Study on Micro–disk Gas Turbine System for Future Thermal Energy Utilization Facilities

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Abstract: - On the recent work, it has been selected a model of micro–disk gas turbine cycle or micro–ceramic Shinla gas turbine cycle as part of high temperature nuclear reactor system which has good potential for the application to electricity generation device. Study is carried out using hydrogen as fuel which produced by nuclear reactor system. Within the micro combustion chamber, this hydrogen will be burned by preheated air to maintain high thermal performance. After leaving micro combustor, those hot gases were flowed through the micro–disk gas turbine that be mounted by micro compressor on the same shaft. Furthermore, exhaust gases were transferred to a ceramic heat exchanger to preheat compressed air before entering the micro combustor. The model configuration was investigated on operating conditions at a compression pressure ratio of 2.5 and a micro–disk gas turbine inlet temperature of approximately 1150 K, it would result in a CER as high as about 65 percent and it had achieved a significant reduction in hydrogen consumption up to approximately 38 percent. In closing, this micro–disk gas turbine system could be coupled to Shinla turbine system with solar collector which offer good potential for higher thermal CER, and will be very promising for the future facilities.

Key-Words: - Micro–disk gas turbine, hydrogen, high temperature nuclear reactor

1 Introduction

From the viewpoint of thermal energy systems and environment, a micro–disk gas turbine or a micro ceramic Shinla gas turbine within combined cycles has been selected for the project of high temperature nuclear reactor (HTNR) system, as described based on reference [1]. A schematic diagram of topping Brayton cycle, bottoming Rankine cycle, and nuclear reactor system is essentially shown in the Fig. 1 as an ideal representation of thermal energy utilization system for a plant with the aim to stimulate on the design of future facilities. In this model of topping cycle, the exhaust heat is recovered through a high effectiveness heat exchanger and transported back to a micro–disk gas turbine combustor to enhance the thermal Carnot efficiency ratio (CER) of the cycle. The present paper addresses to investigate a model of a 3 kW micro–disk gas turbine system using hydrogen fuel that produced by nuclear reactor and it will be burned within its micro combustor. The thermodynamic cycle analyses are described to yield in a higher temperature for the heat addition process in the micro combustion chamber.

2 Potential Applications of

2.1 High Temperature Air Combustion

The technology of high temperature air combustion (HiTAC) could be applied in almost all kinds of combustion, power generation, and propulsion systems and has significant potential for utilizing various kinds of gas, liquid, solid, and waste fuels, and can also provide reduction in the physical size. The potential applications of HiTAC have been successfully demonstrated in a number of publications, and in this paper will be discussed for application to a micro–disk gas turbine system as shown in Fig. 1, including the development of its micro combustion chamber. The temperature of combustion air was preheated to higher 500 K. It is well known that the enthalpy of the exhaust gases will effectively increase the temperature in the region of combustor for micro gas turbine, if the heat from the exhaust gas is used to preheat the combustion air.

2.2 Hydrogen Fuel

The opportunity to enable micro–disk gas turbines to operate on gaseous fuel like hydrogen with a low
heating value (LHV) of approximately 120 MJ/kg are presently being undertaken. From the study on the published book by Tsuji et al. [2], the high temperature air is advantageous for stability limit and good combustibility of hydrogen–air flame compared to normal air combustion case. This information can provide useful insights for practical application to the micro combustor.

3 Micro Gas Turbine System

3.1 State of The Art

A micro–disk gas turbine or micro–ceramic Shinla gas turbine is selected as the topping cycle in the present study. The main reason for this selection is that it is able to operate at a high CER or a high thermal efficiency based on state of the art component technology when utilizing HiTAC technology, and this necessitating the use of ceramic in the hot components including micro combustion chamber, heat exchanger, and micro turbine. An expression for the thermal efficiency of the cycle can be seen in references [1], [3], and [4].

All calculations further were based on the study on references [1], [3], [4] and [5]. As demonstrated in the Fig. 2 that the HiTAC cycle gives the benefit of improved the thermal efficiency or the CER over simple cycle for any inlet temperature of micro gas turbine. It can be stated that for a selected point at operating conditions of pressure ratio of 2.5 and micro gas turbine inlet temperature of 1150 K, the CER of cycle could achieve 65 percent when employed the HiTAC technology. The next discussions are main components of the advanced micro–disk gas turbine system.

3.2 Micro Air Compressor

A micro radial compressor of single stage is adopted since it can generate the required the pressure ratio. By assuming an ideal flow, air enters this micro compressor in the axial direction and leaves in the radial direction. The micro radial compressor and micro gas turbine are mounted on the same shaft in which the power developed by micro gas turbine is utilized to drive micro compressor with power of about 55 percent of power output of micro gas turbine. The operating conditions of this micro compressor are listed in the Table 1. The correlation between pressure ratio and CER under gas turbine inlet temperature (TIT) of about 1150 K is plotted in the Fig. 3.

Table 1 Operating Conditions of Micro Compressor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discharge temperature</td>
<td>389 K</td>
</tr>
<tr>
<td>Pressure ratio</td>
<td>2.5</td>
</tr>
<tr>
<td>Required work</td>
<td>3.7 kW</td>
</tr>
<tr>
<td>Adiabatic efficiency</td>
<td>85 percent</td>
</tr>
</tbody>
</table>

3.2 Micro Combustor

The combustion chamber that is modeled in the present paper is a typical can combustor as had been developed and investigated in the past studies because it is the more widely used in most of the micro gas turbines. Its configuration was shown on references [3] and [4]. Operating conditions of this micro combustor are listed in the Table 2. The optimal cross sectional area of the casing is determined as discussed in the published book by Lefebvre on reference [6].

Table 2 Operating Conditions of Micro Can Combustor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combustion loading parameter</td>
<td>127.7 kg/s/atm (1.8^3) m(^{-3})</td>
</tr>
<tr>
<td>Inlet temperature</td>
<td>650 K</td>
</tr>
<tr>
<td>Outlet temperature</td>
<td>1150 K</td>
</tr>
<tr>
<td>Maximum temperature</td>
<td>1178 K</td>
</tr>
<tr>
<td>Fuel–air ratio</td>
<td>0.004</td>
</tr>
<tr>
<td>Combustion efficiency</td>
<td>95 percent</td>
</tr>
</tbody>
</table>

The variation between the burning efficiency ratio (BER) and the combustion loading parameter (CLP) with certain operating condition is illustrated in the Fig. 4. In the real micro combustor, the combustion efficiencies can be correlated as a function of the \(\theta\) parameter, as described on reference [6]. Then by reading off \(\theta\) value at point along a horizontal line within the hatched area in Fig. 5, the combustion efficiency could be obtained to be 95 percent. From cycle analysis, it could be achieved approximately 38 percent reduction of fuel mass flow rate, whereas physical dimensions could be reduced approximately 15 percent.
3.3 Micro–disk Gas Turbine
A schematic of the rotor of a micro–disk gas turbine or micro–ceramic Shinla gas turbine is shown on the reference [4]. It was assembled by the disks of the ceramic that had the same shape and dimensions. Exhaust gases from micro combustor expands through nozzle and rushes out at supersonic speed to impinge on rotor to perform shaft working. The power produced by this micro–disk gas turbine is partially consumed by a micro compressor is proportional to absolute temperature of gas passing through those devices. After leaving this micro–disk gas turbine, the exhaust gases were flowed through a ceramic heat exchanger to preheat compressed air before entering micro combustor. The operating conditions of this micro–disk gas turbine are listed in the Table 3 below.

Table 3. Operating Conditions of Advanced Micro–Disk Gas Turbine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet temperature</td>
<td>963 K</td>
</tr>
<tr>
<td>Outlet pressure</td>
<td>0.1 MPa</td>
</tr>
<tr>
<td>Gas flow rate</td>
<td>0.048 kg/s</td>
</tr>
<tr>
<td>Resulted work</td>
<td>6.7 kW</td>
</tr>
<tr>
<td>Net work</td>
<td>3 kW</td>
</tr>
<tr>
<td>Adiabatic efficiency</td>
<td>85 percent</td>
</tr>
</tbody>
</table>

4 Future Facilities
In the current work, the Shinla turbine cycle had been developed and investigated by Saitoh et al. is employed as bottoming cycle, and it may be added solar collector as a heat source for working fluid. Rotor of this Shinla turbine was installed from disks, which arranged innumerably with the order spacing of micro meter, as illustrated on references [3] and [7]. Based on the use of micro systems technology, a projection of the combined cycles between topping cycle (micro–disk gas turbine system) and bottoming cycle within the HTNR system will enable to be developed into engineering field to improve the overall thermal CER of system.

5 Conclusion
The performance of a 3 kW micro–disk gas turbine model, which will be applied to topping cycle within an HTNR system, has been investigated. For range of operating parameters, the performance of that with HiTAC cycles always indicate in cycle CER superior to that of a simple cycle. And also, the bottoming cycle of solar Shinla turbine system had been discussed on the present paper. Additional work was focused at preliminary development processing of hydrogen production plant using nuclear heat source (in this case is an HTNR) that will be utilized for a micro–disk gas turbine system that could be operated over the cycle CER of about 65 percent, so that it would provide useful information in considering development of the future facilities.

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References:
Hydrogen Production Processes (i.e. Nuclear Reactor)

Fig. 1 A simplified process diagram for integration of a micro–disk gas turbine and solar Shinla turbine into the high temperature nuclear reactor [1, 3, and 4]

Fig. 2 Influence of TIT on the thermal CER for selected cycles

Fig. 3 Effect of pressure ratio on the thermal CER under TIT condition of 1150 K

Fig. 4 Trend line of burning efficiency ratio

Fig. 5 Chart of combustion efficiency