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CONTROL STRATEGIES FOR VHTR GAS-TURBINE SYSTEM WITH DRY COOLING

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ABSTRACT

An original control strategy for very high temperature reactor (VHTR) gas-turbine system with dry cooling against ambient air temperature fluctuation was established in order to enable the freedom of site selection wherever desired without significant drawbacks on the performance. First, the operability of power conversion system and degradation of power generation efficiency were examined considering not only the thermodynamics but also the mechanical efficiency of compressor based on detailed performance map derived from experimental data. Second, control simulations for large ambient temperature fluctuations were conducted by system analysis code with the built-in control strategy. In addition, the sensitivity of power generation efficiency for typical steam cycle with dry cooling to ambient air temperature changes was assessed for the comparison. It was shown that the design goal can be effectively met simply by monitoring and controlling a few of key operating parameters such as reactor outlet temperature, primary coolant pressure. Furthermore, distinctive advantages of the VHTR gas-turbine system over nuclear power plant employing Rankine cycle was demonstrated when installing in inland area.

INTRODUCTION

Site Selection for nuclear power plants with water cooling is mired by their adverse thermal impact on the aquatic environment and consumption of large water quantity from their waste heat discharge. In addition, Fukushima nuclear plant accident elevated the importance of reactor safety against location-specific external events (e.g. tsunami), which resulted in the uncontrolled release of radioactive materials from the Fukushima plant to the environment. Although dry cooling which ultimately discharge the waste heat to the atmosphere is preferable in order to solve above issues simultaneously, several disadvantages, e.g. efficiency penalty on hottest days, high investment cost of cooling towers, etc., are preventing the penetration of the technology to current nuclear power plants.

A very high temperature reactor (VHTR) direct gas-turbine power generation system is well suited for dry cooling because of the high temperature waste heat, which enables to design the cooler with reasonable size, and low amount of rejection heat due to the high power generation efficiency.

One of the issues to be investigated for the use of dry cooling to VHTR system is impact of ambient air temperature fluctuations on the plant efficiency. A large ambient temperature increase, for instance, could alter the bottom dead center of the thermodynamic cycle and the reactor inlet temperature, which would have the consequence of reducing electrical power. This could erode the surge margin of the compressor, leading to potential operational instability.

In the present study, the operability of gas-turbine power conversion system and degradation of the efficiency are examined for a VHTR gas-turbine system. A control strategy is suggested to overcome the operability issues and control simulations for large ambient temperature variations are performed by a system analysis code in order to assess the technical feasibility. The degradation of electric efficiency obtained is compared with a case of typical steam cycle.

Following sections are organized to describe overall of the VHTR gas-turbine system with dry cooling, proposed control strategy, and simulation results.

VHTR GAS-TURBINE SYSTEM WITH DRY COOLING

Overall Description

JAEA has started a design study of VHTR gas-turbine system with dry cooling named GTHTR300A [1] in light of the Fukushima nuclear plant accident. The layout of the system is shown in **Figure 1**, and major specifications are given in **Table 1**. The configuration of primary system is based on GTHTR300 [2] whose waste heat is assumed to be rejected to seawater. The compelling economics was proven with excellent features such as fully passive safety, high thermal utilization with cascade heat

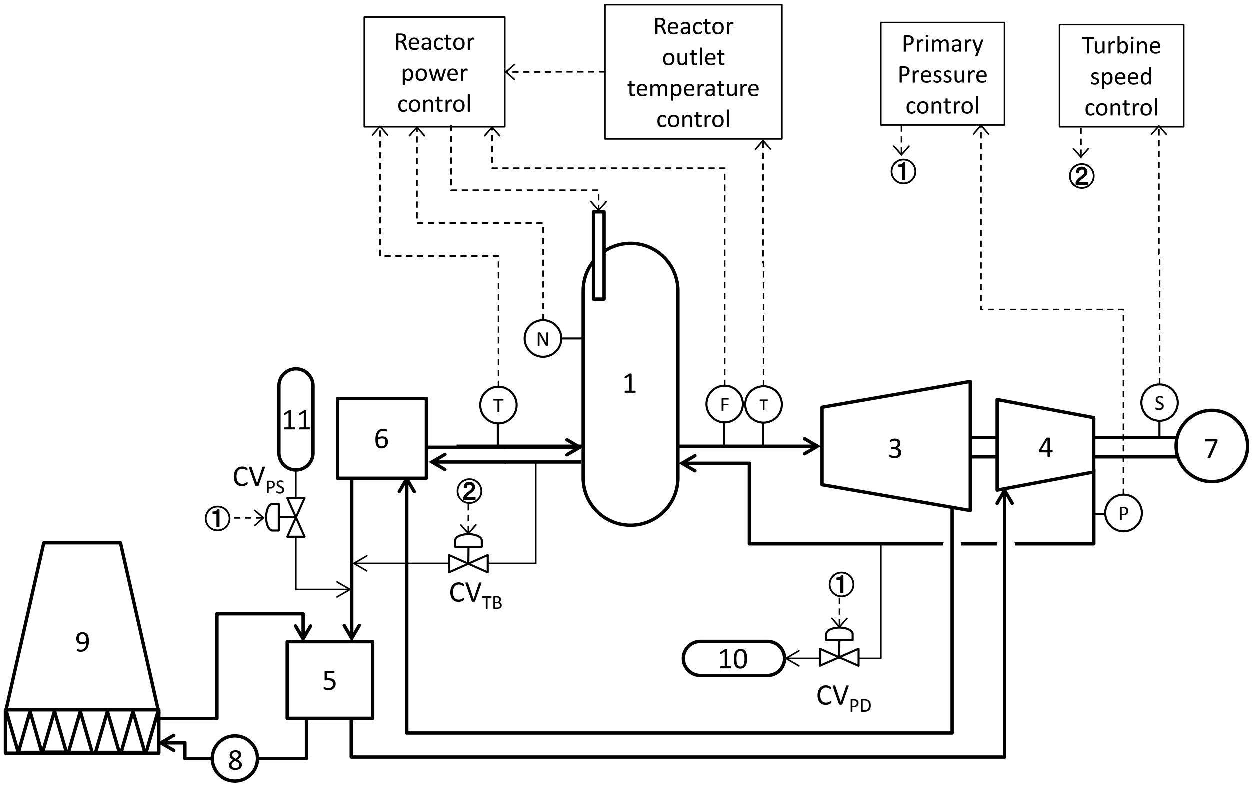

Fig.1 Schematic layout and basic control scheme of GTHTR300A, 1: Reactor, 2: IHX, 3: Turbine, 4: Compressor, 5: Precooler, 6: Recuperator, 7: Generator, 8: Gas circulator, 9: Dry cooling tower, 10: Primary storage tank, 11: Primary supply tank

utilization, and potential of the high temperature heat supply to enable high efficient generation of electricity [3].

Table 1 Major specifications of GTHTR300A

Specifications	Values
Reactor power	480 MWt
Electrical power	224 MWe
Reactor inlet temperature	628^{o}C
Reactor outlet temperature	900^{o}C
Core inlet pressure	5.6 MPa
Average power density	4.3 MW/m^3

The system consists of a reactor, gas-turbine generator module, heat exchanger module, and dry cooling system. The reactor and two modules are connected with coaxial gas duct. The gas-turbine generator module includes helium gas turbine and compressor, and generator connected with a single horizontal shaft by flexible diaphragm couplings. The heat exchanger module consists of recuperator and precooler installed in a vertical steel vessel. The dry cooling system involves intermediate cooling loop, gas circulator and dry cooling tower. Helium coolant heated at the reactor core flows through inside of the coaxial gas duct, expanded by the turbine, flows through the recuperator and precooler, and flows into the compressor. A part of the compressed coolant is guided to a flow path inside the reactor pressure vessel (RPV) in order to cool the RPV, while the remaining compressed coolant is heated at the recuperator and flows back to the reactor. The heat transferred to intermediate cooling loop at the precooler is rejected through the dry cooling tower.

Related technologies for VHTR gas-turbine system have been developed under the HTTR project [4]. Regarding the reactor technologies, the HTTR, Japan's first HTGR, was constructed in Oarai research and development center of JAEA and successfully delivered high temperature helium of 950^{o}C outside its reactor vessel [5]. Also, 50 days continuous high temperature operation was achieved in March 2010 [6]. Regarding the helium gas turbine technologies, aerodynamic test for one third dimensional scale of the full size compressor was conducted to explore the basic helium compressor aerodynamics such as aerodynamic losses particularly near end walls and growth through multiple rotating blade rows, surge predictability, clearance loss and inlet and outlet performance effects. Also, control system design for the magnetic bearing was conducted in order to control higher vibration mode in the continuous operation at the rated speed, and the simulation showed the controllability of the system [7].

Basic Plant Control

A basic plant control scheme of the VHTR gas-turbine system is illustrated in Fig.1. The following is a brief description of fundamental controls;

(1) Turbine speed control

The turbine speed control varies a turbine bypass flow utilizing control valve CV_{TB}. The valve splits the compressor outlet flow into recuperator and precooler inlets corresponding to the manipulated valuable from a turbine speed controller based on proportional-integral (PI) controller. The bypass flow reduces the turbine flow rate while the compressor flow rate is maintained and suppresses the turbine over speed.

(2) Reactor outlet temperature control

Reactor outlet temperature control is employed during the rated operation in order to prevent excess temperature at the reactor outlet due to the small margin of design temperature in structural materials of IHX and turbine blade. The control involves cascade-connected two control loops. The outer loop determines the set point of reactor power for the inner loop corresponding to the error observed in reactor outlet temperature. The outlet temperature is controlled at 850°C by adjusting control rod positions according to the manipulated valuable. However, the withdrawal of control rods is blocked in case that reactor power exceeds the rated value in order to comply with safety regulation.

(3) Primary pressure control

The primary pressure control system consists of high pressurized helium supply and low pressurized helium storage tanks, primary helium supply and discharge flow rate control valves, CV_{PS} and CV_{PD}, and a primary pressure controller.

TRANSIENT RESPONSE DURING AIR TEMPERATURE FLUCTUATIONS

Plant Model

In the present study, GTHTR300 is selected as a reference system for the simulations since the component designs and system configuration of primary cooling system is as same as that of GTHTR300A. Transient simulations for ambient air temperature fluctuations are conducted with a system analysis code developed based on RELAP5 code [8]. The model boundary is defined so as to include the entire primary cooling system. The air temperature fluctuations are mimicked by changing the boundary conditions set at secondary side of precooler inlet. The plant model is constructed based on component designs, and material and thermal-fluids databases obtained under the HTTR project [9, 10]. It is notable that the developed code has the compressor model which incorporates detailed compressor map based on aerodynamic design validated by experimental data [11]. The models and correlations of the modified RELAP5 code can be found in elsewhere [8, 9, 12] and are not repeated here.

Transient Simulation

(1) Increase in ambient temperature

The inlet coolant temperature at the secondary side of precooler is varied from 23°C to 40°C, the highest ambient temperature recorded in Tokyo, for one hour. **Figure 2** depicts transient response of compressor inlet temperature and flow rate, turbine inlet temperature and flow rate, cycle pressure ratio and efficiencies of compressor and turbine, and reactor power and electrical power.

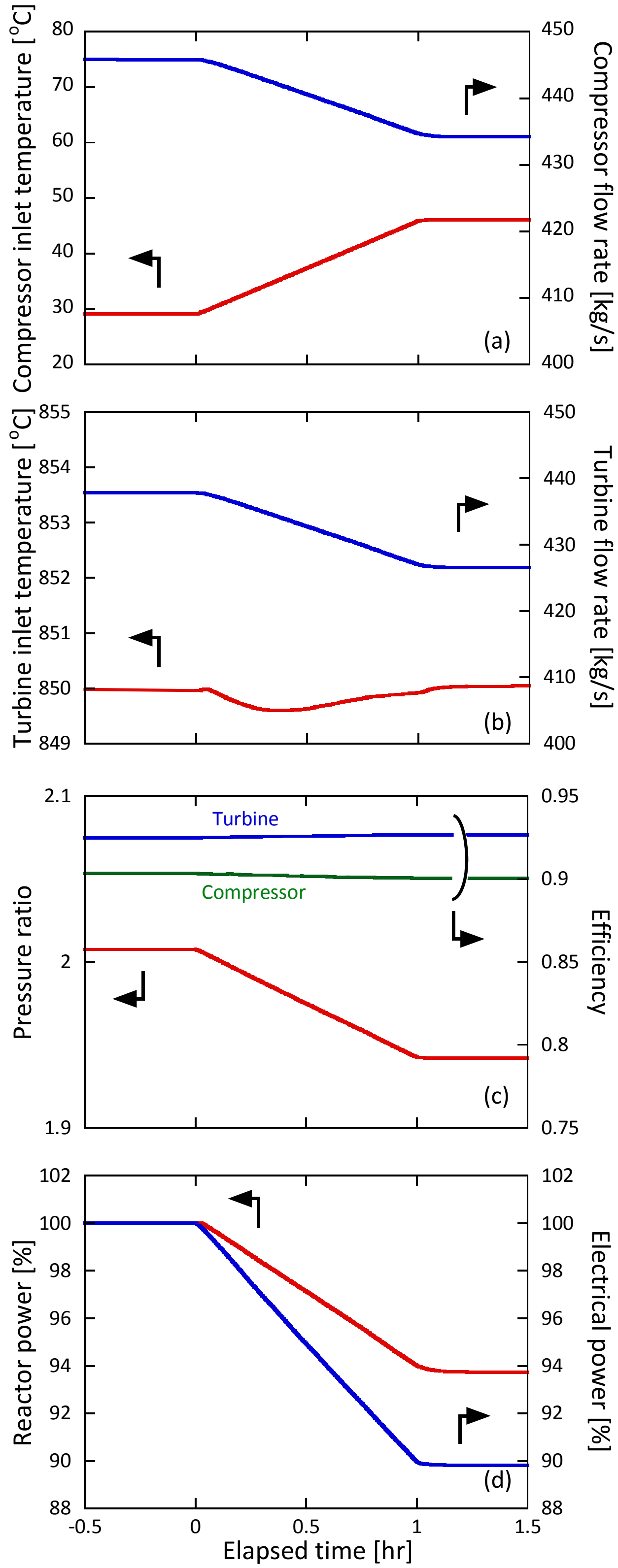

Fig.2 Transient response of major process values during increase in ambient temperature

As the inlet temperature at precooler secondary rises, compressor inlet temperature increases. The increase reduces the pressure ratio, which results in the decrease of primary coolant flow rate. The degradation of compressor efficiency is less than 1%, which is negligible in terms of the cycle efficiency. The temperature increase transfers to reactor inlet, which reduces reactor power from 100% to 94% by the reactor outlet temperature control. In addition, the imbalance of torques between the turbine and compressor occurs since the turbine inlet temperature is kept constant while compressor inlet temperature is increased. As a result, the ambient temperature increase yields reduction of about 10% of electrical power. **Figure 3** shows the history of compressor operating point during the transient. The operating point of compressor shifts to lower region of corrective flow rate, and moves in a direction parallel to the surge limit.

We found that temperature increase initiates reduction of reactor power and difference of torques between the turbine and compressor. These reductions results in undue degradation of power generation rate. Also, the simulation results clarified that compressor operational stability is not affected by the ambient temperature increase.

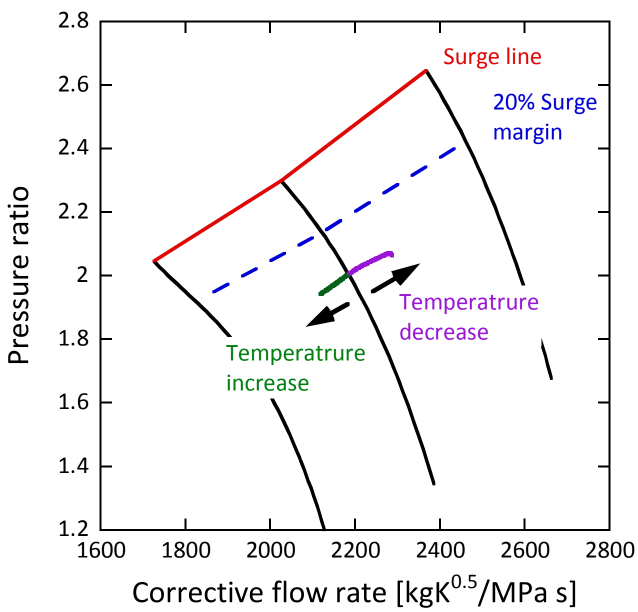

Fig.3 Transition of compressor operating point during ambient air temperature variations

(2) Decrease in ambient temperature

The secondary coolant temperature at the precooler inlet is reduced from 23°C to 4°C, the average winter ambient temperature in Tokyo, for one hour. **Figure 4** depicts transient response of compressor inlet temperature and flow rate, turbine inlet temperature and flow rate, cycle pressure ratio and efficiencies of compressor and turbine, and reactor power and electrical power.

In the first one hour, compressor inlet temperature decreases. As a result, mass flow rate in primary system increases because of the pressure ratio increase. After the completion of temperature decrease in precooler secondary inlet, increase in primary flow rate gradually continues because of primary pressure increase due to the primary pressure control. Compressor and turbine efficiency does not change throughout the transient. Although the temperature reduction at compressor inlet transfers to reactor, reactor power is kept constant by adjusting control rod positions in order to prevent excess power. The electrical power increases for the first one hour due to the increase in pressure ratio. However, the rate ultimately dropped less than rated value corresponding to the transient response of turbine inlet temperature. The transition of operating point starts from rated point, and moves in a parallel direction with the surge line as illustrated in Fig.3.

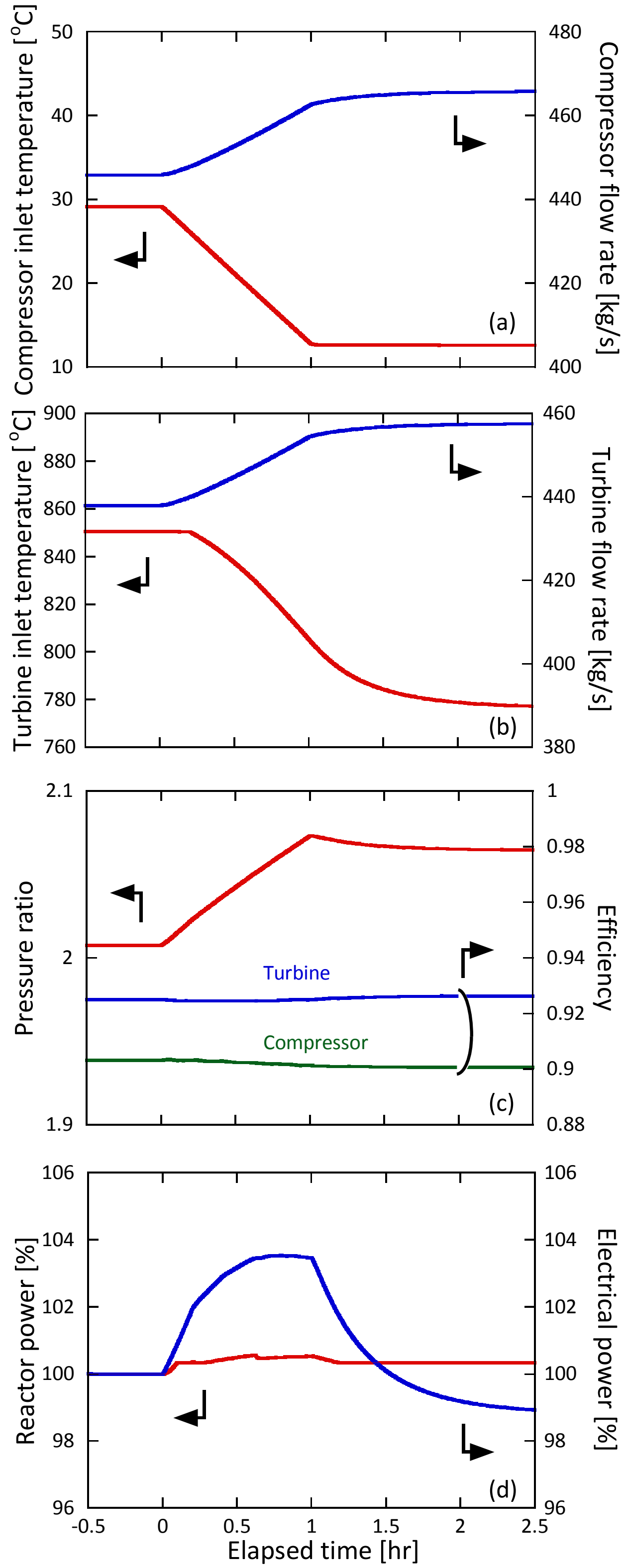

Fig.4 Transient response of major process values during decrease in ambient temperature

It was found that a decrease in ambient temperature results in degradation of electrical power mainly caused by reduction of turbine inlet temperature. On the other hand, the result showed that the compressor is operable with an enough surge margin against ambient temperature decrease.

CONTROL STRATEGY

Mitigation of Electrical Power Degradation

As indicated through the transient simulation, the primary objective of design modifications for control system is to mitigate the electrical power degradation under ambient temperature fluctuations. Corresponding to the transient conditions, we derived the following control strategies in order to meet the design target:

- Maintain reactor power against ambient temperature increase

Though the reduction of reactor power under ambient temperature increase is due to the control rod insertion by reactor outlet temperature control, the reactor outlet temperature should be kept monitored in case of abnormal transients. The approach to achieve the constant reactor power operation is to offset the error of reactor power controller by increasing the reactor flow rate. The offset can simply be done by injecting helium from primary supply tank to the primary cooling system by monitoring the reactor power.

- Maintain reactor outlet temperature against ambient temperature decrease

Not only the reactor power but also reactor outlet temperature should be remained stable in order to take full advantage of cold weather. The approach to offset the error of reactor power controller, that is to reduce reactor flow rate, is also applied for ambient temperature decrease. The helium in primary cooling system is discharged to primary storage tank by monitoring reactor outlet temperature.

The above strategies end up in an inventory control of primary cooling system. The identified control only utilizes two process variables, reactor neutron flux and reactor outlet temperature, which are already included in the current instruments. In addition, the control does not require additional equipment.

Control Simulation

In order to prove that the suggested control scheme is effective in preventing the significant degradation of electrical power, controlled operations under ambient air temperature fluctuations are simulated. The RELAP5 model and calculation conditions used in Figs.2 and 4 are used with adding the suggested control.

(1) Increase in ambient temperature

Figure 5 plots the transient response of compressor inlet temperature and flow rate, turbine inlet temperature and flow rate, cycle pressure ratio and efficiencies of compressor and turbine, and reactor power and electrical power.

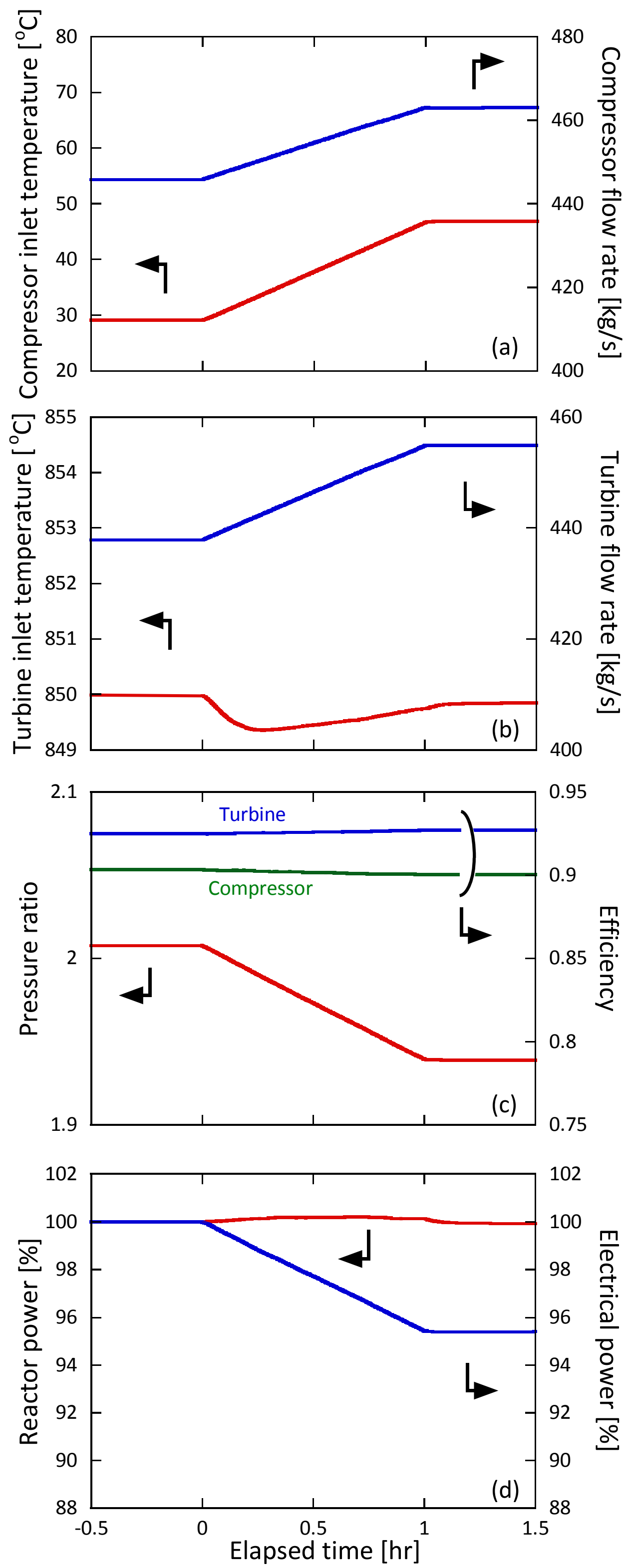

Fig.5 Transient response of major process values during ambient temperature increase with helium injection

Helium is injected from primary supply tank to primary cooling system at 0.09 kg/s for one hour. The helium injection results in increase in primary flow rate. As a result, the flow rate increase offsets the error due to the increase in temperature difference of reactor, and reactor power is maintained constant.

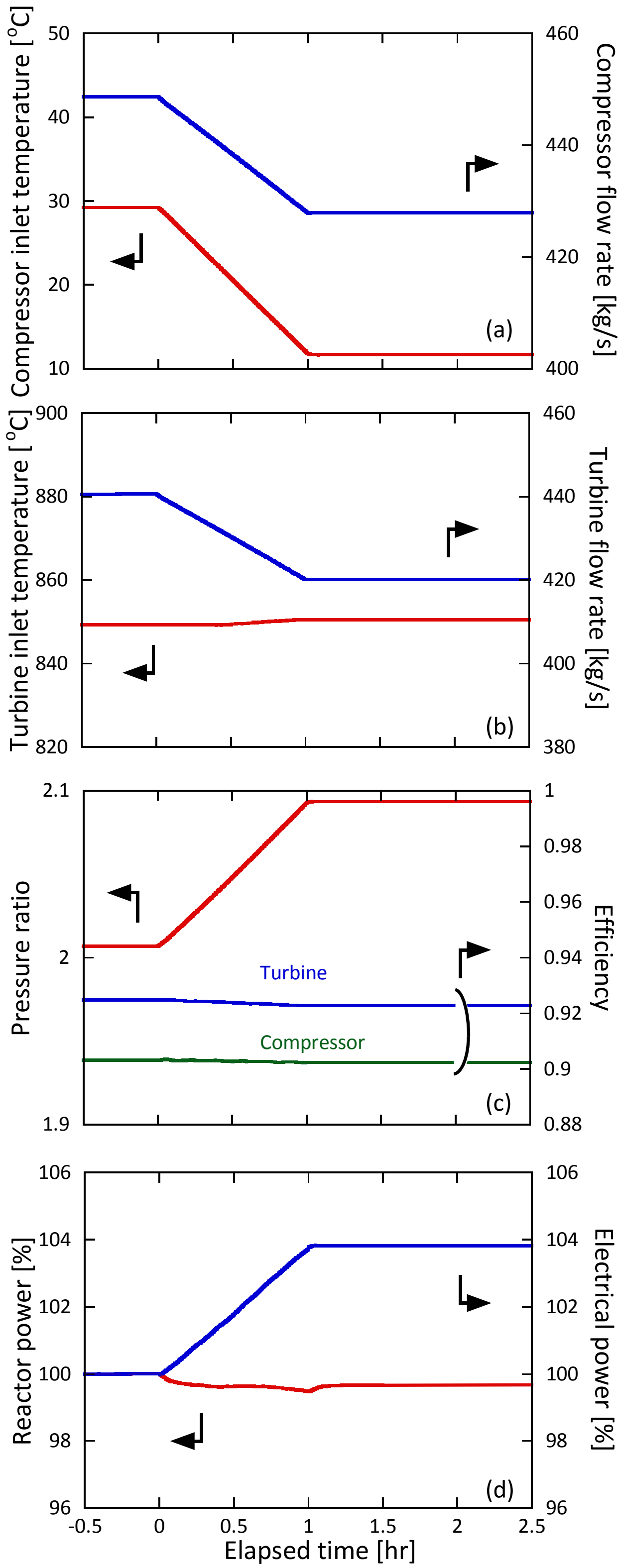

Fig.6 Transient response of major process values during ambient temperature decrease with helium discharge

The variations of turbine and compressor efficiencies are less than 1%, which is negligible in terms of the cycle efficiency. On the other hand, imbalance of torques between the turbine and compressor, which cause degradation of electrical power of 4.6 %, still remains as an unsolved issue.

(2) Decrease in ambient temperature

Figure 6 depicts the transient response of compressor inlet temperature and flow rate, turbine inlet temperature and flow rate, cycle pressure ratio and efficiencies of compressor and turbine, and reactor power and electrical power.

Inventory control withdraws helium from the primary cooling system to helium supply tank at 0.18 kg/s for one hour. The primary coolant flow rate is reduced by the inventory control, and offsets the error of reactor power control. Hence, the reactor outlet temperature is remained at rated condition. Also, turbine and compressor efficiencies do not change during the transient. As a result, electrical power increases approximately 3.8 % because of the reduction in compressor inlet temperature.

A set of control simulations demonstrate that mitigation of electrical power degradation by means of the inventory control is feasible. However, the degradation cannot completely compensated only by the suggested control due to the torque imbalance between the turbine and compressor.

COMPARATIVE STUDY OF THERMODYNAMIC CYCLE SELECTION

A comparative study is conducted to investigate the effect of selecting different power cycles under ambient temperature increase. In the present study, power cycle evaluation for a typical nuclear power plant employing a steam cycle with dry cooling is performed. A simplified configuration of secondary system in a PWR shown in **Fig.7** is utilized for the study. A natural draft tower is assumed as the dry cooling equipment. The reactor power and electrical power of the system is 2970 MWt and 810 MWe, respectively.

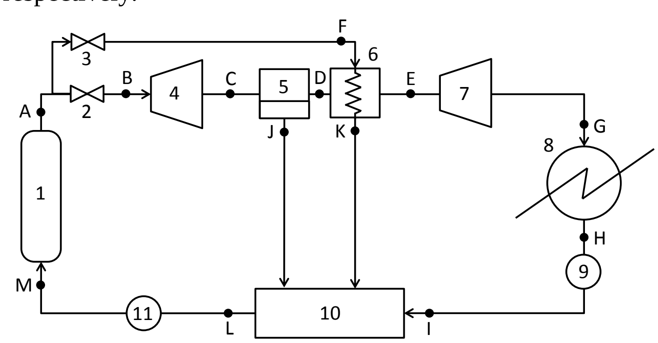

Fig.7 Schematic layout of a secondary system of a typical PWR system [13], 1: Steam generator, 2: Throttle valve, 3: Turbine bypass valve, 4: HP turbine, 5: Moisture separator, 6: Reheater, 7: LP turbine, 8: Condenser, 9: Condensate pump, 10: Feed water heater, 11: Feed water pump

First, a simulation model to evaluate thermodynamic of the system is developed under MATLAB environment [14] utilizing steam table database [15]. Second, the cycle efficiency of the system at rated condition is investigated using state points shown in **Table 2** obtained from a literature [13]. Third, the cycle efficiency is re-evaluated with increasing the ambient temperature 17°C, which is consistent with the case of ambient temperature increase as mentioned in the previous section. In order to taken into account the degradation of turbine efficiency, the following equation [16] is utilized:

$$\eta_T = \eta_{lim} + (\eta_{max} - \eta_{lim})\left[2\frac{\tau_{max}}{\tau} - \left(\frac{\tau_{max}}{\tau}\right)^2\right] \qquad (1)$$

Here, η_T is turbine efficiency, η_{lim} is asymptotic turbine efficiency limit, η_{max} is turbine efficiency at rated condition, τ_{max} is the pressure ratio at rated condition, and τ is the pressure ratio at the condition to be evaluated. The heat supply at steam generator is fixed. The condenser temperature is defined as ambient temperature plus initial temperature difference [17].

Table 2 State points at the secondary system of a typical PWR

State points	Temperature [°C]	Pressure [bar]	Quality	Flow rate [kg/s]
A	271	56	1	1200
B	264	50	0.997	1100.4
C	184	11	0.891	1100.4
D	184	11	1	981.6
E	253	11	1	981.6
F	264	50	0.997	99.6
G	39	0.07	0.882	981.6
H	39	0.07	0	981.6
I	39	15	0	981.6
J	184	11	0	118.8
K	264	50	0	99.6
L	73	11	0	1200
M	74	70	0	1200

Figure 8 shows the transition of cycle efficiency under ambient temperature increase. As can be seen, the maximum degradation of electrical power is approximately 36 %.

Comparing gas turbine power generation cycle to steam power generation cycle, the degradation rate of electrical power for steam power generation cycle is more than three times larger than that of gas turbine cycle. The difference of impact by the ambient temperature increase is significantly large because of the large turbine efficiency reduction in the Rankine cycle. Since the condenser pressure in Rankine cycle depends on the temperature condition. Hence, back pressure at LP turbine rises as the temperature rises, and with a resultant reduction in turbine efficiency.

CONCLUSIONS

An original control strategy for a VHTR gas-turbine system with dry cooling against ambient air temperature fluctuation was established in order to enable the freedom of site selection wherever desired without significant drawbacks on the performance. A fundamental control to mitigate the degradation of electrical power is identified corresponding to the findings obtained through transient simulations. Control simulations are performed in order to assess the technical feasibility of the suggested control. In addition, the sensitivity of power generation efficiency for typical steam cycle with dry cooling to ambient air temperature changes was assessed for the comparison. Conclusions drawn are as follows:

- Ambient temperature increase in VHTR gas-turbine system induces the reactor power decrease since the temperature increase transfers to reactor inlet, which results in control rod insertion.
- Decrease in ambient temperature with constant reactor operation results in degradation of electrical power because of turbine inlet temperature decrease.
- The suggested control, which monitors neutron flux, reactor outlet temperature and controls primary coolant pressure is effective to mitigate the degradation of electrical power.
- Electrical power reduction of 4.6% is observed due to the torque imbalance between turbine and compressor under ambient temperature increase of 17°C.
- Compressor operating point moves in a direction parallel to the surge line. The compressor operational stability is not affected by ambient temperature fluctuations.
- The degradation of electrical power for a typical nuclear power plant employing Rankine cycle with natural draft cooling tower is 36%, which is approximately three times larger than that VHTR gas-turbine system.

It was shown that the design goal can be effectively met only applying a simple fundamental control without reliance on additional equipment. The results demonstrated that deployment of VHTR gas-turbine system in inland area is promising. Further studies should be made for recovering the electrical power to rated condition under ambient temperature increase in terms of economics.

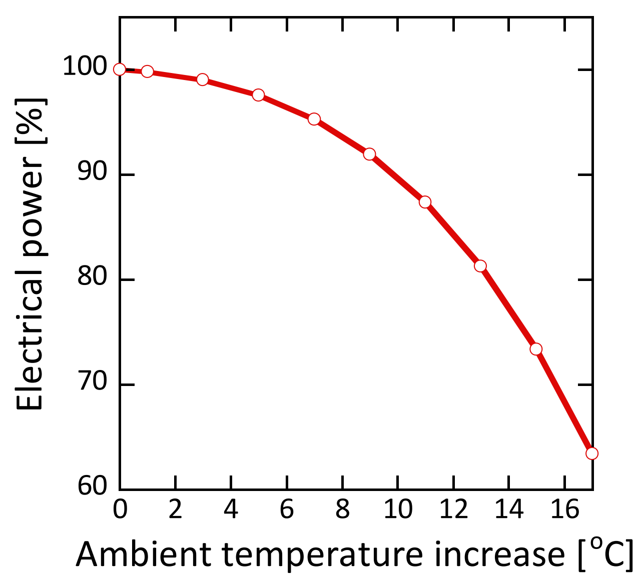

Fig.8 Degradation of electrical power under ambient temperature increase

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