JOURNAL OF PROPULSION AND POWER
Vol. 16, No. 4, July–August 2000

# Double Reheat Rankine Cycle for Hydrogen-Combustion, Turbine Power Plants

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**At Toshiba an advanced Rankine cycle for a hydrogen-combustion turbine system is being investigated as a part of World Energy Network, a national project. Our initial study indicates that the system has significant potential for use as a future large-scale system for electrical power generation fueled by hydrogen. The gross thermal efficiency of the advanced Rankine cycle is estimated to be 61.7% high heating value, while its only emission is clean water, free of $CO_2$, $NO_x$, $SO_x$, and other toxic wastes.**

## I. Introduction

THE sources of fossil fuels from which all nations derive the bulk of their energy needs are estimated to be depleted within 50–60 years. By then, fossil fuel prices will increase even higher than current predictions as a result of the world's growing economies, population growth, and continuously rising living standards.

The need to adapt alternative energy sources is increasing as a result of worldwide efforts to reduce environmental pollution by use of sustainable sources such as solar energy, wind power, and hydraulic power. Hydrogen is a potential candidate for use as a transportable source of sustainable energies to consuming areas.

To use hydrogen efficiently and economically, we have been developing hydrogen-combustion turbine technology as part of the Japanese national project World Energy Network (WE-NET). The project is promoted by Japan's New Energy and Industrial Technology Development Organization (NEDO), Japan's Central Research Institute of Electric Power Industry, and the Japan Power Engineering and Inspection Corporation.

The basic concept of hydrogen-combustion turbine has been studied.[1,2] Jericha et al.[3] developed this concept to a Brayton cycle hydrogen turbine system. Moritsuka and Koda[4] also proposed a high-efficiency turbine system employing a double reheat Rankine cycle, which had significant potential for use as a large-scale power plant system.

This paper presents design and development concepts for an advanced Rankine-cycle and hydrogen-combustion turbine technologies.

## II. Global Energy System

The only byproduct of burning hydrogen in oxygen is water. It is expected that the hydrogen combustion technology for a 1973 K (1700°C) class turbine will result in a gross thermal efficiency [high heating value (HHV)] higher than 60% with no emissions other than clean water.

We are currently developing such a technology under the NEDO WE-NET project. The project's goal is to establish a feasible hydrogen-energy network that can eventually be applied on a worldwide scale. Figure 1 shows the concept with respect to the major sources, producers, and users of a hydrogen-based energy system. Hydrogen can be produced from various sustainable-energy sources such as water, solar, geothermal, and wind power in global areas abundant with such sources.

Hydrogen will be used as a transportable source of sustainable energies to consuming areas. Figure 2 shows the predicted energy balance of a hydrogen-fueled turbine. Current research shows that 37.3% of electricity produced by a sustainable-energy source for example, hydraulic power, will be recoverable through use of a hydrogen-combustion turbine system.[5] The efforts aimed in achieving higher thermal efficiency of such a hydrogen-turbine system must also result in reduced construction cost and cost-effective electrical power generation.

## III. Hydrogen-Combustion Turbine

### A. Basic Concept

Figure 3 shows a sample system configuration for a hydrogen-combustion turbine. It is a high-temperature, double-reheat Rankine cycle. It uses two hydrogen–oxygen combustors for heating and reheating. They generate high-temperature steam by combusting hydrogen and oxygen, whereas the conventional Rankine cycle uses a superheater and a reheater as part of a boiler in which steam temperature must be kept under 873 K (600°C) because of the boiler material's temperature limit. Use of a combustor instead of a boiler enables significantly higher steam temperatures, which boosts thermal efficiency.

Figure 4 shows a comparison of the advanced and conventional Rankine cycles in a temperature-entropy diagram. Performed calculations show that the hydrogen turbine's gross efficiency could reach 61.7% (HHV) if its firing temperature can be raised to 1973 K (1700°C). In addition to its higher efficiency, a hydrogen-fueled turbine would also provide superior environmental performance because its only byproduct is clean water.

### B. System Design

Figure 5 shows mass and heat balance for the advanced Rankine cycle, for which we optimized the temperatures and pressure ratio of turbines to obtain a reliable and high-performance turbine system. We chose basic design conditions by considering likely future technology developments for turbine systems, as shown on Table 1. Calculation was performed to satisfy the basic physical thermodynamic balance as follows.

For turbines,

$$Ht1 - Ht2 = \eta(Ht1 - Ht2ad), \qquad W = Gt(Ht1 - Ht2)$$

where

$Gt$ = steam or gas flow through a turbine
$Ht1$ = inlet steam or gas enthalpy
$Ht2$ = outlet steam or gas enthalpy
$Ht2ad$ = steam or gas enthalpy at the end of isentropic expansion through the turbine
$W$ = turbine output work
$\eta$ = adiabatic efficiency

Received 1 February 1999; revision received 24 February 2000; accepted for publication 16 March 2000. 

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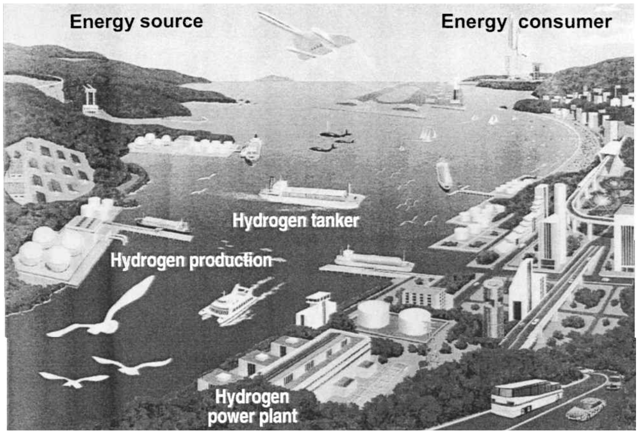


**Fig. 1 Schematic of the concept of a hydrogen energy system.**

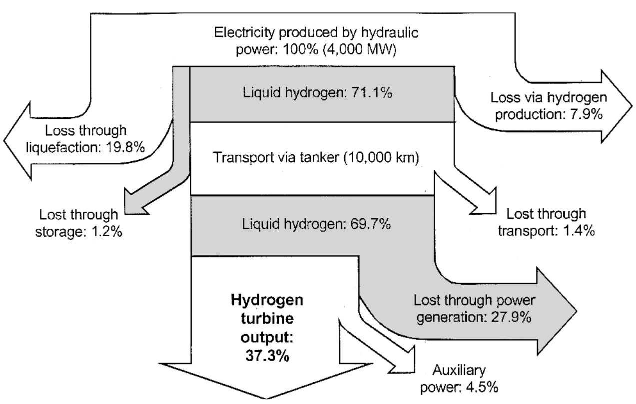


**Fig. 2 Estimated energy balance for a hydrogen-fueled turbine.**

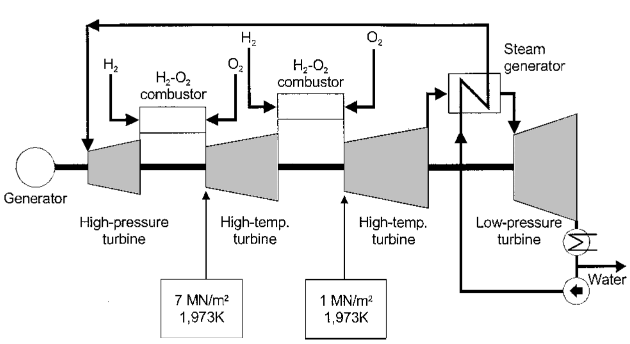


**Fig. 3 Schematic of a hydrogen combustion turbine.**

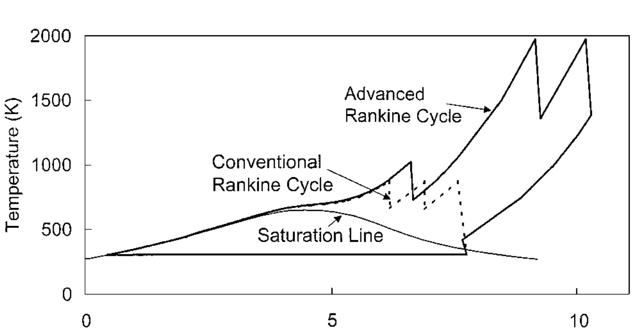


**Fig. 4 Entropy-temperature diagram of double reheat Rankine cycles.**

**Table 1 Basic design parameters**

| Parameter | Value |
|---|---|
| HPT inlet pressure | 34 MPa |
| HPT inlet temperature | 1023 K |
| HT inlet temperature | 1973 K |
| Combustor inlet pressure (maximum) | 7 MPa |
| Turbine efficiency | 93% |

**Table 2 Predicted plant performance**

| | |
|---|---|
| Gross output power, MW | 500 |
| HP1 | 52.5 |
| HT1 | 183.8 |
| HT2 | 204.7 |
| LPT | 59 |
| Gross thermal efficiency (HHV), % | 61.7 |

Note that a cooled turbine was modeled as a combination of turbines and heat exchangers.

For combustors,

$$Gc1 \cdot Hc1 + Gh(Hh + Hv) + Go \cdot Ho = (Gc1 + Gh + Go)Hc2$$

where

$Gc1$ = inlet steam or gas flow
$Gh$ = hydrogen flow
$Go$ = oxygen flow
$Hc1$ = inlet steam or gas enthalpy
$Hc2$ = outlet steam or gas enthalpy
$Hh$ = hydrogen enthalpy
$Ho$ = oxygen enthalpy
$Hv$ = hydrogen heat value

For heat exchangers,

$$Gxh(Hxh1 - Hxh2) = Gxc(Hxc2 - Hxc1)$$

where

$Gxh$ = fluid flow to hotter side
$Gxc$ = fluid flow to colder side
$Hxh1$ = hotter side inlet fluid enthalpy
$Hxh2$ = hotter side outlet fluid enthalpy
$Hxc1$ = colder side inlet fluid enthalpy
$Hxc2$ = colder side outlet fluid enthalpy

In this turbine system, pressurized water from the boiler feedwater pump (BFP) is heated in a steam cooler, then vaporized and superheated in a heat-recovery boiler (HRBL). The resulting high-pressure steam (35 MPa) is fed to a high-pressure turbine (HPT) and expands to medium pressure (7 MPa) to drive the turbine's rotor.

In a high-pressure reheat combustor (HPCOMB), combustion of hydrogen and oxygen raises the temperature of medium-pressure steam to 1973 K (1700°C). Heated steam expands in high-temperature turbine 1 (HT1), then flows into the low-pressure reheat combustor (LPCOMB) for reheating to 1973 K (1700°C). The steam, which expands again in high-temperature turbine 2 (HT2), goes to HRBL to heat the pressurized water. This steam expands again in the low-pressure turbine (LPT), then condenses to water in a condenser. A part of the water, which is pumped from the condenser, is discharged from this turbine system. The amount of this excess water is equivalent to the amount of hydrogen and oxygen supplied to the combustors. The remaining water is sent to feedwater heaters for warming, then sent back to the BFP. Table 2 summarizes plant performance.

A key parameter to be achieved is the 1973 K (1700°C) gas temperature at the system's high-temperature turbine inlet. Figures 6 and 7 show a plant layout and a view of the system's in-line power train. The HRBL is located next to the turbine building. The required area to contain this plant (0.0135 $m^2$/kW) is significantly

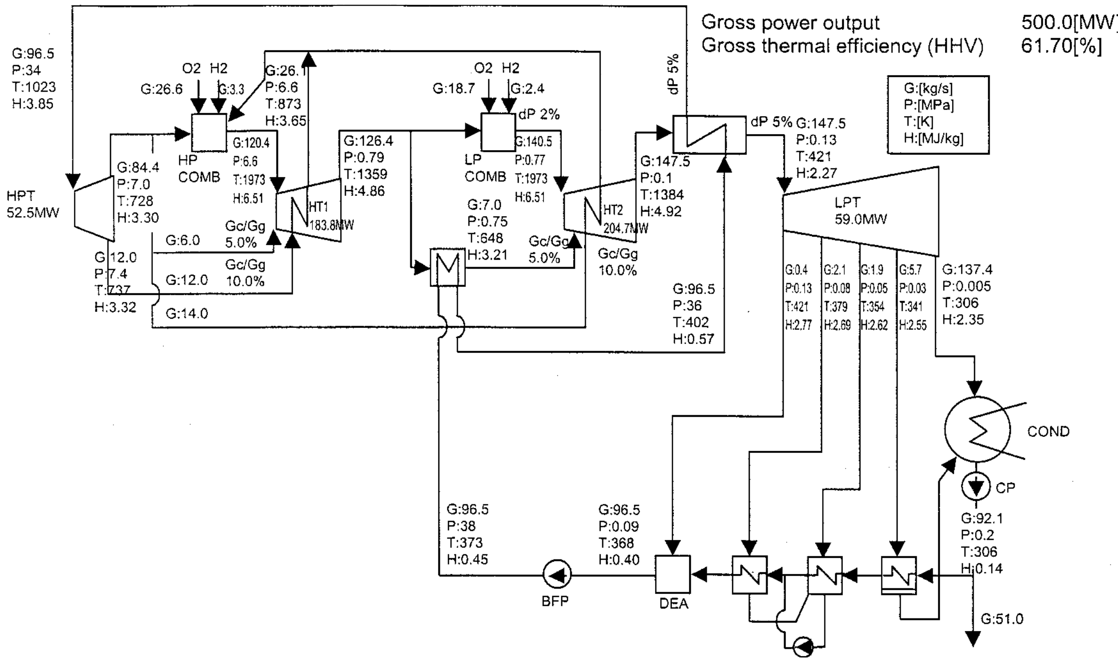


**Fig. 5 Mass and heat balance of advanced Rankine cycle.**

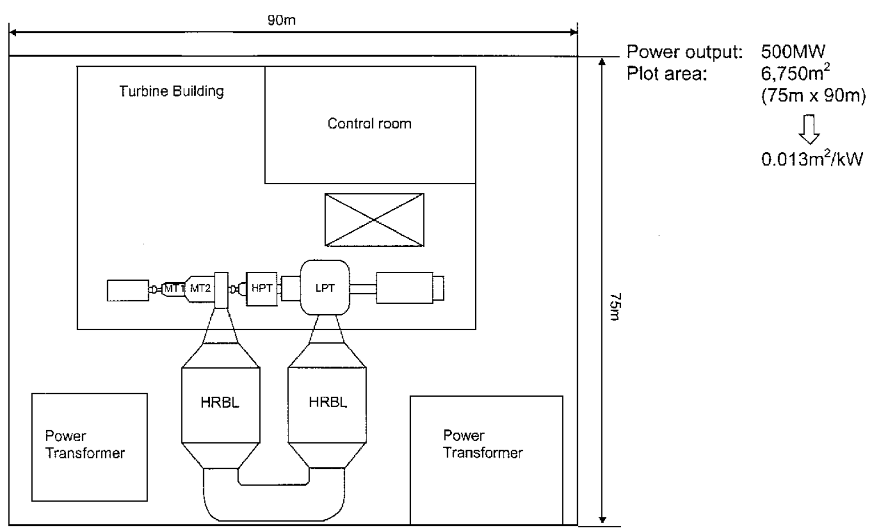


**Fig. 6 Plant layout.**

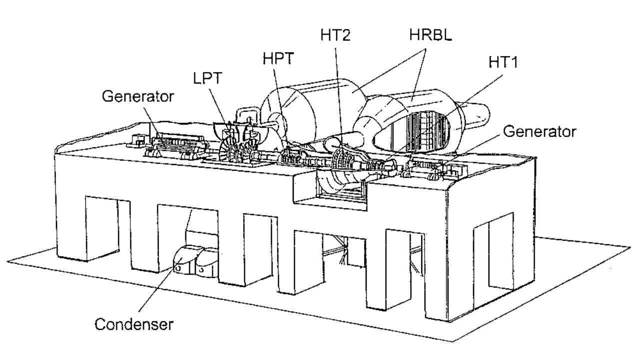


**Fig. 7 Power train.**

smaller than a standard combined-cycle power plant that typically uses 0.03 $m^2$/kW.

### C. Component Design

#### 1. *High-Temperature Turbine*

Figure 8 shows the system's high-temperature turbines. Their design is based on recent high-temperature gas-turbine technology rather than steam-turbine technology, although the working medium is steam.

In an HPCOMB, hydrogen and oxygen are burned within steam exiting the HPT, becoming 1973 K (1700°C) steam. The HT1 is a five-stage, steam-cooled steam turbine. The turbine's exhaust is connected to a LPCOMB by a duct. Hydrogen and oxygen are supplied again in this combustor to reheat steam to 1973 K (1700°C). HT2 is a four-stage, steam-cooled steam turbine. Exhaust steam exits to an HRBL through the turbine's exhaust diffuser to generate 35 MPa high-pressure steam.

The length of these turbines is only 10 m nevertheless, they can generate 388 MW of electricity.

#### 2. *High-Temperature Steam Generator*

Figure 9 illustrates the concept of an HRBL, a once-through type boiler. Hot steam from HT2 is led to the body of the 7 and 8 tube bundle, then passes through tubes 5, 6, 1, 2, 3, and 4. High-pressure water from the steam cooler is fed to the 1 tube bundle, then evaporation and superheating of the steam take place while water/steam is passing through those tube bundles. High-temperature material is used for the 7 and 8 tube bundles because their steam temperature is considerably higher than the other bundles.

The volume of the system's HRBLs is quite small, about one-fifth that of a heat-recovery steam generator (HRSG) for a 350 MW, combined-cycle power plant.

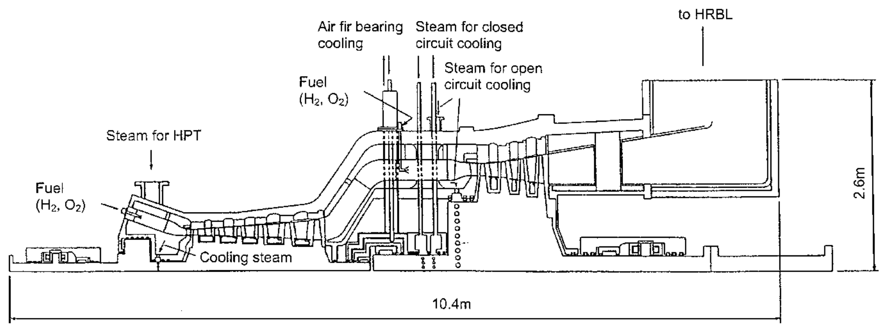


**Fig. 8 High-temperature turbines.**

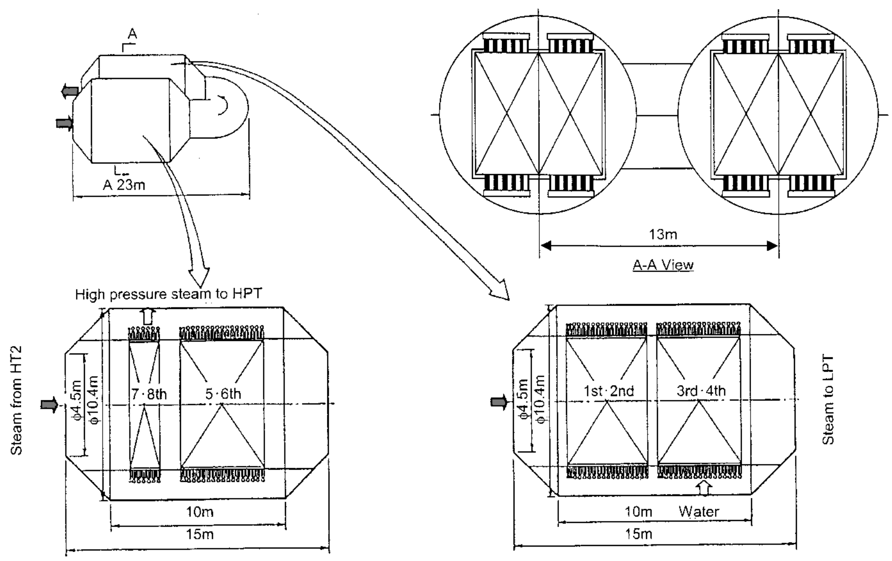


**Fig. 9 Heat-recovery steam generator.**

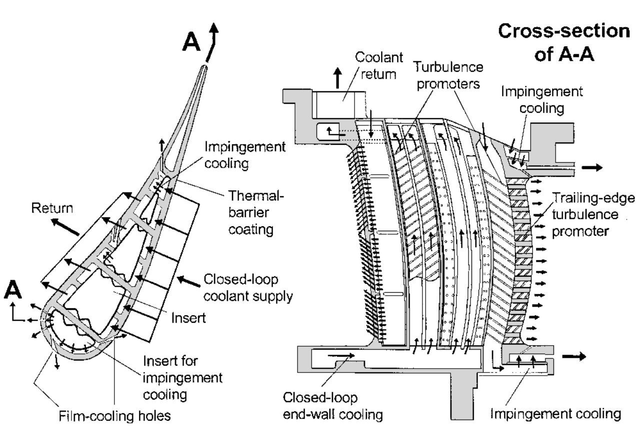


**Fig. 10 Steam flow within hybrid cooling nozzle.**

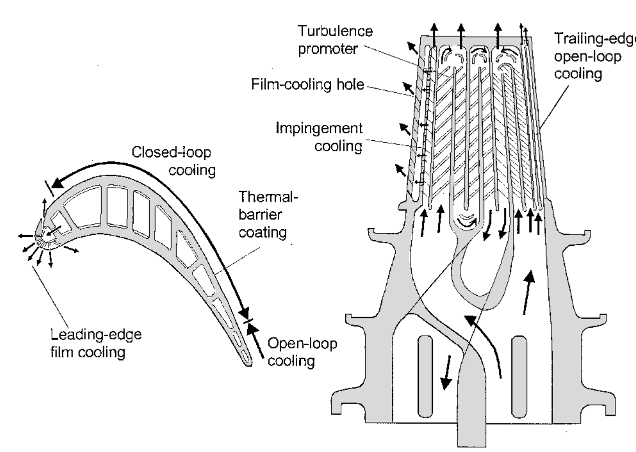


**Fig. 11 Steam flow within hybrid cooling blade.**

## D. Technology Developments

### *1. Cooling Technology*

The success of developing hydrogen-fueled turbines requires new cooling technologies. A hybrid cooling concept for cooling 1973 K (1700°C) turbines has been proposed, rather than using known closed- or open-circuit cooling concepts.

In an open-circuit design, the medium used for cooling internal blades is discharged into the turbine's hot steam path for film and trailing-edge cooling. A closed-circuit concept does not discharge the turbine's cooling medium into its hot gas path, but instead recovers it for use in the system's other components. Both concepts have been evaluated during the design process.

An efficient cooling performance has been achieved by using the open-circuit concept, as reflected in the blade metal's low- and flat-temperature distribution. However, large amounts of cooling medium discharged when quenching the main steam flow lowered the plant's thermal efficiency. The closed-circuit concept is superior from the point of view of thermal efficiency because there is no cooling medium discharged to the main steam flow, although a portion of the blade metal temperature becomes considerably high.

To harness the best of both cooling methods, a hybrid-cooling concept has been developed. We applied the closed-circuit concept for most cooling within the turbine and the open-circuit concept for locations where thermal loading is extremely high. Figures 10 and 11, respectively, show the nozzle and blade designs for this hybrid concept. Figures 12 and 13 show the expected metal temperatures using the hybrid cooling concept.[6]

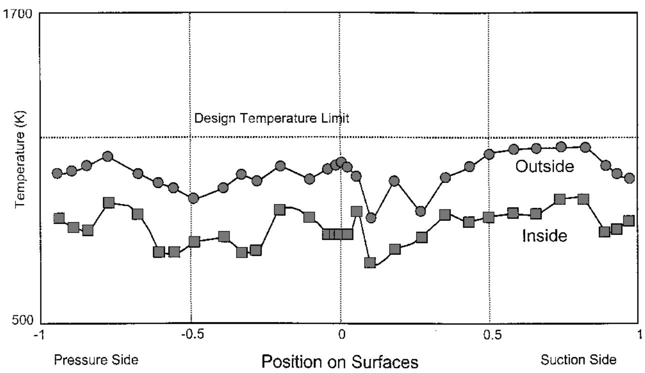


**Fig. 12 Metal temperature of a nozzle.**

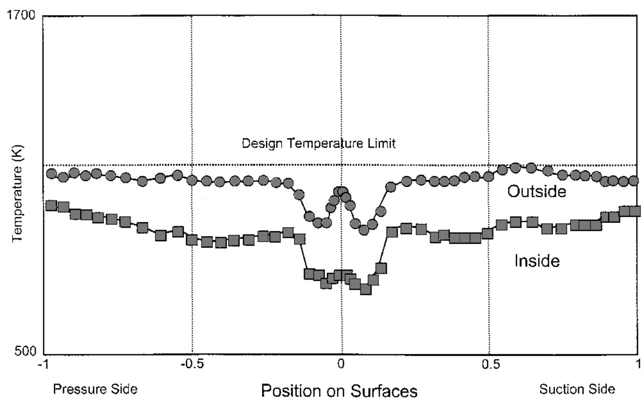


**Fig. 13 Metal temperature of a blade.**

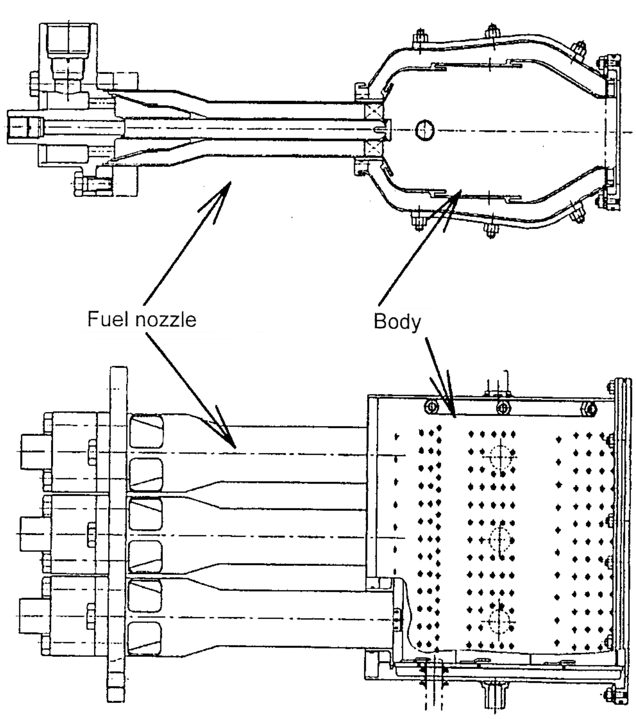


**Fig. 14 Hydrogen–oxygen combustor.**

Successful deployment of the hybrid cooling system requires use of high-temperature materials to assure blade reliability. The design uses single-crystal superalloy and thermal barrier coatings. Because of the high thermal conductivity of the steam used both for the turbine's main hot stream and for its cooling medium, the ceramics used for the thermal barrier coating must be consistent with higher thermal stress and temperatures than were encountered using previous designs.

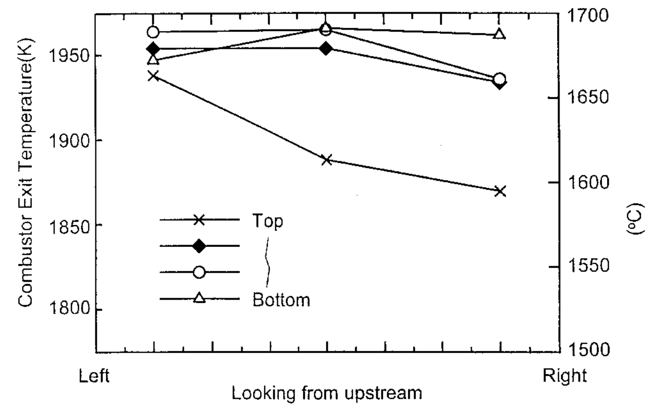


**Fig. 15 Steam temperature at combustor exit.**

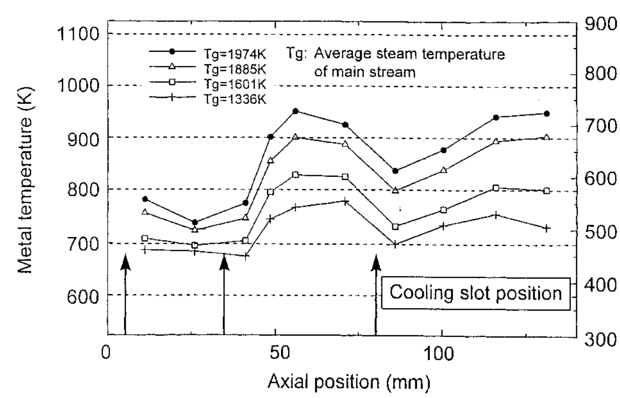


**Fig. 16 Combustor metal temperature (top skin).**

Testing these cooling blades in a high-temperature wind tunnel is the next stage of program, under the WE-NET project.

*2. Combustion Technology*

We are investigating combustion technologies to provide pure hydrogen and oxygen combustion within a turbine's steam flow. Figure 14 shows a combustor developed for a hydrogen-combustion turbine. This design is based on a recent airplane engine, as well as heavy-duty gas turbine combustion technologies for electrical power generation.

Pure hydrogen is supplied directly to the turbine's fuel nozzles and injected. Pure oxygen is also supplied to fuel nozzles, but mixed with part of the steam before injection. Then the oxygen–steam mixture is injected into the turbine body from a fuel nozzle. The remaining steam is used for dilution and body cooling. The mass flow rate of oxygen is controlled to match chemically the amount of hydrogen to make pure steam under stoichiometric combustion conditions.

Full temperature testing has been performed for this combustor. Figure 15 shows a steam-temperature profile at the combustor's exit. A temperature of 1973 K (1700°C) was achieved, and its distribution is remarkably uniform. As shown in Fig. 16, the combustor's body-wall metal temperature remains within the design considerations.[7]

## IV. Conclusion

An advanced Rankine cycle for a hydrogen-combustion turbine has been investigated. The preliminary study indicates that the system reveals a significant potential for use as a future large-scale electrical power generation system fueled by hydrogen. The gross thermal efficiency of the advanced Rankine cycle is expected to be 61.7% (HHV), while its only emission is clean water, that is, free of $CO_2$, $NO_x$, $SO_x$, and other pollutants.

Further development is directed forward to realize such superior performance for a large-scale industrial application by developing a 1973 K (1700°C) turbine-cooling system by applying the hybrid cooling concept. Testing the cooling blades in a high-temperature wind tunnel is planned. Design and testing of a hydrogen–oxygen combustor have been done, confirming the combustor's excellent performance.

## Acknowledgments

The authors are grateful to the New Energy and Industrial Technology Development Organization, Japan's Central Research Institute of Electric Power Industry, and the Japan Power Engineering and Inspection Corporation for their support and suggestions.

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