Chapter 1 Turbopump of Rocket

Form of a liquid propellant rocket

This chapter describes a role, a function, composition, etc. of the rocket turbopump described in this book.

A liquid propellant rocket burns the liquid propellants (fuel and oxidizer) carried in the tanks, spouts this hot gas back, and generates a thrust (impelling force) by the reaction. The thrust obtained by the propellant of unit mass is called specific impulse, which is an important index regarding rocket performance.

There are two methods to send the propellant from the tank to an engine combustion chamber. One is performed using gas pressurization (gas pressurization type) and the other is performed using pumps (pump type). Two systems are shown in Fig. 1.1. If the velocity of jet gas increases, a bigger thrust and higher engine performance will be obtained. It can be made by higher pressure combustion. Furthermore, since the thrust is proportional to the quantity of propellants, a bigger thrust is obtained by increasing the amount of propellants. If we are going to obtain both high performance and a large thrust by the gas pressurization system, the large scale tank which bears pressurization pressure will be heavily thick and the rocket will be very powerless.

A pump solves this problem, because the pump can inhale the propellant of low pressure, raises its pressure irrespective of the amount of flow and sends to the combustion chamber. Generally, the pump is driven by a gas turbine. This combination is called a turbopump. However, the save of weight of a rocket can be attained only by the use of a light weight turbopump. The weight saving of a turbopump is attained by the increase of rotational speed. If the rotational speed increases twice, the diameter of an impeller can be decreased to half, because discharge pressure of a pump is proportional to the square of the peripheral velocity of an impeller.

However, some important factors prevent the speeding up of impeller. They are stress of the pump impeller and turbine blades which is proportional to the square of rotational speed, the excessive vibration of axis and cavitation of propellants at the pump inlet (boiling phenomenon due to decreased pressure) at the high rotational speed. Furthermore, there are some restrictions of the rotating speed due to limits of application of bearings and shaft seals. In addition, since the temperature of the combustion chamber of the engine reaches 2,000 K, special cooling is necessary. The wall of the chamber is cooled with the fuel supplied from the pump. The temperature of the fuel rises by this cooling and burned with the oxidizer in the combustion chamber. The higher the combustion pressure, the more difficult the cooling of the chamber is.
The engine cycle decided first

The gas which drives a turbine is generated from the propellant carried in a tank of rocket. Engine cycles are closely related to the method of generation of turbine driving gas, and they have decisive influence on the performance of a rocket engine and the difficulty of engine development. The cycles are distinguished by the method of generation of turbine driving gas. The schematic diagram of these engine cycles are shown in Fig. 1.2(2).

Fig. 1.2 (a) shows a gas generator cycle. The turbine driving gas is generated by the combustion with a part of propellant delivered from pumps. At this time, fuel is burned with fuel rich so that the gas temperature is within the permissible condition (generally below 1000 K). In this system, since the interaction between the power head consisting of the gas generator and turbopumps and the main combustion chamber is weak, the engine of the gas generator cycle has an advantage that the engine can be developed a turbopump and a combustion chamber separately during many periods. However, as the quantity of the turbine driving gas which is not effectively convertible into a thrust, will increase if the firing pressure is heightened too much, engine performance will be rather lower. The LE-5 engine which was used in the second stage of H-1 rocket applied this system. In the U.S., many engines used the gas generator cycle besides J-2 engine used for second and third stage of the Saturn rocket of the Apollo Project.
Fig. 1.2 (b) shows a coolant bleeding cycle. The turbine driving gas is the gasified fuel which cools the wall of the combustion chamber. Since the turbine driving gas is not efficiently changed into a thrust like the gas generator cycle, high engine performance is not obtained. However, as the gas generator is omissible, the development cost is considered to go down and also engine reliability will increase. This system was put to practical use in the LE-5A engine which was the succeeding engine of LE-5.

Fig. 1.2 (c) is called a two-stage-combustion cycle. The turbine driving gas was produced by the combustion in the preburner using all the fuel delivered from the fuel pump and a part of oxidizer from the oxidizer pump. Driving turbines, the gas reached the main combustion chamber and burns with the oxidizer delivered from the main oxidizer pump for the second time. Because the gas which drives the turbine, burns in the main combustion chamber, it is effectively changed into the thrust. Therefore, high engine performance will be obtained in this system.

Fig. 1.2 Typical engine cycles of liquid propellant rocket

However, because this system originally is used to attain high combustion pressure and the flow of the propellant from the pump to the main burner becomes in-series, the discharge-pressure of thea pump becomes very high. After all, the turbopumps with excessively high power are needed and the development of the turbopump becomes very difficult. The two stage combustion cycle was applied to both the LE-7 and LE-7A engines which were used to the first stage of H-2 and H-2A rockets, respectively. The development of the LE-7 engine turbopumps was extremely difficult.

SSME (Space Shuttle Main Engine) is the most famous engine in the world, the turbopumps of which experienced many problems during both development and actual operation. As the result, the development of the alternate turbopump was newly performed.
In order to clarify the role and function of a turbopump of a liquid rocket engine, the flow of the propellant in the LE-7 engine is shown in Fig. 1.3. This engine uses the two-stage-combustion cycle. Liquid hydrogen and liquid oxygen of 550 liters/s and 180 liters/s, respectively, are consumed to generate the thrust of 110 tons. The liquid hydrogen whose pressure was raised to about 27 MPa by the liquid hydrogen pump, reaches the preburner after cooling the surface of the wall of the main combustion chamber. About 20% of whole liquid oxygen whose pressure is raised to about 18 MPa by the main liquid oxygen pump, is further raised by the pressure of 10 MPa with the preburner pump and sent to the preburner. The turbine driving gas is produced using both the liquid hydrogen of the pressure of 27 MPa and the liquid oxygen of the pressure 28 MPa by the preburner. However, since the quantity of hydrogen is more excessive than the quantity required for perfect combustion, the temperature of the gas is below 1,000 K. Therefore, the gas is a mix of vapor and hydrogen. After driving turbines, the mixed gas reaches the main burner and burns with about 80% of liquid oxygen which is directly sent to the main combustion chamber from the main liquid oxygen turbopump. Being accelerated with a high expansion nozzle, this combustion gas turns into supersonic and is emitted into the atmosphere. As the turbopump is similar to the function of the heart which sends blood to all the corners of the body, it may be called the heart of a rocket engine. The turbopump is just a core of a rocket engine.

**An inducer which determines the weight of a rocket**
Weight saving of turbopumps will be a little considered. What the difference between the sum of static pressure and dynamic pressure (energy of the fluid velocity) and the saturated vapor pressure (pressure in which fluid begins evaporation) in the pump entrance is converted to the height of fluid is called the Net Positive Suction Head (NPSH). For example, if this pressure difference is 0.1 MPa, NPSH will be 10 m in the case of water.

If it becomes below the critical value (NPSHe), evaporation of fluid will violently take place and the pressure rise and efficiency of a pump will fall rapidly. The evaporation phenomenon of the fluid due to the decreased pressure is called cavitation. The rotational speed of the pump n (rpm) are experientially shown by the following formula using a volumetric flow of pump, Q (m³/min), the suction specific speed obtained from the similarity rule of pump, S (rpm, m³/min, m).

\[ S = \frac{n\sqrt{Q}}{(NPSH_{cr})^{3/4}} \] (1)

If NPSHe is fixed and the amount of flow is the same, the larger suction specific speed results in the higher rotational speed and the larger weight saving of turbopumps. With regard to a rocket pump, the value of S is enlarged by using an inducer shown in Fig. 1.4, which is a kind of axial flow pump with a few blades. Even if the cavitation occurs, the fall of performance is suppressed low because of the small blockage of channels of the inducer. As an index expressing the cavitation phenomenon, cavitation number shown in Equation (2) is used. The smaller this value, the easier the generation of cavitation, and the larger scale phenomenon occurs.

\[ \sigma = \frac{P_i - P_v}{\gamma(U_T^2 / 2g)} \] (2)

Where \( p_i \), \( p_v \), \( \gamma \), \( U_T \) are the static pressure at inducer inlet, saturated vapor pressure at inducer inlet, specific gravity and the peripheral velocity of inducer, respectively. Moreover, what \( (P_i - P_v)/\gamma \) is replaced by NPSH in Equation (2) may be called cavitation parameter (\( \tau \)), and is used instead of a cavitation number (\( \sigma \)).
The design criteria of inducer which NASA proposed on rocket pumps is shown in Fig. 1.5. In order to remove the influence of the boss of the inducer entrance, the corrected suction specific speed ($S^1$) is used. Where, $v$ in Fig.1.5 is the boss ratio of inducer entrance.

In Fig1.5, the value of $S^1$ of liquid hydrogen (LH$_2$) and liquid oxygen (LOX) is larger than that of water. It is based on the thermodynamic effect on cavitation which is shown by a simple model of Fig. 1.6. The propellant which flows into the inducer generates cavitation in the low pressure area of the blades. Because the latent heat of evaporation is derived from the circumferential fluid of this cavitation, the temperature of the fluid falls. This drop of temperature is especially the most remarkable with liquid hydrogen. As the result, NPSH in the upstream of inducer decreases by ($\Delta h_v = h_{si} - h_v$) in Fig. 1.6. This phenomenon is called the thermodynamic effect of cavitation. Due to this phenomenon, the ultra-high-speed operation of liquid hydrogen pump is possible.

Also, it is shown in the data of NASA that this prominent thermodynamic effect with liquid hydrogen pump extremely decreases in the operating range of low cavitation number. This was shown in Fig. 1.7. The relationship between the inlet flow coefficient
Fig. 1.5 Suction performance of inducers (proposed by NASA\(^{(4)}\))

![Graph showing suction performance of inducers]

Fig. 1.6 Explanation of the thermodynamic effect of cavitation (inlet flow velocity / inducer peripheral speed) and suction specific speed (Equation 1) of many...
rocket pumps and inducers was indicated. The suction specific speed is extremely large in the operating range of large flow coefficient. For example, even if the liquid hydrogen is in the condition of saturated vapor pressure, that is, \( \text{NPSH}/(C_{\text{m}1}^2/2g) = 1.0 \) in Fig.1.7, the pumps and inducers show extremely high suction performance. Where, \( C_{\text{m}1} \) and \( C_{\text{m}1}^2/2g \) are the flow velocity and the dynamic pressure head in the inlet, respectively.

![Graph showing suction performance of liquid hydrogen pumps and inducers](image)

**Summary of empirical data on suction performance of various pumps and inducers**

Fig.1.7 Suction performance of liquid hydrogen pumps and inducers

However, when the flow coefficient is less than 0.07, the suction specific speed sharply decreases. The extreme reduction of inlet flow coefficient can be considered to weaken the thermodynamic effect of cavitation. Although this phenomenon seems to be related to the back flow of inducer inlet, it is not completely explained even now. The information of Fig.1.7, mentioned above, was instructive for the improvement of the inducer of the liquid hydrogen pump of the LE-7A engine,
which will be described in Chapter 9 in this book.

The rotational speed of rocket turbopump are decided, so that the total weight (strictly weight of rocket) of turbopumps and tanks may amount to the minimum. The rotational speed of turbopump is so high that NPSHcr will increase and result in the increase of the total weight due to the increase of tank wall thickness, though the weight of turbopump decreases. An example of the relationship between the rocket weight and the rotational speed of turbopumps is shown in Fig. 1.8.

Fig. 1.8 The relationship between the rotational speed and the weight change of rocket.

Fig. 1.8 (a) shows the relationship between the rotational speed and the weight change which was examined with the liquid oxygen turbopump of the H-II rocket$^{(5)}$. φ is the inlet flow coefficient of inducer. The weight changes were compared with a criterion obtained on the basis of N= 20,000 rpm, φ = 0.07 and NPSHcr = 30 m.

It turns out that the inlet flow coefficient of inducer has remarkable influence on the weight change besides the rotational speed of turbopump. The weight of turbopump increases with the decrease of rotational speed at the lower rotational speed range. On the other hand, the weight of tank increases by the increase of inducer NPSHcr in the higher rotational speed range, which results in a concave curve with constant φ. The influence of inlet flow coefficient is related to the suction performance of inducer shown in Fig. 1.5 and Fig. 1.7. If the inlet flow coefficient increases, the suction specific speed will decrease, which results in the increase of both NPSHcr and tank weight.
Similarly, Fig. 1.8 (b) shows the case of liquid hydrogen turbopump of LE-7. It is calculated on the basis of N=46,000 rpm, $\phi = 0.08$, and NPSHcr=136 m. Compared with liquid oxygen, there is little influence of both rotational speeds and inlet flow coefficient. Since the liquid hydrogen turbopump is designed with the extremely high rotational speed, there is little influence of the decrease of turbopump weight. Moreover, there is little change of the inlet pressure (density xNPSHcr) of an inducer because of the low density of liquid hydrogen.

**Singularity of liquid hydrogen**

Until now, the properties of liquid hydrogen was shown in fragments. They will be shown collectively once again. The main properties of liquid hydrogen, liquid oxygen and water of normal temperature are shown in Table 1.1.

<table>
<thead>
<tr>
<th>Name of liquids</th>
<th>Liquid hydrogen</th>
<th>Liquid oxygen</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>204</td>
<td>90.2</td>
<td>293.2</td>
</tr>
<tr>
<td>Saturated vapor pressure (MPa)</td>
<td>0.10</td>
<td>0.10</td>
<td>0.0023</td>
</tr>
<tr>
<td>Latent heat of vaporization (kJ/kg)</td>
<td>449</td>
<td>213</td>
<td>140</td>
</tr>
<tr>
<td>Specific gravity (kg/ m$^3$)</td>
<td>70</td>
<td>1.140</td>
<td>998</td>
</tr>
<tr>
<td>Viscosity (kg s/m$^2$)</td>
<td>$1.37 \times 10^6$</td>
<td>$1.93 \times 10^6$</td>
<td>$1.03 \times 10^4$</td>
</tr>
<tr>
<td>Specific heat (kcal/kg/°C)</td>
<td>2.27</td>
<td>0.217</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Table 1.1 Main properties of liquid hydrogen$^{(6)}$, liquid oxygen and water

The specific gravity of liquid hydrogen is around 1/16 of liquid oxygen. Moreover, although the viscosity of liquid hydrogen is extremely small, the dynamic viscosity (viscosity/density) is almost the same as liquid oxygen due to the density is also low. However, compared with water, it is as small as 1/5. Fluid friction occurs in the surface of rotational parts in a pump. It is well known that the loss of energy by fluid friction is proportional to the 3rd power of the peripheral velocity of rotating parts. Such the
extremely small dynamic viscosity has good influence on the efficiency of liquid hydrogen pump of ultra-high-speed. However, when pump fluid is used as the lubricant, this small dynamic viscosity conversely becomes a defect. A new device is necessary for a turbopump with many parts to be lubricated by pump fluid.

In Table 1.1, the large value of latent heat of evaporation of liquid hydrogen is predominant. Since it is expectable to take more heat, it is convenient for the cooling of combustion chamber of rocket engine. Naturally, it is used also for cooling of turbo pumps. It is the property indispensable to special cooling system of turbopump bearings and high-temperature turbines, which will be mentioned later. The relationship between temperature and saturated vapor pressure of liquid hydrogen, liquid oxygen, and liquid nitrogen is shown in Fig. 1.9.

Fig.1.9 The saturated vapor pressures of liquid hydrogen, liquid oxygen, and liquid nitrogen.

The slope of saturated vapor pressure curves to temperature change is the steepest with liquid hydrogen. Since the thermodynamic effect of cavitation as mentioned above is strongly influenced by the slope of saturated vapor pressure, the thermodynamic effect of cavitation of liquid hydrogen is the most remarkable. The following equation (7) was proposed by Ruggeri, et al. of NASA to calculate the head drop of saturated vapor pressure, $\Delta h_v$, due to the thermodynamic effect of cavitation.

$$\Delta h_v = \rho_r V_r \frac{L}{c_{pl}} \left( \frac{dh_v}{dT} \right)$$

(3)
where \( \rho_r, V_r, L, \) and \( c_{pl}, T \) are the ratio of density of steam and liquid, the volume ratio of steam and liquid which participates in the thermodynamic effect of cavitation, the latent heat of evaporation, the specific heat of liquid and temperature, respectively. It is very difficult to calculate the volume ratio of steam and liquid \( (V_r) \), so the exact numerical value has not been attained. From Fig. 1.9 and Equation (3), it is clarified that the slope of saturated vapor pressure curve of liquid hydrogen \( (d\rho_v/dT) \) mainly enlarges the thermodynamic effect of cavitation.

**Composition of turbopump**

**Pump** In order to show the composition of turbopumps, the liquid oxygen turbopump of LE-5 engine for H-1 rocket is shown in Fig. 1.10.

\[
\frac{4}{3}H = \frac{Q}{n_s N}
\]

(4)

In order to improve the suction performance of pump, an inducer is attached just before the main impeller, which can inhale the propellant of lower pressure. The propellant which is raised a little by the inducer, is further raised to the pressure with a centrifugal impeller. The impellers for propellant with high density, such as kerosene and liquid oxygen, are designed by almost the same technique as general industrial pumps. The design of pump impeller for liquid hydrogen, which has extremely small density (about 1/16 of liquid oxygen) demands some specific devices. The geometry of pump impeller is determined by specific speed \( (n_s) \) of Equation (4) according to the similarity rule.
where $N$, $Q$ and $H$ are rotational speed (rpm), flow rate ($m^3$/min), and pump head (m), respectively. If the rotational speed is constant, as for the pump impeller with small flow rate and large pump head, the diameter of impeller will be large, and the width of impeller will be small. On the other hand, the pump with large flow rate and small pump head has an impeller with the small diameter and large width.

With the pump impellers of liquid oxygen and kerosene, the specific speed is around 200~300 in many cases. Since many technical data were accumulated with the pumps of this range of specific speed, particularly the general industrial pumps, the design of impeller is comparatively easy. Incidentally, the specific speed of the liquid oxygen pump of Fig. 1.10 is around 200.

![Relationship between specific speed and pump geometries](image)

**Fig. 1.11** specific speed and pump impeller geometries

The pressure rise of pump is proportional to the density of pump fluid and the square of the peripheral velocity of impeller. Therefore, if the liquid hydrogen pump is required the same pressure rise as liquid oxygen using the same pump, its rotational speed around 4 times as large as the rotational speed of liquid oxygen is needed. When priority is given to the simplification of structure with the liquid hydrogen pump of high delivery pressure, the decrease of number of impellers is generally preferable. The limit of peripheral velocity of centrifugal impeller made from titanium alloy is around 650 m/sec \(^4\). Therefore, the pressure rise of one centrifugal impeller is around 18 MPa. The pressure rise per one impeller can be enlarged by the increase of impeller exit angle and the number of impeller blades. For this reason, the specific speed of liquid hydrogen pump tends to be extremely small, and some specific devices are needed for the design of liquid hydrogen impeller. Incidentally, the specific speed of LE-5 liquid hydrogen pump was 100, which made the turbopump system of LE-5 engine with the liquid oxygen turbopump of Fig. 1.10. As an example, the centrifugal impeller of liquid hydrogen pump for rockets is shown Figure 1.12. It is near the impeller of compressor rather than the pump
impeller, because liquid hydrogen has extremely small density and remarkably large compressibility. The number of impeller blades increases from inlet to outlet in three steps using the partial blades. This is a device for reducing the blockage of impeller blades near the inlet and earning the larger pressure rise.

![Fig. 1.12 Impeller of liquid hydrogen pump](image)

With regard to the material of pump impeller for liquid oxygen, the aluminum alloy is used for the low-pressure pump and the nickel based super alloy for the high-pressure pump. The nickel based super alloy has the good quality for ignition in oxygen environment.

In order to obtain the performance of a high-pressure liquid hydrogen pump, especially efficiency, it is necessary to take into consideration the large compressibility of liquid hydrogen. The efficiency of the pump used for the usual liquid is calculated by the following equation on the assumption of incompressibility.

\[
\eta_p = \frac{\gamma QH}{L} = \frac{\gamma QH}{T\omega}
\]

(5)

where \( \gamma, Q, H, L, T, \) and \( \omega \) density, volumetric flow, the pump head, driving power, torque, and angular velocity, respectively. In addition, \( \gamma H \) is a pressure rise of pump.

Adiabatic efficiency which is calculated thermodynamically takes into consideration compressibility of pump fluid. This efficiency is calculated using the enthalpy which is determined by
the temperature and pressure at pump inlet and outlet.

\[
\eta_{ad} = \frac{\Delta h_{is}}{\Delta h_{act}}
\]  

(6)

where \(\Delta h_{is}\), in Fig. 1.13, is the increase of enthalpy in the isentropic change from the pump inlet (1) to exit (2is), and \(\Delta h_{act}\) is the increase of enthalpy in the actual exit (2act). The increase of enthalpy due to pressure rise of pump and various losses are included in this value. \(\Delta h_{act}\) is equivalent to the pump head of Equation (5). The difference of two isobars of inlet pressure \(P_1\) and delivery pressure \(P_2\) shown in Fig. 1.13, tends to increase with the increase of entropy. Therefore, \(\Delta h_{is}\) of Fig.1.13 increases with the increase of entropy. In order to obtain the true efficiency of high pressure liquid hydrogen pump, it is necessary to rectify the above-mentioned increase of enthalpy.

Fig. 1.13 Explanation of adiabatic efficiency

Since compression within a pump is performed gradually, the total compression process from 1 to 2act can be assumed that the innumerable adiabatic processes are performed as shown in Fig. 1.14. Replacing \(\Delta h_{is}\) with \(\delta h_{is}\) and summing up this \(\delta h_{is}\) from \(P_1\) to \(P_2\), the adiabatic efficiency of pump can be obtained, which is considered to be nearly true efficiency. The efficiency is shown by the following equation.

\[
\eta_{\nu} = \frac{\sum \delta h_{is,j}}{\Delta h_{act}}
\]  

(7)
The difference between the adiabatic efficiency ($\eta_{ad}$) and the pump efficiency ($\eta_{tr}$) obtained by Equation (7), which is considered to be nearly true efficiency, is shown in Fig.1.15. The efficiency difference increases with the increase of pump discharge-pressure rise, because the amount of compressed liquid hydrogen increases. Moreover, the temperature rise due to hydraulic loss of pump increases the amount of compressed liquid hydrogen. This tendency is more remarkable with a pump of lower efficiency. For example, the difference of both efficiencies of LE-7 liquid hydrogen pump is around 5%, since its true efficiency is 70%. It is clarified that we should use $\eta_{tr}$ rather than the adiabatic efficiency.

In order to express the performance of pump, pressure coefficient ($\psi$) and flow coefficient ($\phi$) are always used. The pressure coefficient is usually set between 0.07 and 0.15 with the inducer of rocket pump. In order to enlarge the flow coefficient, flow inside an inducer will be stabilized, but the
special cavitation appears which worsens the suction performance of the inducer. The pressure coefficient is that the pressure rise of pump is non-dimensionalized, and is shown by \( \psi = \frac{\Delta p}{(\rho \frac{U^2}{2})} \), where \( \Delta p, U, \rho \) are pressure rise, peripheral velocity and fluid density, respectively. The pressure coefficient can be increased by the increase of the exit angle and the number of impeller blades (refer to Fig. 1.12).

**Balance piston** Pressure acts on all the surfaces of turbopump rotating parts in contact with the pump fluid and turbine driving gas. As the result, load (axial thrust) occurs to the shaft and the same load acts to bearings. When it exceeds the acceptable load of bearings, it is necessary to adjust this axial thrust. There are many turbopumps using the balance piston mechanism\(^4\) which uses the back shroud of pump impeller as the balance disk. As shown in Fig. 1.16, two orifices with the shape of ling are made between the rear shroud of impeller and casing, and the axial thrust is adjusted using the pressure change of balance piston room which is formed between the two orifices. For example, if the shaft moves to the right, the main impeller fixed to the shaft will move similarly to the right. Then, the gap of balance piston orifice with bigger diameter spreads, and the gap of another orifice narrows. As the result, the higher pressure pump fluid flows into the balance piston room from the side of pump discharge. If the pressure of this balance piston room rises, the impeller will be shortly pushed to the left, and the gap of the balance piston orifice with big diameter narrows. Thus, a kind of self-adjustment is performed. This balance piston mechanism is one of the most important system which secures the durability and reliability of turbopumps which generate extremely high pressure.

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**Fig. 1.16 Balance piston mechanism\(^{11}\) adopted to LE-5 liquid-hydrogen pump**
**Turbine** Rocket turbopumps usually uses the impulse turbine, which has larger pressure ratio (the ratio of turbine inlet pressure and turbine gas exit pressure) and the turbine blades rotate at higher speed in order to obtain the simple structure at the sacrifice of some efficiency. Since the turbine of Space Shuttle Main Engine (SSME) was required higher turbine efficiency, the reaction turbine, which could also make use of expansion of gas, was applied, although the structure was considerably complicated.

In the design of turbine, the number of turbine rotors is examined at the first. Fig. 1.17 shows the relation of the number of turbine rotors, efficiency and the velocity ratio with impulse turbines. Although the turbine of one rotor shows the higher efficiency, the two rotor turbine as shown in Fig. 1.17, is usually used, which shows higher performance in the small velocity ratio from the restriction of the velocity ratio (the ratio of peripheral velocity and gas velocity at the nozzle exit), which is decided by the geometries and the strength of material.

If the temperature of turbine driving gas is raised, not only the gas can be reduced, but also the discharge-pressure of pump can be lowered with the engine of two stage combustion cycle. However, materials with the excellent strength in high temperature are necessary. The turbines of the SSME and the LE-7 engine were cooled using low-temperature gas hydrogen. In particular, in SSME, the high pressure liquid hydrogen was supplied to not only the rotor but the stator blades.

Since the start and stop are performed within in several seconds, the rocket engine receives the severe temperature change within this short time. For example, with the engine of liquid hydrogen and liquid oxygen, before starting engine, it cools until the pump inlet is filled with liquid so that the pump may not be raced.
This is called pre-cooling. The temperature of turbine directly connected with the pump will be near the temperature of liquid hydrogen (20K) or liquid oxygen (90K). Since the engine start makes the hot gas flow into the turbine, the drastic change of temperature occurs. The turbine will be exposed to the difference of temperature nearly 1,000 K within in several seconds. The small cracks were generated in the turbine blades by such the big thermal stress. The use of a long term is possible in high temperature environment for the material which was developed for jet engines. However, such the material does not necessarily have sufficient intensity to the thermal stress which occurs in an instant. With the turbine materials of rocket engine, the nickel based super alloy is used almost without exception. In order to prevent the occurrence of cracks, the turbine blades manufactured by the directional solidification method were used in the turbines of SSME and LE-7. These days, the more advanced single crystal blades are also examined.

The bearings and shaft seals \(^{(12)}\)

If kerosene can be used as lubricant with the rocket engine which uses kerosene as fuel, it is very easy to lubricate the bearings and seals of turbopumps. It is impossible to use the oil lubrication of bearings and seals of both liquid oxygen and liquid hydrogen turbopumps, because it must be considered the ignition of oil with liquid oxygen and the freeze of oil at low temperature. As liquid oxygen and liquid hydrogen have very low viscosity as shown in Table 1.1, fluid lubrication (state where steel balls rotates forming the thin oil film between the inner and outer races) is not expectable. For this reason, the ball bearing is used, in the cages of which lubricant of PTFE (Teflon) is included. The Teflon is transferred to the steel ball surfaces during rotation, and the self-lubricating bearing is cooled by pump fluid (liquid oxygen or liquid hydrogen) as shown in Fig. 1.18.
The value of \(dn\) of bearing is used to show the high-speed performance of a ball bearing, where \(d\) and \(n\) are the inside diameter (\(mm\)) and the rotational speed (\(rpm\)), respectively. The \(dn\) of LE-7 hydrogen turbopump bearing is over 1,800,000, which is almost the same as that of the oil lubricated bearing of the JT9D engine which was used for the jumbo jet aircrafts.

Shaft sealing of turbopump is used for the following the two purposes. The first is to decrease the propellant and turbine driving gas leakage from the high-pressure area to the low pressure one to prevent the performance decrement of turbopump, and the second is to prevent the mixture of oxidizer (for example, liquid oxygen) and fuel (for example, liquid hydrogen) or oxidizer and turbine driving gas (for example fuel rich hot gas). When both mix, explosive combustion takes place and it may lead to a big accident.
With regard to the shaft sealing of turbopump, a mechanical seal, a segment seal, a labyrinth seal, a floating ring seal, etc. are used. A mechanical seal is often used as shaft sealing of liquid propellant. The seal action is performed by the contact surface of rotating metal ring and stillness carbon ring, this carbon ring is held with the metal bellow as shown in Fig. 1.19. The mechanical seal cannot be used in the environment of high pressure, because it uses the metal bellows.

![Fig. 1.19 Mechanical seal](image)

The sealing action of the segment seal is made by the contact surface of the shaft surface or metal runner and the carbon ring. With a special segment seal, shallow slots are made on the surface of carbon ring, which contact with the meal runner. The shallow slots generate the force which floats the ring itself due to the hydrodynamic effect called the wedge effect and lessen the contact with a metal ring. This shaft seal is called a dynamic pressure type segment seal, and is used for turbopumps of our country. The above-mentioned two kinds of shaft seals are used in the environment where pressure is comparatively low from the restriction of the strength of carbon rings.

A labyrinth seal and a floating ring seal are used in the environment of higher pressure. Regarding the labyrinth seal, it has several concavo-convex grooves between the rotating axis and the fixed casing, which lowers pressure gradually. Because the gap of the labyrinth cannot be so small that metallic contact can be prevented, fairly large leakage is unavoidable. However, the labyrinth seal has been used in order to control the leak from the pump impeller exit to the pump inlet because of almost no restrictions to fluid pressure. An example of the labyrinth seal used in the rocket pump is shown in Fig. 1.16, which is called as the wearing ring seal of pump.
A floating ring seal consists of a carbon ring reinforced with the metal ring which can move radially and its housing. The seal gap (below 0.05 mm) is formed between the carbon ring and the shaft surface, which is coated with the hard chromium as shown in Fig. 1.20. The carbon ring has the same function as a journal bearing, and prevents the carbon ring from contacting with the shaft surface. Furthermore, if it is made the geometry in which the gap narrows to the flow direction, it produces the another fluid force for the carbon ring not to contact with the shaft surface. Since the leakage is less than the labyrinth seal, the floating ring seals were used to the liquid oxygen of 5MPa and also to the hydrogen rich hot gas of 17MPa in the high-pressure LE-7 liquid-oxygen turbopump.

The critical speed and shaft vibration

The history of rocket turbopumps is fairly old and goes back to the Germany V-2 in the 1940s. Since then a lot of turbopumps have been developed in the world. The high rotational speed of turbopumps has caused many serious shaft vibrations, which has been the bottleneck of the turbopump development. The rotating shaft which fixes the pump impellers, the turbine disc, bearings, and etc. has the natural frequency. In the turbomachinery, this frequency is called as the critical speed. There are many critical speeds, such as the first critical speed, second one, third one and so on. In general, the natural frequency and the rotational speed are expressed with $Hz$ and $rpm$, respectively. With regard to the industrial pumps and turbines, it is common to operate them with the rotational speed which is lower than the critical speed.

However, the rotational speed of rocket turbopumps is so high that they must be often operated with the higher rotational speed than the critical one. There are some examples of turbopumps, the
rotational speed of which are below the 3rd critical speed. The turbopump with a not good dynamic balancing, the severe shaft vibration often occurs when it passes through the critical speed. Moreover, the impeller of turbopump produces the fluid force, which whirs the impeller itself. This force may generate the shaft vibration with big amplitude at the frequency of the critical speed.

![Diagram](image)

**Fig. 1.21 Arrangement of bearings of turbopump\(^{(4)}\)**

In the design of the turbine pump, it is an important issue to make lower the critical speed. Although some forms which combine a pump and a turbine are considered, the position of bearings which support the shaft is very important in order to lower the critical speed. The typical forms are shown in Fig. 1.21.

The form (a) which arranges the bearings between a pump and a turbine is the most common. When the weight of the pump impeller is large, or the number of impellers increases, the form (b) and (c) often are used, which can decrease both overhang and the deflection of the shaft. However, if this method is adopted, the cooling of bearings will be complicated. Incidentally, two sets of the turbopumps of the H-1 rocket developed in our country adopted the form of (a). Moreover, the two sets of each turbopumps of the H-2 and H-2A rocket, the form (b) was applied to give priority to the decrease of the deflection of shaft as much as possible. The liquid hydrogen turbopump of the SSME adopted the form (c).

**The examples of turbopumps**

In order to show the operation conditions of turbopumps, the main specification of rocket engines developed in our country, the SSME and the Ariane 5 rocket are shown in Table 1.2. All the rockets use liquid hydrogen and liquid oxygen as the propellant. This is because the propellants produce high performance, that is high specific impulse, in the large operating region from low to high.
altitude. Incidentally, the specific impulse of the first stage engine (MB-3) of the H-1 rocket which uses kerosene and liquid oxygen as the propellant is about 250 seconds. The H-1 rocket used the pump feed rocket engine first developed in our country. The LE-5A was the succeeding advanced engine of the LE-5. The coolant bleeding system of Fig.1.2 (b) was adopted in order to simplify the engine structure.

The LE-7 engine is our country's first stage engine. The LE-7A engine is the succeeding engine of the LE-7. The LE-7A engine has fairly high reliability, because of no failure of launch until now. The Valcain 5 was developed as an object for the first stage of European Ariane rocket. The gas generator cycle was used to give priority to the ease of development. The space shuttle played the important role as the reusable and manned space rocket from the first flight in 1981 to 2012. In particular, it contributed to construct the International Space Station. The reusable SSME was developed as the main engines of the space shuttle orbiter. Because the two-stage-combustion cycle was applied in order to obtain the higher performance, its combustion pressure amounts to around 20MPa. The sum total of the output of turbines which drive the two pumps amounts to 100,000 H.P.

Various kinds of problems such as the explosion of high-pressure liquid oxygen pump, shaft vibration and breakage of the turbine blade, etc. occurred during development of the turbopumps and a lot of time was spent to solve these problems. Furthermore, the alternate turbopump was newly developed, since the problem arose with reliability of the turbopump during the operation phase.

With regard to the LE-7 and LE-7A engines, the two-stage-combustion system was adopted in order to obtain the high performance. However, since the ease of development was thought to be important, their combustion pressure was decided to be around 13MPa which was quite low compared with the SSME. Moreover, in the SSME, two sets of boost pumps were adopted ahead of the main pumps in order to obtain high suction performance and long durability of inducers.

In the LE-7 and LE-7A, both functions mentioned above are given to the inducers of the main pumps for the simplification of engine. Although priority was given to the ease of development, it was the first experience of large-scaled rocket engine in Japan. Many difficult problems were encountered during the development which will be mentioned in the chapter 5.
<table>
<thead>
<tr>
<th>Engines</th>
<th>LE-6</th>
<th>LE-5A</th>
<th>LE-7</th>
<th>LE-7A</th>
<th>SSME</th>
<th>Vulkain</th>
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<tr>
<td>Rockets</td>
<td>H-1</td>
<td>H-2A</td>
<td>H-3</td>
<td>H-3A</td>
<td>Shuttlespace</td>
<td>Ariane 5</td>
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<td>U.S.</td>
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<td>LOX/LH2</td>
<td>LOX/LH2</td>
<td>LOX/LH2</td>
<td>LOX/LH2</td>
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<tr>
<td>Thrust (kN)</td>
<td>10.5</td>
<td>12.4</td>
<td>11.0</td>
<td>11.2</td>
<td>913</td>
<td>105</td>
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<tr>
<td>Engine weight (kg)</td>
<td>225</td>
<td>248</td>
<td>1,720</td>
<td>1,890</td>
<td>3,177</td>
<td>3,380</td>
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<tr>
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<td>Gas generator</td>
<td>Coolant bleed</td>
<td>Two-stage C</td>
<td>Two-stage C</td>
<td>Two-stage C</td>
<td>Gas generator</td>
</tr>
<tr>
<td>Specific impulse (sec)</td>
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<td>446</td>
<td>446</td>
<td>440</td>
<td>453</td>
<td>450</td>
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<tr>
<td>Combustion pressure (MPa)</td>
<td>5.7</td>
<td>4</td>
<td>13.7</td>
<td>15</td>
<td>300</td>
<td>98</td>
</tr>
</tbody>
</table>

### Turbo pumps

| Liquid hydrogen (kg) | 50,000 | 51,000 | 43,200 | 41,800 | 34,400 | 34,600 |
| Liquid oxygen (kg) | 16,000 | 17,000 | 18,100 | 18,300 | 3,100 | 1,3000 |
| Horsepower (ps) | 30,400 | 30,400 | 10,800 | 18,900 | |
| Pump maximum pressure (MPa) | 5.6 | 6.8 | 27 | 28.6 | 42.6 | |

Table 1.2 Specification of typical rocket engines and turbopumps(1)