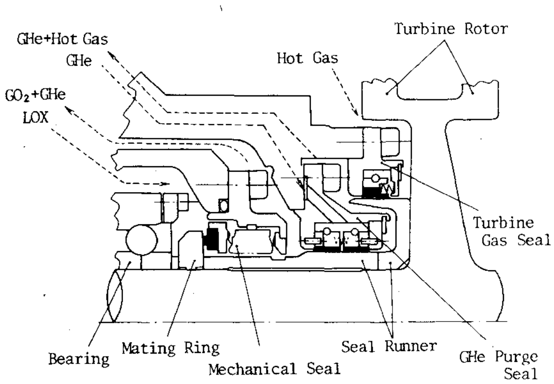


**Fig. 6 LOX turbopump shaft seal.**

**Table 6 Materials of $LH_2$ turbopump components**

| Component | Material |
|---|---|
| Pump | |
| Inducer | A-286 |
| Impeller | Titanium alloy (5 Al-2.5 Sn) |
| Volute casing | Aluminum alloy (A-356) |
| Shaft | INCO 718 |
| Turbine | |
| Nozzle | INCO 718 |
| Rotor blade | INCO 718 |
| Stator blade | INCO 718 |
| Manifold | INCO 718 |
| Mechanical seal | |
| Mating ring | INCO 718 (chromium plating) |
| Seal ring | Carbon |
| Bearing | |
| Retainer | Glass-fabric-supported or glass-fiber-filled Teflon |
| Ball and race | SUS 440C |

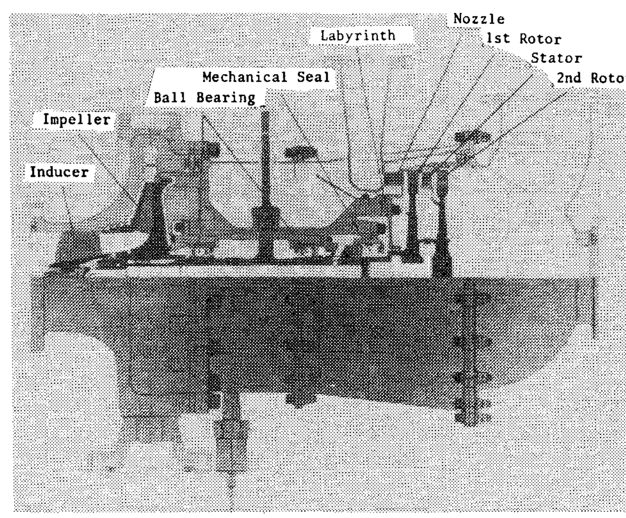


**Fig. 7 Liquid hydrogen turbopump.**

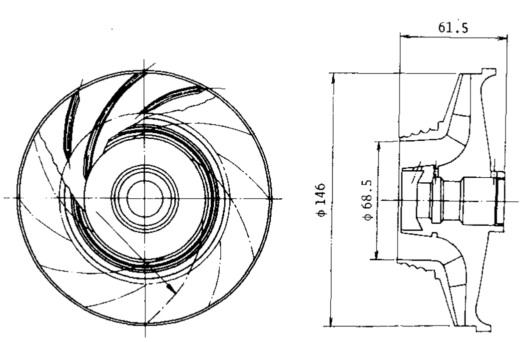


**Fig. 8 $LH_2$ pump impeller.**

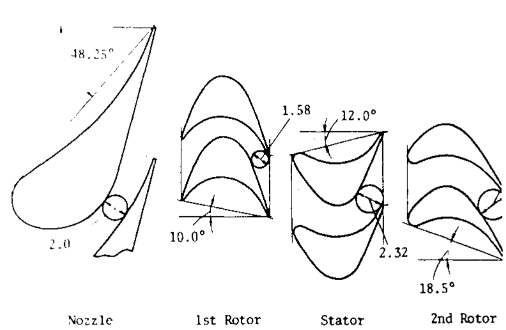


**Fig. 9 Blade profiles of $LH_2$ turbopump turbine.**

supersonic partial admission nozzle consists of 44 blades. The gas flow in the first rotor was designed to be supersonic and those in the stator and the second rotor to be subsonic. The turbine has no reaction in the first rotor, 5% in the stator, and 5% in the second rotor. Honeycomb seal strips were mounted on the casing against the unshrouded rotor blades.

The axial thrust of the $LH_2$ turbopump rotor was balanced by the balance piston[3] shown in Fig. 10. The pressure in the balance piston cavity is controlled by two orifices which are formed by the backshroud and casing. The balance piston absorbs the axial thrust and the self-lubricated ball bearings can function well in these improved operating conditions. Part of the balance piston flow cools the two bearings, passes through a labyrinth seal and returns to the impeller inlet through the passage inside the shaft. Liquid hydrogen is sealed by a newly developed metal-bellows mechanical seal.

The nominal speed of the $LH_2$ turbopump is between the second and the third critical speeds. Detailed analyses of the shaft deflections were carried out for the rotor assembly design.

Materials of the major $LH_2$ turbopump components are presented in Table 6.

### Gas Generator

The gas generator assembly shown in Fig. 11 consists of an injector, a combustion chamber, and an igniter. The nominal operating parameters of the gas generator are presented in Table 7. The injector has 12 coaxial injection elements which discharge liquid oxygen from center posts and liquid hydrogen from annuluses. Film cooling of the combustion chamber is conducted by eight shower-head orifices in the injector, which consume about 5% of the total $LH_2$ of the gas generator. The ignition source is an air gap igniter mounted in the center of the injector.

## Test Procedures and Results

### Test Facility

The LOX and $LH_2$ turbopumps and their major components have been tested at two test sites, the Kakuda Branch of NAL and the Rocket Test Center of IHI. Testing of the turbopump system was performed at the Kakuda Propulsion Center of NASDA. A schematic diagram of the turbopump system testing is presented in Fig. 11. Closed-loop operations were conducted according to the following procedures. First, the gas generator igniter was fired, and then ambient-temperature gaseous hydrogen from the facility gas supply propelled both turbopumps. When pump delivery pressures reached appropriate levels, the gas generator start valves (GFV and GLV) were opened. The gas generator was fired and turbopump steady-state operation was achieved. Turbopump power control was performed by two valves: a hydrogen turbine bypass valve (HTBV) and an oxygen turbine bypass valve (LTBV).

### LOX and $LH_2$ Pumps

The LOX and $LH_2$ pumps were powered by 450- and 880-kW dc motors, respectively. Before LOX and $LH_2$ testing, liquid nitrogen ($LN_2$) testing was conducted in order to obtain approximate hydraulic performance and to confirm mechanical integrity.

With the LOX pump, almost the same head coefficient and efficiency were obtained in both the $LN_2$ and LOX testing as shown in Fig. 12. The measured head coefficient and efficiency were close to the designed value. The relationship between LOX temperature and required NPSH, which was predicted[4,5] using the results of the $LN_2$ testing, is presented in Fig. 13.

The fairly good agreement of the $LH_2$ pump performance in both the $LN_2$ and $LH_2$ testing is presented in Fig. 14. The $LH_2$ pump head coefficient, which was calculated using pump delivery $LH_2$ density, was slightly higher than the predicted value. However, the measured efficiency was almost the same

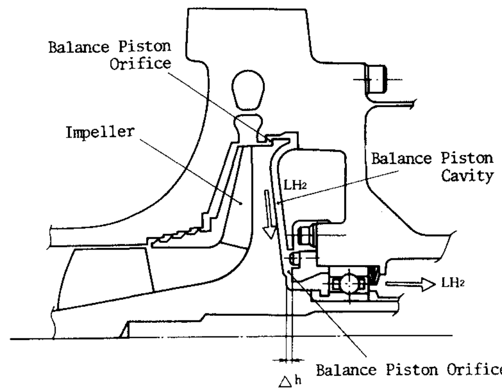


Fig. 10 $LH_2$ pump balance piston.

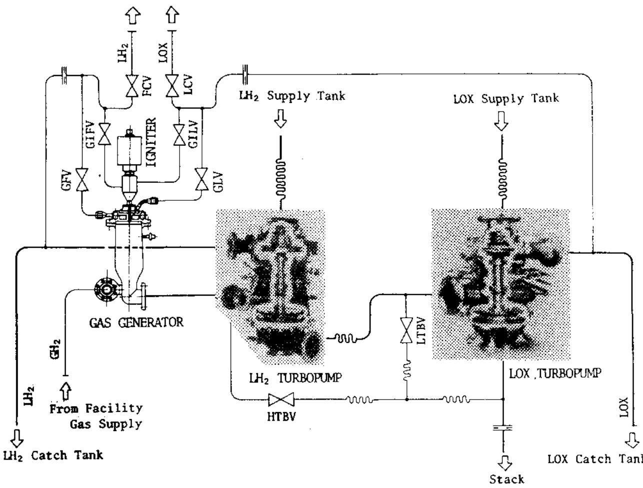


Fig. 11 Schematic diagram of turbopump system testing.

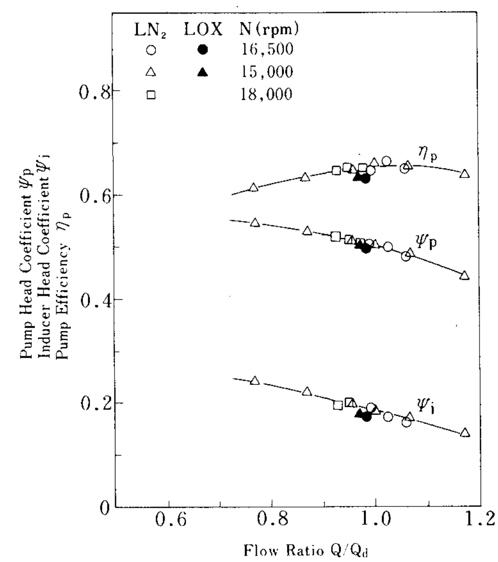


Fig. 12 LOX pump performance.

Table 7 Design parameters of gas generator

| | |
|---|---|
| Flow rate, kg/s | 0.466 |
| Mixture ratio | 0.9 |
| Combustion pressure, $kg/cm^2a$ | 26 |
| Combustion temperature, K | 890 |

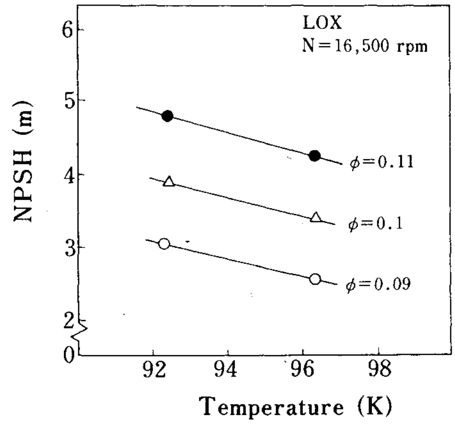


**Fig. 13 Predicted suction performance of LOX pump inducer.**

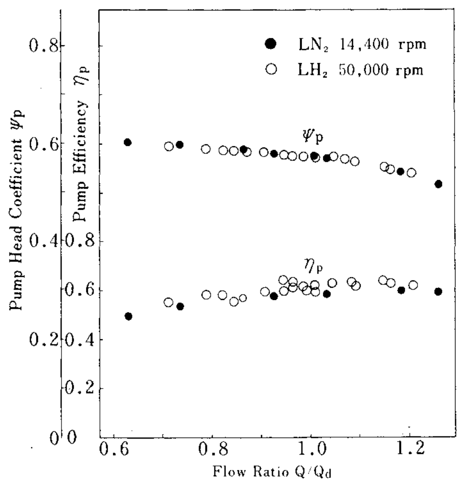


**Fig. 14 $LH_2$ pump performance.**

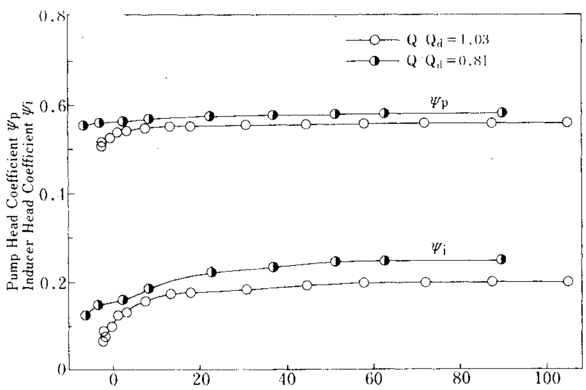


**Fig. 15 Suction performance of $LH_2$ pump.**

as the predicted value. The $LH_2$ pump satisfied the required NPSH (=56 m), as shown in Fig. 15. In the initial phase of the $LH_2$ pump testing, heavy shaft vibrations and hard balance piston orifice rubbing occurred with pump speed buildup. These problems were completely solved by improvement of rotating assembly dynamic balance and modification of the balance piston mechanism.

### LOX and $LH_2$ Turbopump Turbine

The output of the LOX and $LH_2$ turbopump turbines was measured by an electric dynamometer and a water brake, respectively. Before hot gas testing, two turbines were tested

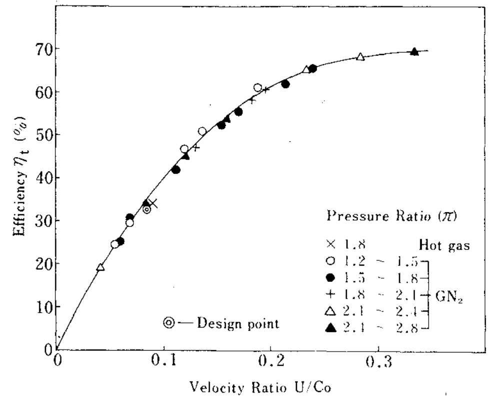


**Fig. 16 LOX turbopump turbine efficiency.**

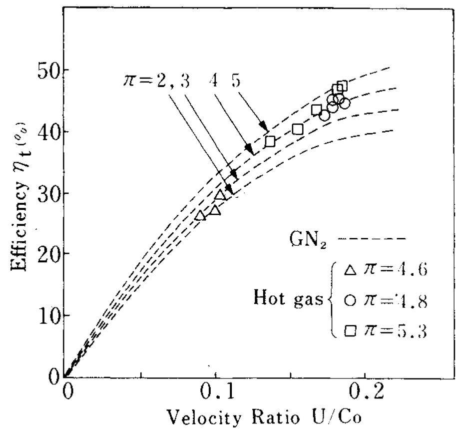


**Fig. 17 $LH_2$ turbopump turbine efficiency.**

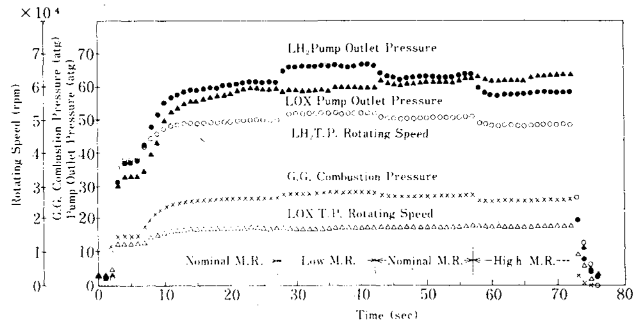


**Fig. 18 Close-loop operation of turbopump system.**

utilizing gaseous nitrogen as the driving medium in order to investigate approximate performance. Their measured performance is presented in Figs. 16 and 17, respectively. Efficiency of both turbines showed fairly good agreement with the predicted value. The effect of pressure ratio on LOX turbopump turbine efficiency was very small, as expected.

### Gas Generator

Testing of the gas generator was performed taking into consideration the LE-5 engine operating ranges. The gas generators were smoothly fired during ignition and steady-state operations. Gas temperature uniformity was confirmed by measuring temperatures at several points of the combustion chamber exit.

### LOX and $LH_2$ Turbopump Assemblies

In the first stage, testing of the LOX turbopump assembly was performed with LOX as the pump fluid and $GN_2$ or $GH_2$

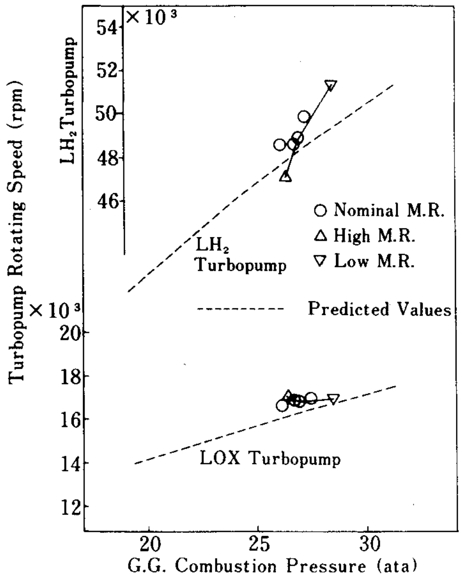


**Fig. 19 Operating points of closed-loop turbopump system testing.**

as the turbine working fluid. In the next stage, a gas generator was used to propel the turbine, in which case there was severe wear of the helium purge seal ring. This problem was solved by reducing the seal runner surface roughness.

Testing of the $LH_2$ turbopump assembly was also conducted with $LH_2$ as the pump fluid and $GH_2$ as the turbine driving medium in the initial test phase, and the gas generator was used in the remaining tests. In this case, severe shaft vibration occurred. It was caused by a sticking of the ball bearing outer race to the bearing housing, and resulted in a no load bearing operation. This problem was completely solved by making the clearance between the bearing outer race and the bearing housing appropriate.

### Turbopump System

Testing of the turbopump system, a schematic diagram of which is presented in Fig. 11, was performed by using two pairs of turbopump assemblies according to the following procedures.

1) $GH_2$ from the facility gas supply was used as the turbine driving medium (open-loop testing).

2) Gas generators were used. Their propellants were supplied from the facility tanks (open-loop testing).

3) Gas generators were used. Their propellants were supplied from the LOX and $LH_2$ pumps (closed-loop testing).

In the first and second steps, there were almost no problems. In the third step (closed-loop operation), it took much time to establish the turbopump system start buildup because of gas generator ignition troubles. Detailed studies including start transient computer analyses made it clear that insufficient preconditioning of the gas generator feed line caused an increase in LOX feed line resistance.

Pump discharge pressure, rotating speed, and gas generator combustion pressure in the closed-loop testing are presented in Fig. 18. In this testing, turbopump power control was satisfactorily performed. The relationship between turbopump rotating speed and gas generator combustion pressure is presented in Fig. 19. The planned operations were almost all conducted. It was confirmed that the turbopump system balance was almost perfect.

The two LOX turbopump assemblies and the two $LH_2$ turbopump assemblies were satisfactorily operated with an accumulated duration of about 3500 and 1300 s, respectively, including testing of the turbopump assembly and testing of the turbopump system.

## Conclusions

A liquid oxygen and liquid hydrogen turbopump system for the LE-5 rocket engine has been developed since 1977. Development of a prototype turbopump system was accomplished in 1980. The turbopump system satisfactorily operated in the engine system tests in 1980.

Further improvements of the turbopumps, limits testing of the turbopump system, and durability testing of the turbopump shaft seals and self-lubricated ball bearings are now being conducted.

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