# AN EVALUATION OF A HYDROGEN PEROXIDE-BASED BI-PROPELLANT GAS GENERATOR FOR AN ADVANCED AIR TURBO RAMJET

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## Abstract

*This paper describes results of an exploratory test of a hydrogen peroxide-based bi-propellant Gas Generator (GG) for an advanced Air Turbo Ramjet (ATR). Results indicated that the GG has a capability of operating an ATR turbo-unit up to the designed rotation speed. Propellant flow rate of the GG at the designed turbine rotation speed, however, was much higher than predicted with lower bottom-side turbine inlet temperature. The turbine inlet temperature indicated that condensed water within the combustion products of the bi-propellant system accumulated at the bottom of the GG, and thus, reduced the available mass flow rate of the working fluid for the turbine. By draining the condensed water, the turbine inlet temperature was largely increased and required propellant flow rate of the GG at the designed turbine rotation speed was reduced significantly.*

## 1 Introduction

The use of an Air Turbo Ramjet (ATR) as a propulsion system for advanced tactical missiles and unmanned aerial vehicles offers attractive advantages, such as higher throttling ratio and a larger thrust margin compared to conventional ramjet systems. These advantages enable the ATR to operate both at sub- and supersonic flight speeds.

The concept of the ATR was presented by elsewhere [1-7], showing wide range operational capability and simplicity. Several investigators built technology demonstrators and validated operational characteristics of the ATR with either a Solid Fueled Gas Generator (SFGG) for tactical applications [1-6], or a liquid hydrogen powered GG for space applications [7]. Major technical barriers pointed out were, for example, high compressor development, SFGG with wide throttling ratio, etc.

Most investigators utilized a single-stage mixed flow or a centrifugal compressor for increased compression ratio. Some considered energetic solid fuels for their SFGG to achieve high energy content and a wide throttling ratio at the same time [8].

Among several variations of the ATR, Hydrogen Peroxide (HP) -based bi-propellant GG cycle was selected and investigated in this paper. The GG is always driven under oxygen rich condition, so that portion of the GG gases can be applied for the turbo-unit sealing and cooling. Throttling ratio of bi-propellant GG is much higher than that of the SFGG since mass flow rate and a chamber pressure can be designed arbitrarily by selecting an appropriate equivalence ratio. Penalty of carrying reactive oxidizer would be compensated by carefully selecting composition of the oxidizer.

The ATR R&D project at Technical Research & Development Institute (TRDI) has been conducted since 1995, and started with design and component testing of a liquid oxidizer, a SFGG with energetic materials, a bi-propellant GG, a high compression ratio compressor, a variable exhaust nozzle, and variable ramp sub-to-supersonic inlets. The bi-propellant GG was fully installed in the ATR demonstrator and evaluated, as an exploratory ground test at an Akashi Works test stand, Kawasaki Heavy Industries (KHI), Co. Ltd.

## 2 Objectives

The objective of this study is to demonstrate capabilities of the bi-propellant GG with the integrated ATR technology demonstrator under Sea Level Static (SLS) condition. Relations between turbine rotation speed and propellant flow rate of the GG, were obtained and investigated.

## 3 Test Articles Used in This Study

### 3.1 Liquid Oxidizer and Bi-propellant GG

As a fundamental requirement from air-launched missiles, oxidizer as well as fuel must maintain liquid phase from -54 to 74 deg. C as referred to MIL-STD-810. Though melting point of HP and water mixtures varies as concentration changes, 60wt% HP and 40wt% water mixture meets the requirement as shown in a phase diagram (Fig.1) [9]. Additives were carefully adopted so as to avoid catalyst deterioration and to improve stability during storage.

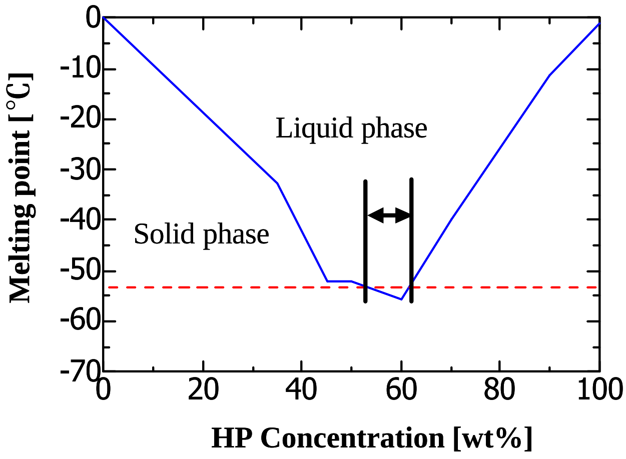


Fig.1. Phase diagram of HP and water mixture

Since the oxidizer contains large amount of water, and HP itself produces water vapor as a combustion product, there is a possibility of condensation of the water vapor within the GG, which might decrease power retrieved by the turbine. The amount of liquid phase water at the designed pressure (1.89MPa) can be as high as 42wt% of the total gases at the saturated condition (473K). The mass fraction of the liquid water decreases as the temperature increases as shown in Table 1. In order to eliminate the mass fraction of the condensed water, GG combustion gas temperature was set to 1273K.

JP-4 was selected as a standard non-energetic liquid fuel, since it is widely distributed and available in commercial markets.

Table 1. Combustion product at 1.89MPa

| | $O_2$(g) | $H_2O$(g) | $H_2O$(l) | $CO_2$(g) |
|---|---|---|---|---|
| wt% (gas temperature 1273K) | 8.8 | 85.3 | 0 | 5.8 |
| wt% (gas temperature 473K) | 8.8 | 43.1 | 42.2 | 5.8 |

Figure 2 shows a schematic of the bi-propellant GG developed in this study. The liquid oxidizer is first decomposed into gaseous oxygen and water vapor in the Pt-Pd catalyst beds shown in the figure, and then mixed with a liquid fuel (JP-4 in this study) within the combustion liner, in which oxygen rich condition is maintained throughout the test. This arrangement allows the JP-4 fuel injection into an oxidizing atmosphere, and thus, permits introduction of conventional combustor design and control techniques of jet engines. Ignition of the mixture is assisted with an electric igniter. The decomposition catalyst beds of the GG are placed circumferentially to minimize length of the GG unit.

Though the liquid oxidizer is storable, it still requires precautions for handling. Every contacting surface of the test equipment was carefully passivated.

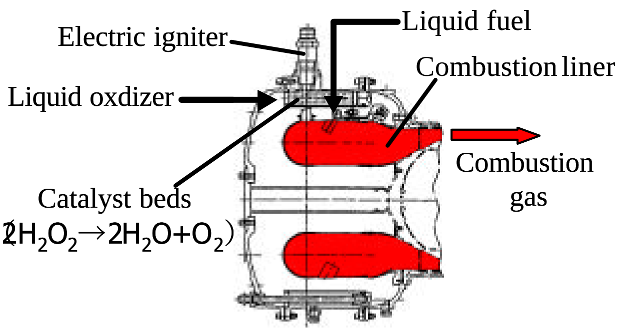


Fig.2. Schematic of the bi-propellant GG

## 3.2 ATR demonstrator and Test Stand

Figure 3 shows a cross-section of the ATR demonstrator developed by TRDI, under a contract with the KHI Co. Ltd.

The bi-propellant GG controls turbine/compressor rotation speed independently of incoming air condition through bell-mouth ducts attached at the inlets of subsonic diffusers.

A single-stage axial turbine is located in front of a compressor. This unique arrangement allows larger turbine diameter than conventional ATR design.

Tandem cascade rotor design was applied to the single-stage compressor because of its higher compression ratio as high as 2.2, with reduced internal loss associated with flow turning and reduced frontal area compared with a centrifugal compressor [10]

A compact ram combustor consists of two rings of V-gutters [11] and a variable convergent exhaust nozzle.

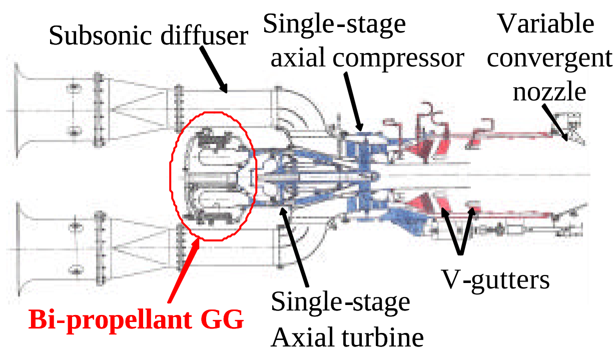


Fig.3. Cross-section of the ATR demonstrator (for SLS tests)

Figure 4 illustrates a SLS test stand arrangement. Fuel, oxidizer and cooling gases were yet supplied from the test facility in this exploratory test. The operations were conducted through the engine controller, which also works as a data acquisition system with 0.5 sec sampling rate.

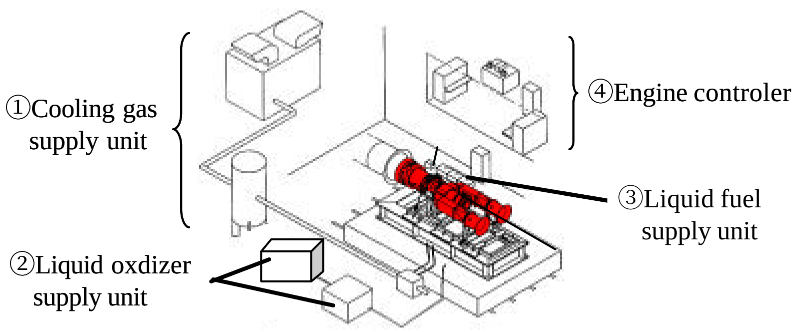


Fig.4 SLS test stand arrangement

## 4 Test Results and Discussions

### 4.1 Turbine Rotation Speed

Figure 5 shows a typical example of the measured turbine rotation speed. The turbine rotation speed was first raised to 70% and the ram combustor was ignited. The turbine rotation speed was then increased further and reached 100%. The turbine rotation speed increased without any fluctuation, and no significant mechanical vibrations were observed. Thus, the bi-propellant GG proved to have a capability of operating the ATR turbo-unit up to the designed rotation speed.

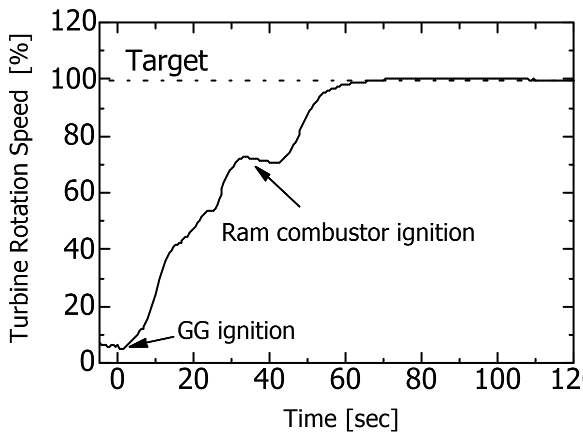


Fig.5. Typical example of measured turbine rotation speed

### 4.2 Mass Flow Rate

Figure 6 shows the relation between the turbine rotation speed and normalized propellant flow rate of the GG, $m_p$, which is defined as;

$$m_p=(m_{ox}+m_f)_{ex}/(m_{ox}+m_f)_{design} \qquad (1)$$

where,

$m_{ox}$ : mass flow rate of the oxidizer,
$m_{of}$ : mass flow rate of the fuel,
$_{ex}$ : experimental data, and
$_{design}$ : design point/target value.

The propellant flow rate was obviously higher than the prediction and increased more rapidly as the rotation speed increased, especially above 95%. At the designed speed, excessive propellant flow rate turned out to be 16.3wt%.

This also means while the GG produces enough power to drive the turbo-unit and produces sufficient level of net thrust, the propellant consumption rate is to be improved. In order to investigate the reason, gas temperatures of the GG were then investigated.

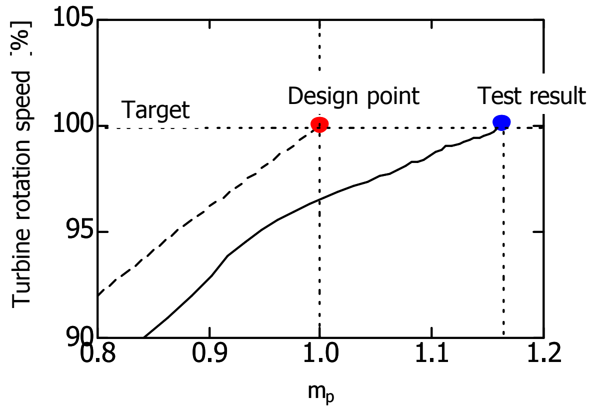


Fig.6. Turbine rotation speed vs. propellant flow rate

### 4.3 Heterogeneity of the Gas Temperature

Figure 7 shows normalized turbine inlet temperatures (TIT), which also represents GG combustion gas temperature. The top-side TIT reached the target, while the bottom-side TIT was much lower than expected. The bottom-side TIT once reached to the target at t=30sec, though, the temperature went down by 20% and remained unchanged without any perturbation until the GG operation ended at t=200sec.

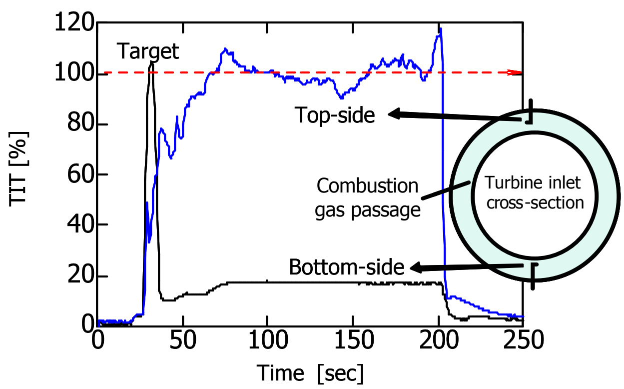


Fig.7. TIT profiles

Temperature profiles of reacting gases usually reveal small perturbation associated with local perturbation of reaction and velocity. On the other hand, liquid temperatures have relatively smooth profiles regardless of reaction since molecules of liquid are much more compactly contacted to each other.

Furthermore, the bottom-side TIT was very close to that of a saturated water vapor temperature, at the corresponding pressure. Therefore, condensation of water vapor was suspected at the bottom side of the GG.

Resident time of water droplets within the GG is estimated in the order of 0.1sec, and a small droplet at the top-side can fall down to the bottom-side of the GG within the estimated resident time. Thus, there is a good possibility that the condensed liquid water was accumulated during GG operation. Figure 8, the water phase diagram with top-side and bottom-side TIT, also supports the idea.

Once the water vapor is condensed and accumulated, free volume of the GG is decreased. Besides, some of the catalyst beds might sank into the accumulated water, which further decreases oxidizer decomposition by the catalyst. Some of fuel nozzles also might sank into the accumulated water, which would cause fewer fuel be injected to the liner than expected. Then combustion efficiency is expected to decrease.

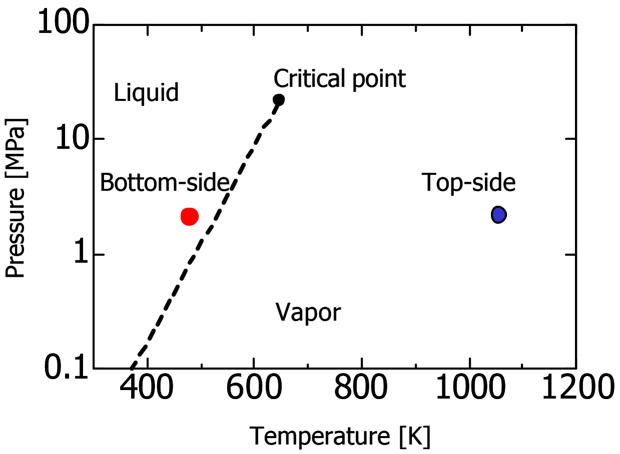


Fig.8. Water phase diagram

### 4.4 Improvement of the Bottom-side TIT

As described in the previous section, it is necessary to reduce the amount of liquid water accumulated within the GG to increase the bottom-side TIT, and thus, to reduce excessive oxidizer.

Since condensation and accumulation of water is inevitable as long as the bi-propellant system is selected, draining the accumulated water from the bottom-side of the GG was considered. Figure 9 shows a schematic of the GG with a draining tube. The tube is connected to the ram combustor, so as to recover the mass of the water to compensate the momentum loss associated with the draining as much as possible.

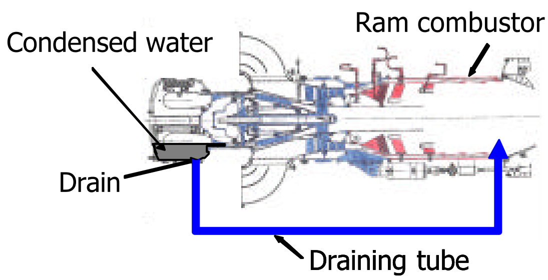


Fig.9. Schematic of the GG with draining tube

The result is shown in Fig. 10. The excessive propellant flow rate once required was reduced significantly by draining the water. The draining tube was designed to remove the accumulated water by 9.4%. As indicated in this figure, 1.7% out of 9.4% was still remained within the GG. In turn, 7.7% out of 9.4% was removed. Thus, “effectivity” of the draining tube in terms of propellant flow rate improvement reached 82%.

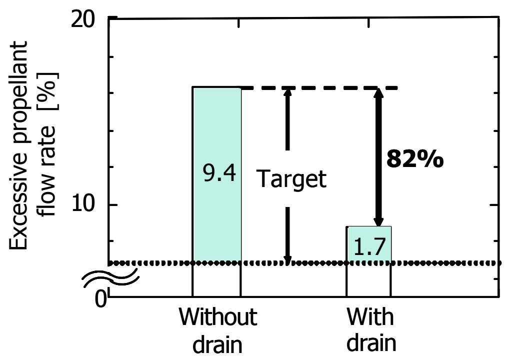


Fig.10. Improvement of excessive propellant flow rate

The bottom-side TIT is shown in Figure 11. Though gradual increase (40sec-60sec), and decrease (70sec-100sec) of the temperature show that there is still a room for optimization, the temperature increased again and reached the target at t=120sec. It is clear that draining the accumulated water from the bottom-side of the GG drastically increased the TIT.

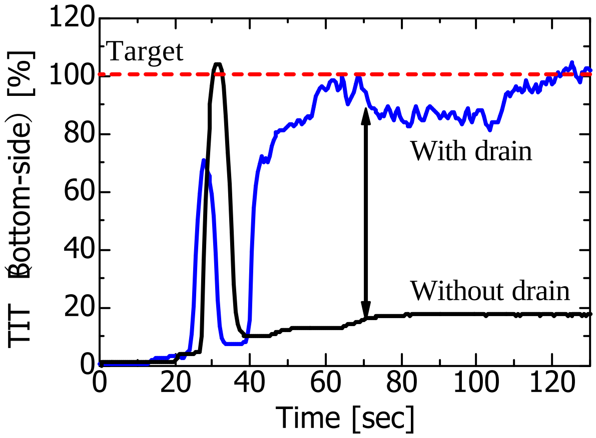


Fig.11. Improvement of TIT profile

Results of the exploratory test successfully demonstrated the bi-propellant GG capabilities with the ATR demonstrator. Further optimization of the drain is expected to decrease the accumulation of the condensed water, and to improve the propellant consumption rate of the bi-propellant GG.

## 5 Conclusions

An exploratory test of the bi-propellant GG with the advanced ATR demonstrator was conducted and results indicated;

(1) The GG demonstrated a capability of operating ATR turbo-unit up to the designed rotation speed.

(2)The propellant flow rate was larger than the designed value by 16.3% at the target rotation speed and the reason turned out to be the lower TIT at the bottom-side due to condensation and accumulation of water vapor within the GG.

(3) By draining the condensed liquid water, the TIT increased largely and the excess propellant flow rate of the GG reduced significantly.

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