Kawasaki Gas Turbine Engines for Generator Sets

Since 1972, Kawasaki Heavy Industries, Ltd., in Japan has been promoting development of a series of smaller size industrial gas turbine engines. Kawasaki now has eight models of their own gas turbines in production. These models, which include increased power types and twin types, consist of three base series ranging in output power from 260 PS to 4,000 PS. All of these engine models were successfully completed in a short period with the aid of the scale-up and -down design development method. They are assembled as a prime mover into a series of Kawasaki gas turbine generator sets. About 360 units are now in service with a large variety of customers. This paper gives a general description of these Kawasaki development industrial gas turbines with some of the features highlighted.

INTRODUCTION

Of recent years there has been an increasing demand for industrial gas turbines in Japan. Most of these gas turbines are used for generating electrical power. And their demand is growing even in the area of relatively smaller unit sizes of 100 KW to 2,000 KW. This demand has particularly been created by the enactment of the installation requirement for emergency power sources for people-gathering buildings such as hospitals, hotels, department stores, banks, and office buildings. This legislation is intended for coping with accidents which may be caused by power failures resulting from fires or other disasters.

Gas turbines by nature have two great advantages in comparison with other internal combustion engines such as diesel engines: Poorer fuel consumption and higher manufacturing cost. These drawbacks, which might have caused some delay in penetrating into industrial applications particularly in the field of smaller capacity units, have been overpowered by a great many advantages, which are not found in other conventional engines, such as,

- Compact and light, so relatively small area required for unit
- No dependence on cooling water
- Low vibration
- Low noise
- Easy maintenance and inspection
- Operable on a variety of fuels
- Excellent generating characteristics

These features provide wider applications suitable for gas turbines such as emergency/stand-by and mobile power plants, thus gradually increasing the demand for industrial gas turbine applications in Japan. Figure 1 shows an annual installation record of smaller gas turbine generator sets in the range of 100 KW to 2,000 KW, which have been manufactured in Japan and delivered by Japanese manufacturers since 1968, indicating a sharp increase in the number of units installed since 1975.

In the past, gas turbines manufactured in Japan using her own technology were small in number. Most of them were manufactured under license by importing technology from foreign manufacturers. Kawasaki Heavy Industries, Ltd., was not an exception. We have also been engaged in overhauling or manufacturing aircraft jet engines and gas turbines under technical tie-up with gas turbine manufacturers in both the U.S. and the U.K. Since 1972, Kawasaki has energetically been doing research and development work on a series of industrial gas turbine engines for their wider application.

Based on the results obtained from this work, we developed SLA-01 type turbine engine for use primarily in generating electrical power, and in 1977 we began production of generator sets using these engines as a driving source for sale in the domestic market. Kawasaki has now in production a series of eight models of smaller size gas turbines ranging in output power from 260 PS to 4,000 PS, which are assembled as a prime mover into a series of Kawasaki gas turbine generator sets covering the rated capacity range from 150 KW to 2,000 KW. About 360 units have already been delivered to a large variety of customers as shown in Table 1 for use primarily as an emergency power source during a power failure. Fig. 2 shows the outside view of MIT-01 for example. Applications other than those for emergency use include mobile power units and peak lopping stand-by power units, all of which are now in service with the factories and the power companies.

DEVELOPMENT POLICY

Kawasaki has, as mentioned before, been engaged in overhauling and manufacturing jet engines and gas turbines under license. Most of these are aircraft...
engines or industrial versions of aircraft engines, and naturally have a cost problem. This, at first, made it difficult for us to increase sales in the field of general industrial applications.

We, however, began work by ourselves to develop industrial gas turbines in the belief that simple construction and a small number of parts of a gas turbine basically allow it to be manufactured at lower cost.

For industrial applications, competitors of smaller power gas turbines are diesel engines. As compared with the diesel engine, the best advantage of the gas turbine is in simple construction which will provide greater reliability, improved maintainability and cost reduction. At the same time, taking the performance characteristics of gas turbines into consideration, and from the standpoint of requirements and applications it is considered most suitable for use particularly in generating electrical power. These thoughts have led us to select a simple open-cycle single-shaft gas turbine of robust and simple construction.

Increasing sales requires arranging a full product line in a wide capacity range to meet a wide variety of demands and requirements.

At the first stage of development, we handled relatively small gas turbine model, S1A-01, in order to reduce development costs, shorten development period, and also enable as many operational experiments as possible to be carried out as if they were clinical trials, so that all kinds of technical problems or troubles could be exposed and solved.

As soon as hopeful prospect of S1A-01 development was acquired, we set out to develop the basic engines of M1A-01 (1,600 PS) and S2A-01 (950 PS), which are the resemblances of S1A both structurally and aerodynamically, with the aim of providing a product line in the shortest time.

In succession of these models, we developed S1A-02 (310 PS) and M1A-03 (2,000 PS) whose output powers were increased over their predecessors. Furthermore, to supplement the mid and larger power ranges, we developed S1T-02 (600 PS), M1T-01 (3,200 PS) and M1T-03 (4,000 PS) individually. These are equipped with twin engines that are gear coupled with existing gas turbine models. Figure 3 shows the outline of this development program.

Table 2 shows individual engine models of the Kawasaki gas turbine series. These engine models are roughly classified under the three series, S1, S2 and M1. The S1 and M1 series each consist of a base type, an increased power type and a twin type. Each model of

<table>
<thead>
<tr>
<th></th>
<th>S1A-01</th>
<th>S1A-02</th>
<th>S1T-02</th>
<th>S2A-01</th>
<th>M1A-01</th>
<th>M1T-01</th>
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<td>4</td>
<td>15</td>
<td>38(11%)</td>
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Table 1. USER SEGMENTS OF THE KAWASAKI GAS TURBINES (AS OF MARCH, 1981)

Figure 1. The annual installation record of smaller 100-2,000 KW gas turbine generator set in Japan (as of March, 1981)
these engines is of a single-shaft type and is very similar in construction and configuration. All components of the models were designed by the use of the scale-up and -down design method. This method, as previously mentioned, greatly helped towards minimizing the development period by not only reducing the design period but also making common the problems which appeared during the development.

Models S1A-02 and M1A-03 are both increased power versions of models S1A-01 and M1A-01 previously developed. The output power of model S1A-02 is approximately 20 percent more than that of model S1A-01. This power increase has been achieved by making modifications primarily to the S1A-01 compressor section for an increased volume of air flow. The turbine inlet temperature remains unchanged because integrally cast turbine wheels of the S1 series are difficult to cool.

Model M1A-03 has achieved a power increase approximately 25 percent more than model M1A-01 by not only increasing air flow, but also cooling the turbine nozzles and blades for increased turbine inlet temperature.

These power increased versions are identical to their base type in appearance, and use many similar parts. Twin type versions, which have two power producers attached to the reduction gearbox for interlocking, include three models S1T-02, M1T-01 and M1T-03. Model S1T-02, which has two power producers attached to the reduction gearbox, cannot operate in
a single engine mode.

For models M1T-01 and M1T-03, an over riding clutch is provided in the reduction gearbox and is designed such that it allows either of the power producers to operate independently.

Each ancillary is constructed to meet a wide variety of requirements for economical operation of load.

CONSTRUCTION AND PERFORMANCE

Power Producer

Figure 4 shows a typical sectional view of the S1A-02 power producer. The power producers of other engine models are similar to each other in configuration except that the S1 series has a 2-stage axial flow type turbine, while the S2 and M1 series have a 3-stage axial flow turbine. The power producer is cantilevered from the reduction gearbox by the front flange of the air inlet housing. Torque is transmitted from front to the reduction gearbox through the coupled spline.

Rotating parts such as impellers and turbine wheels are jointed together through curvic couplings and are secured with threaded part of a shaft passing through the bore of the rotating parts.

To staying away from the critical speed, the rotor assembly must have an enough bending stiffness, which depends on a tightening force of the rotating parts. As shown in Figure 5 which is the actual data for S1A-01, a tightening force decrease to a level lower than a given value causes a sudden drop in the bending stiffness with consequent vibration of the rotating parts. On the other hand, this force being restricted by the allowable surface stress on the curvic-coupling tooth and the tensile strength of the shaft, the shaft must be so designed as to handle thermal expansion of the rotating parts which vary with operating conditions.

![Figure 4. A typical sectional view of the power producer for model S1A-02](image)

![Figure 5. The bending stiffness of the rotor for model S1A-01](image)
second stage impeller is precision cast iron, with its surface as cast.

In using a gas turbine to drive a generator, it should be considered that the smaller is the rated power of the generator set, the larger over-load capacity is required for motor starting. This is because the inertia moment of the load is not proportionally smaller even though the engine becomes smaller in rated power.

At the moment of start, a current surge occurs (1.5 - 2 times of the rated load) resulting in a sudden speed drop, causing compressor surging at times. Consequently, the small S1A-01/02 Engines have an operating zone on the choke side in combination with a little larger turbine nozzle than optimum at the sacrifice of performance under steady state.

Figure 7 shows the operating state of a 187.5 KVA generator set with 45 kW turbo-blower when line started.

When a motor start is made with no load 103% of engine speed, the speed falls to about 3%, whereas when the motor start is made with no load 96% of engine speed to check the utmost limit of the motor start, the speed drops sharply as low as 8%. The engine will then go into a light surging condition, and then restore speed, indicating this is the limit for this load.
Figure 9. Compressor performance map for model S2A-01

In case a water pump is used, its inertia moment is so less than that of a blower, that with this generator set, the start of 75 kW water pump can be made without surging.

Compressors for all engine models are basically designed by the same technique, but those for later models have many more improvements.

Since the amount of air flow of model S1A-02 is approximately 20 percent more than that of model S1A-01, the relative Mach number of the inducer tip of the first stage impeller, with which the S1A-02 is equipped, will reach as much as 1.16.

The limited length of the inducer part due to restriction of the engine construction required a sharp leading edge, bringing about a considerable difference in performance between a blunt edge and sharp one as shown in Figure 8. Therefore, the inducer part of this model is finished machined.

Figure 9 shows a compressor performance map for model S2A-01. For this model, the compressor has a longer part of the inducer so as to minimize the effect of comparatively high inducer tip relative Mach number of 1.14.

All the engine models are provided with a single can type combustor which is simple in construction and is easy to handle. Figure 10 shows a typical combustion chamber for model S1A-01.

The combustion liner is made of thin sheet HASTELLOY-X, and has a fuel nozzle fixed on top of it. The fuel nozzle for liquid fuels is of a dual orifice type which contains combined primary and main fuel system for better ignition at low temperature. The fuel nozzle for gaseous fuels is of a single orifice type.

An ignitor plug is located at a point where the fuel spread along the atomizing angle of the fuel nozzle reaches the combustion liner wall. A CDI exciter sparks a spray of fuel for ignition once every 0.5 seconds.

For single can type combustion chamber, axisymmetric flow leaving the compressor tends to cause deflected flow when going into the combustion chamber perpendicular to the rotating shaft, causing variable flow around the combustion liner with resulting hot spots. To prevent these hot spots, guide vanes are provided at the inlet of the combustion liner in order to give a turn to the flow for uniformity (See Figure 11.).
For better ignition, it is basically effective to reduce volumes of air in the primary zone with reduced air flow velocity. This, however, increases smoke density. To settle this conflicting phenomenon, a baffle is placed in the swirler for better mixture of fuel and air with reduced smoke (See Figure 12.). This also serves to blow away carbon around the nozzle.

Tests with the S2A-01 combustion liner show the difference in smoke density between the combustion liner with and without the baffle (See Figure 13.).

**Turbine**

The turbine is of a 2-stage axial flow type for the S1 series, and of a 3-stage axial flow type for the S2 and M1 series. The turbine wheels for the S1 series are integrally cast from MM007 for the first stage and INCO713LC for the second stage. No cooling is provided to the blades.

The turbine wheel for the S2 and M1 series consists of a disc, to which blades are typically root attached. The blades are precision cast from MM007 for the first stage and INCO713LC for the second and third stages. The disc is forged from materials Waspaloy and INCO718. The nozzles for all the models are integrally precision cast from X45 for the first stage and Ni55 for the others.

The first stage turbine nozzles for the S2 and M1 series have slits in their circumference in order to alleviate thermal stress imposed on the blades.

Model M1A-03 and M1T-03 have achieved a power increase by cooling the first stage turbine nozzles and blades of model M1A-01 to increase turbine inlet temperature by 100°C. No cooling is provided for other models.

A generator set for emergency use often requires a rapid start-up or a sudden load application. In particular, turbines, which are exposed to high temperature, tend to undergo severe stresses due to a sudden thermal variation.

**Figure 11.** Air flow pattern of the combustor

Repetition of these stresses can cause damage or distortion to the turbine. Therefore, it is of prime importance that in designing parts exposed to high temperature, consideration be given to how to lessen stresses caused by sudden thermal variations.

For example, the 1st turbine nozzle to the S2A-01 has been designed rather simple and rigid at first, consequently being cracked at the leading edge of the vane. To avoid this, it was redesigned more flexible and slits were provided on the outer shroud of the nozzle. Figure 14 shows this design change.

Particular emphasis is placed on low cycle fatigue testing which repeats 1,000 to 2,000 times the cycle of a rapid start-up, a sudden load application, a sudden load rejection, shutdown and cooling.

**Figure 12.** An improvement of the combustor

**Figure 13.** Comparison of smoke with/without the baffle for model S2A-01
Particularly for smaller power gas turbines, a turbine tip clearance has a great effect on efficiency.

Measurements with the S1A-01 engine (See Figure 15.) show a decrease in efficiency by about 1% with an increase in the tip clearance by 0.1 mm (The tip diameter is 148 mm). This requires maintaining the constant tip clearance at all times so as to hold the smallest possible deformation of the shroud.

To minimize the deformation of the shroud, the approach used in the past was by segmentation of the shroud for support by means of the nozzle support which has relatively low external temperature. This technique added to cost due to complex construction of a smaller power gas turbine.
To prevent this problem, the method as shown in Figure 16 has been devised and is now applied to the Si and S2 series engines.

This shroud has slits on its inner side connected to round holes which not only avoid extreme stresses caused by sudden thermal gradients in the radial direction but also cool its external part to minimize distortion caused in the circumferential direction.

Reduction Gearbox

The reduction gearboxes for all the engine models are of a simple two-stage spur gear type except those for models MIA-01/03 which are of planetary type, and have an output shaft speed available in either 1,500 rpm or 1,800 rpm.

A power producer and all of the other major equipment are attached to the reduction gearbox.

The gas turbine engine is secured to a common bed at the bottom of the reduction gearbox.

The MIA-01/03 engines are provided with an accessory gearbox on top of the main gearbox, with which it is meshed, and also have provisions for installation of starters, a fuel pump and an oil pump.

For other engine models, each of the accessories is driven by the accessory-driving gear meshed with the final stage gear of the main gearbox train.

Reduction gearboxes for the twin type gas turbines, (model S1T) use in principle the S1A gears, and are constructed of two pairs of S1A gear trains meshed at the final stage.

The MIT gearbox is different from that of the S1 or S2 which is similar to the S1T except that the MIT gearbox is provided with a one-way clutch at the intermediate gears to permit independent operation of either engine.

The lower gearbox section forms the oil tank to provide storage of lubricating oil necessary for operation.

Fuel Control System

The fuel control system for all Kawasaki gas turbines is comprised generally of the components shown in Figure 17.

Two fuel pumps are independently provided: One is for the start-up, and the other for the main. The starting fuel pump is provided for better atomization through increased fuel pressure at low speed.

The starting fuel pump for the S1 series is driven by a DC motor which goes on or off through electrical interlock with the starter, while for the S2 and ML series, a small capacity pump, is driven by the starter shaft through mechanical interlock with the starter. Fuel delivered from the fuel pump divides into a primary fuel line and a main fuel line.

Primary fuel is fed unmetered directly to the fuel nozzle so as to raise fuel pressure as quickly as possible for better ignition. Whereas, fuel to the main line goes through the pressure raiser valve, the differential pressure valve, the fuel metering valve, and the main solenoid valve into the main fuel part of the fuel nozzle.

Fuel flow regulation during acceleration: The CDP actuator operated by the discharge pressure of the compressor operates the fuel metering valve for regulation of the main fuel flow.

Speed control: A change in speed is detected by an electromagnetic pickup provided on the side of the gearing in the reduction gearbox so that the fuel metering valve is controlled by an electrohydraulic governor actuator.

The governor is of Kawasaki-developed rotary pilot valve type, and is constructed in such a way as shown Figure 18. The use of anti-friction type bearings for the pilot valve eliminates contact surfaces, providing a very quick response with less hysteresis even at low temperature.

CONCLUSIONS

A series of small size gas turbines of low cost and high reliability has been successfully developed in a wide range of output power to compete with conventional diesel engines. The scale-up and -down design approach has allowed all these engines to be developed in a short period with a successfully completed series. The best use of gas turbine features has resulted in the simplest possible construction with reduced manufacturing cost. These serialized gas turbines have since 1977 been commercially available as the prime movers for emergency/standby generator sets, and about 360 units are now in service.