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Load-following Operations of VHTR Gas-turbine Cogeneration System for Developing Countries

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ABSTRACT

This paper presents an original control system design that enables electrical load-following with GTHTR300C, a nuclear gas turbine cogeneration plant under development by JAEA for potential deployment in developing countries. The plant operates on a closed Brayton cycle directly heated by the helium gas coolant of a small-sized Generation IV High Temperature Gas-cooled Reactor (HTGR), also known as Very High Temperature Reactor (VHTR).

The control system is designed to follow daily electric load by taking advantage of the unique operation characteristics of the nuclear reactor and closed cycle gas turbine and the direct interface of the nuclear heat source and gas turbine engine. The control system integrates several fundamental control methods and permits wide-ranging load follow at constant reactor power and high thermal efficiency, which maximizes plant economics.

Control simulation of the overall plant system to follow daily load changes representative of developing countries are performed using a system analysis code in order to demonstrate a technical feasibility of the system. The observable operation parameters essential to the system control are identified that include reactor outlet temperature, turbine inlet temperature, gas turbine rotational speed, and so on. The simulations results show that the load-follow can be effectively carried out by monitoring these parameters and controlling them with suitable control apparatus.

INTRODUCTION

Recently, nuclear power generation is gathering worldwide attention since it does not release carbon dioxide from the thermal energy production and enables to preserve fossil resources. Especially, developing countries express a strong interest in deployment of nuclear energy in the field of electricity generation.

One of the challenges for expanding the proportion of nuclear power generation is stability of electricity grids since drastic decrease in proportion of fossil fire and hydraulic power plants, which are the primary functions to match the electricity demand in peak time, can disrupt the balance of electricity supply and demand in the grids. Especially, when newly introducing nuclear power plants to the area which belongs to small grids such as developing countries, scheduled load-following operation would be imposed in order to prevent the degradation of grid frequency and voltage induced by small amount of load rejection; nevertheless nuclear power plants do not prefer partial load operation because of the high-capital and low-operating costs, and low power generation efficiency due to pressure loss increase in the steam turbine.

This paper presents an original control system design which offers electrical load-following capability at constant reactor power and high thermal efficiency with GTHTR300C [1], a nuclear gas-turbine cogeneration system employing a small-sized Generation IV High Temperature Gas-cooled Reactor (HTGR) known as Very High Temperature Reactor (VHTR). Control simulations of scheduled daily load-following operation in representative developing countries are performed to demonstrate the efficacy of design.

The following sections are organized to discuss the overall system of GTHTR300C, the control system design, the system analysis code, and the simulation results of load-following operation using the GTHTR300C.

OVERALL DESCRIPTION OF GTHTR300C

The GTHTR300C cogeneration system employs a helium-cooled, graphite-moderated, thermal-neutron-spectrum reactor with nominally 950°C core outlet temperature and 600 MW (thermal) power. The system is based on technologies developed under the High Temperature engineering Test Reactor (HTTR) project [2]. The HTTR is Japan's first HTGR constructed in Oarai research and development center of Japan Atomic Energy Agency and successfully delivered high temperature helium of 950°C outside its reactor vessel [3]. Also, 50 days continuous high temperature operation was achieved in March 2010 [4]. Based on the technologies, the system offers compelling economics with excellent features such as fully passive safety, high thermal utilization with cascade heat utilization, and potential of the high temperature heat supply to enable high efficient generation of electricity and process heat. **Figure 1** shows a layout of the system, including the reactor, intermediate heat exchanger (IHX), direct gas turbine power conversion unit, process heat application plant and heat exchangers. **Table 1** and **Table 2** show base parameters and state points (cf. Fig. 1) of the GTHTR300C during cogeneration operation, respectively.

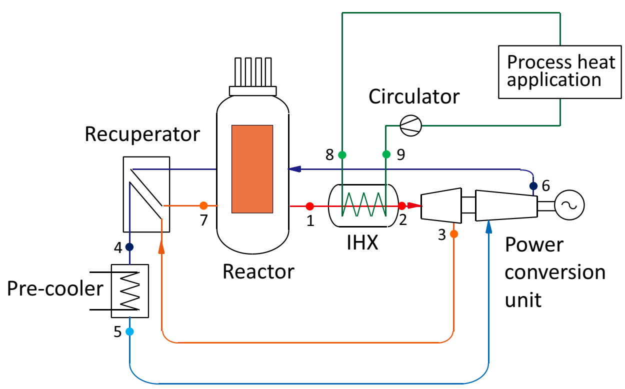

Fig.1 Schematic layout of the GTHTR300C

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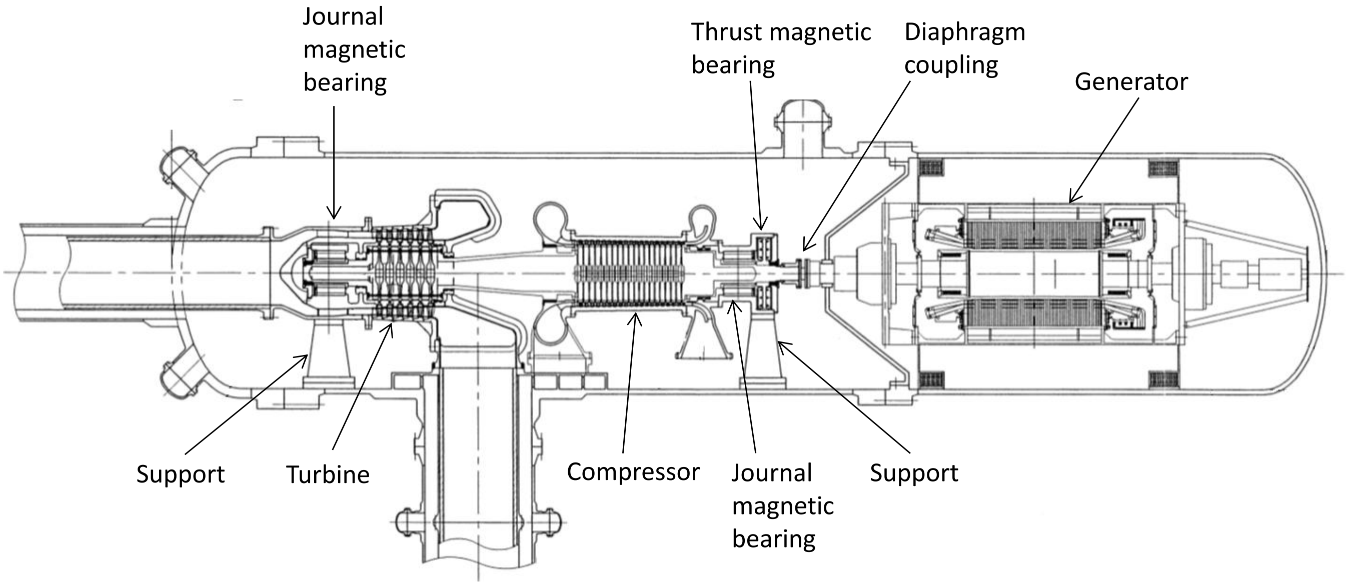

Fig.2 Horizontal view of the GTHTR300C power conversion unit [5]

Helium coolant heated at the reactor core flows through outside of the hot gas duct and provides heat to the secondary cooling system at the IHX. The coolant 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. Rejected waste heat of Brayton cycle at the precooler is used for district heating or desalinations. The secondary helium coolant heated at the IHX flows through inside of the hot gas duct and provides heat to process heat applications. After providing the heat, the coolant is compressed by the secondary circulator and flows back to the IHX through outside of the hot gas duct. The vessel cooling system (VCS) is installed for residual heat removal in case of loss of forced cooling conditions.

Table 1 Base parameters of the GTHTR300C

Specifications	Values
Reactor power [MWt]	600
Electricity generation [MWe]	202
IHX heat rate [MWt]	170
Reactor inlet /outlet temperature [^{o}C]	594/950
Reactor pressure [MPa]	5.0
Power density [W/cc]	5.4

Table 2 Base state points of the GTHTR300C

State points	Pressure [MPa]	Temperature [^{o}C]
1	5.02	950
2	4.99	850
3	2.67	614
4	2.61	159
5	2.58	26
6	5.16	134
7	5.12	594
8	5.09	900
9	5.15	500

Figure 2 shows the horizontal view of power conversion unit in GTHTR300C. The direct Brayton cycle power conversion unit is comprised of an axial-flow helium gas turbine and compressor, and generator which are connected in a single shaft and installed horizontally in order to reduce the bearing loads. Electric power of 202 MWe is produced at high efficiency of 46.8 % [5] during the rated operation. JAEA has conducted research and developments for the helium gas compressor and rotor magnetic bearing in order to achieve design target. Regarding the compressor technology, 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. Regarding the magnetic bearing technology, control system design 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 [6].

Heat rate of 170 MW is supplied to industrial production plants for hydrogen or steam through the IHX at the rated operation. One of the promising candidate for the process heat application is a hydrogen production utilizing Iodine-Sulfur process [7], which is a method of hydrogen production by splitting water thermo chemically without CO_2 emission. The process performs closed-cycle operation which reuses the reactant except water repeatedly within the process. JAEA has been conducting research and developments related to control technologies, efficiency improvements, and component designs which can endure corrosive circumstances [8]. The results showed the feasibility of high efficient, mass production of hydrogen in commercial stage.

COTROL SYSTEM DESIGN

Control Strategy

The following strategies are employed for a control system design to maximize plant economics while minimizing concerns given from the load-following operation:

(a) Maintain constant reactor thermal power operation

Maintaining constant reactor thermal power during the load-following operation is favorable in order to maximize the plant economics. The approach to achieve the constant reactor power operation is to assign produced heat at the reactor to the power conversion unit and process heat application plant appropriately. During off-peak time, GTHTR300C is operated as a cogeneration mode producing both electricity and process heat. In peak time, heat supply rate to the IHX is reduced to zero while electricity is increased to match the demand. Unlike the electricity, industrial products such as hydrogen can be stored and can be supplied complying with demand of users. Although, plant availability of the process heat application plant will decrease, the reactor plant availability remains high even in the off-peak time. The capital cost of the process heat application plant would be only a fraction of the reactor plant [9]. In addition, electricity price in peak time could be several times of the price in off-peak time [10]. Hence, the operation strategy has substantial economic advantage over the partial load operation of reactor.

(b) Reduce thermal stress generation of reactor internal components

Thermal stress generation in reactor internal components due to the temperature variation should be minimized since accumulation of damage due to the thermal fatigue results in replacements of the components. The approach is to employ a constant reactor outlet temperature control with maintaining the reactor flow rate. Since reactor inlet temperature is remained stable by the precooler, which serves as a passive thermal absorber, temperature variation inside the reactor would be suppressed without manipulating control rods excessively.

(c) Reduce thermal stress generation of turbine blades

Turbine inlet temperature should be controlled within acceptable temperature during the load-following operation since non-cooling turbine blades are employed in the GTHTR300C in terms of reliability enhancement. The approach is to control the turbine inlet temperature by introducing lower temperature coolant into turbine inlet using a control valve. The location of the control valve would be discussed in the following section.

(d) Keep the high-efficient power generation

Turbine operating parameters such as turbine inlet temperature and pressure ratio should be maintained during the load-following operation in order to keep the plant power generation efficiency high. The approach is to control the primary cooling system inventory, namely, to control the mass flow rate of primary cooling system. The control enables to maintain cycle pressure ratio and temperatures conditions in the primary cooling system. As a result, operating points of the turbine and compressor are maintained at optimal design values.

Control System Design

In accordance with the strategies discussed above, an automated control system is designed. **Figure 3** shows the basic control scheme of GTHTR300C. The following fundamental control methods are integrated:

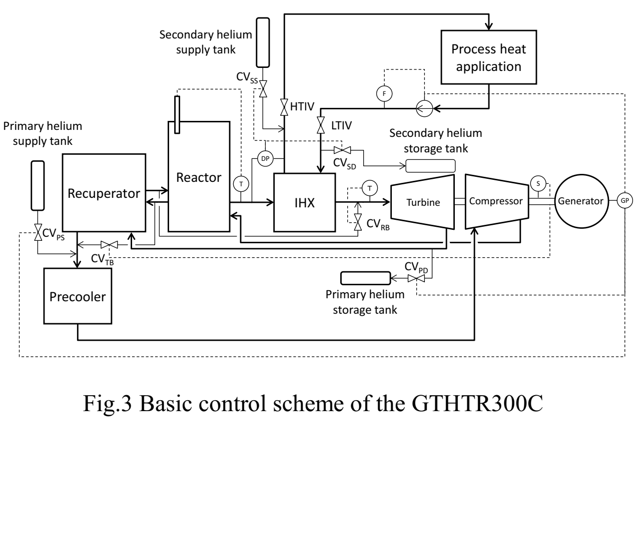

Fig.3 Basic control scheme of the GTHTR300C

(1) Inventory control

The inventory control system consists of high pressurized helium supply and low pressurized helium storage vessels, primary helium supply and discharge flow rate control valves, CV_{PS} and CV_{PD}, and a primary pressure controller. **Figure 4** shows the block diagram of controller and controller parameters are shown in **Table 3**. Control valves installed between the vessels and primary cooling system adjust the supply and discharge flow rates from and to the primary cooling system corresponding to the signal from primary pressure controller. Pressure set points are scheduled in accordance with electrical load schedule. As for the load reduction, primary coolant is discharged from compressor outlet, while coolant is supplied to precooler inlet during the load increase.

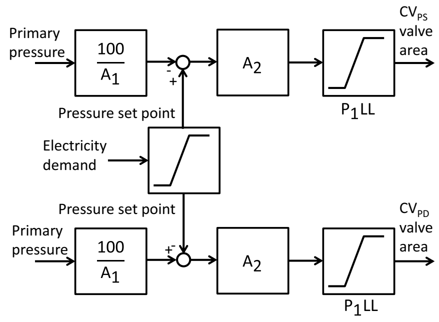

Fig.4 Block diagram of inventory controller

(2) Turbine inlet temperature control

The turbine inlet temperature control system consists of a reactor bypass flow control valve, CV_{RB}, and turbine inlet temperature controller. **Figure 5** shows the block diagram of controller and the controller parameters are shown in Table 3. The flow rate control valve is installed between the reactor inlet and turbine inlet. According to the pressure increase due to the inventory control, the flow rate at control valve is adjusted by the control signal from turbine inlet temperature controller.

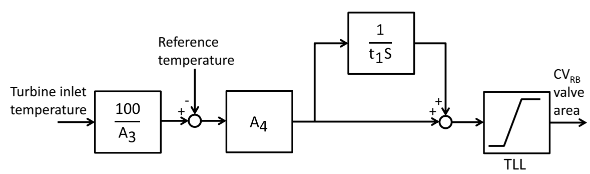

Fig.5 Block diagram of turbine inlet temperature controller

(3) IHX heat rate control

The IHX heat rate control system consists of a secondary helium gas circulator and an IHX heat rate controller. **Figure 6** shows the block diagram of controller and the controller parameters are shown in Table 3. Corresponding to electrical load schedule, the IHX heat rate is adjusted by controlling the secondary coolant flow rate.

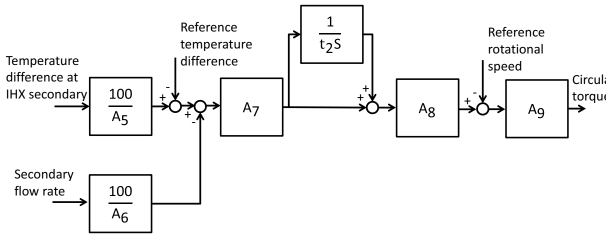

Fig.6 Block diagram of IHX heat rate controller

Table 3 Controller parameters of controllers

Controller parameters		Values
A_1	Conversion factor	5.16
A_2	Proportional gain	38
A_3	Conversion factor	1123
A_4	Proportional gain	1
A_5	Conversion factor	586
A_6	Conversion factor	120.0
A_7	Proportional gain	0.6
A_8	Conversion factor	7.6
A_9	Conversion factor	1604
A_{10}	Conversion factor	377
A_{11}	Proportional gain	6
A_{12}	Conversion factor	0.15
A_{13}	Proportional gain	38
P_1LL	Saturation lower limit	0.2
P_2LL	Saturation lower limit	1.0
TLL	Saturation lower limit	0.7
t_1	Integral gain	60
t_2	Integral gain	60
t_3	Integral gain	60

(4) Turbine speed control

The turbine speed control system consists of a turbine bypass flow control valve, CV_{TB}, and turbine speed controller. **Figure 7** shows the block diagram of controller and the controller parameters are shown in Table 3. The bypass flow control valve installed at the compressor outlet splits the compressor outlet flow into recuperator and precooler inlets corresponding to the control signal from turbine speed controller. The bypass flow reduces the turbine flow rate while the compressor flow rate is maintained and suppresses the turbine over speed.

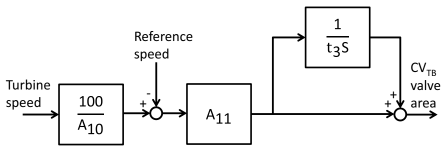

Fig.7 Block diagram of turbine speed controller

(5) IHX differential pressure control

The IHX differential pressure control system consists of high pressurized helium supply and low pressurized helium storage vessels, secondary helium supply and discharge flow rate control valves, CV_{SS} and CV_{SD}, and an IHX differential pressure controller. **Figure 8** shows the block diagram of controller and the controller parameters are shown in Table 3. The IHX differential pressure is controlled at approximately 0.15 MPa [1] by adjusting the flow rates at the control valves installed between the vessels and primary cooling system due to the signal from the IHX differential pressure controller. Corresponding to the primary coolant pressure decrease, secondary coolant is discharged from circulator outlet, while coolant is supplied to circulator inlet during the primary pressure increase.

In addition, reactor outlet temperature control is incorporated in order to prevent excess temperature at the reactor outlet due to the small margin of design temperature limit in structural materials. The reactor outlet temperature control system consists of control rods and reactor outlet temperature controller. The control rod positions are determined by the signal from the controller referring the reactor core temperature difference and flow rate. Notice that the control rod would not move if the reactor flow is kept constant.

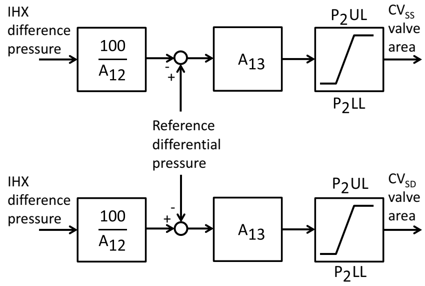

Fig.8 Block diagram of IHX differential pressure controller

CONTROL SIMULATION

Control simulations of scheduled daily load-following operation for representative small grids in developing countries are performed to confirm the efficacy of the control system design. Almaty in Kazakhstan and Jeddah in Saudi Arabia are selected for the present study. The following section describes the brief description of system analysis code used in the simulation, and control simulation results.

System Analysis Code

A system analysis code developed by JAEA is used for the present control simulation. The code based on RELAP5 MOD3 code [11], which was originally developed for light water reactor systems, was improved in order to extend its applicability to VHTR cogeneration systems [12, 13]. The code covers the reactor power behavior, thermal fluid characteristics of helium coolants and two-phase steam-water mixture, turbomachinery performances, chemical reactions and phase change in the process heat exchangers and control system characteristics. Mass continuity, momentum conservation and energy conservation equations with two-fluid model, and continuity and energy conservation equations are considered for the reactor system and process heat exchangers, respectively. An angular momentum conservation equation is considered for the shaft rotational dynamics. The reactor power is calculated by point reactor kinetics equations considering reactivity feedbacks. The code was validated by the experimental data obtained in the HTTR operations and mock-up test facility [12, 14].

Figure 9 shows a nodalization diagram of the model used in the simulation. The reactor consists of a reactor core, flow path inside the permanent reflector (component R1), reactor upper plenum (component R2), reactor lower plenum (component R5), RPV cooling flow path (component 12), control rod guide tube flow path (component R23), support plate cooling flow path (component R18), reflector block, and RPV. The reactor core is grouped into a hot channel (component R4) and average channel (component R3). The recuperator is represented by a high pressure side (component R20), low pressure side (component R11) and heat transfer plate. The precooler is represented by a helium side (component R13), pressurized water side (component R26), and heat transfer tube. Inlet of pressurized water side of precooler is set as boundary conditions of temperature and flow rate, and the outlet is set as a boundary condition of pressure. The IHX is represented by a primary side (component R7), secondary side (component R25) and heat transfer tube. Notice that inlet of IHX secondary side is set as boundary conditions of temperature and flow rate, and the outlet is set as a boundary condition of pressure for the simplification. The co-axial hot gas ducts which connect reactor, heat exchangers and power conversion system are represented by inner pipes (component R6, R9 and R21), outer pipes (component R15, R17 and R19), inner and outer tubes. A set of heat transfer correlations is incorporated corresponding to their flow geometries and regimes. Performance maps of the helium gas turbine and compressors are incorporated based on the aerodynamic design of GTHTR300C [15].

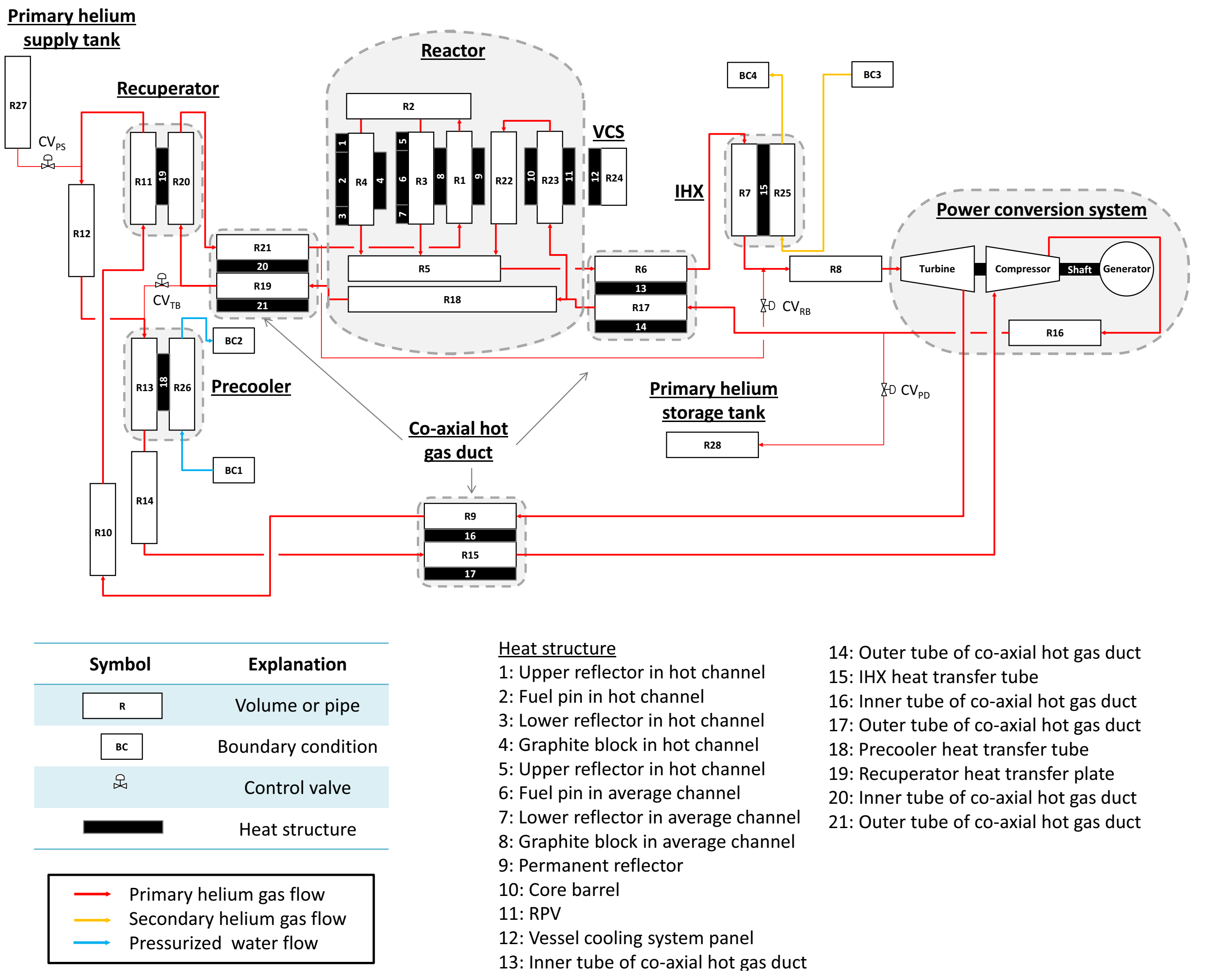

Fig.9 Nodalization of GTHTR300 model

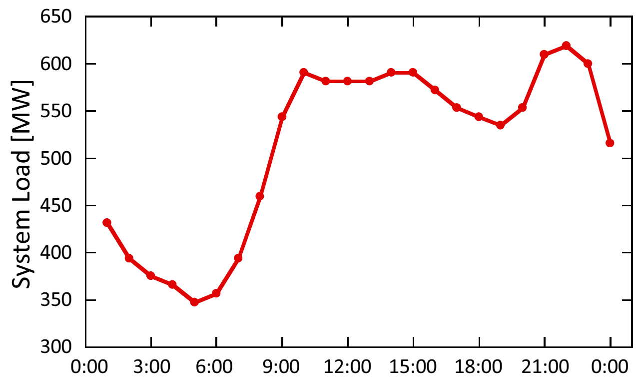

Fig.10 Daily load curve in Almaty on June 15, 2005 [16]

Daily Load-following Operation in Kazakhstan

Almaty is the largest city in Kazakhstan and the electric load accounts for 50 % of total demand in southern Kazakhstan. One of the issues related to power supply in Almaty is environment degradation due to NOx and SOx gas emissions from old cogeneration plants fueled by coal and oil. Also, chronic power shortage is reported [16]. Because of the small amount of total electric demand and large daily load variation, load-following operation with VHTR gas-turbine cogeneration systems can offer a potential solution to the present issues.

Figure 10 shows the daily load curve in Almaty on June 15, 2005 which recorded the minimum power demand in the year [16]. As can be seen, the maximum load of the day is approximately 600 MW and the daily variation amount is approximately 40 % of the maximum load.

Based on the daily load curve, scheduled operation curve is created as shown in **Fig. 11**. For the simplification, the data is reordered to be started from 1 a.m. assuming the load from 11 p.m. to 0 a.m. in the next day is same as the current day. Relative electricity generation and heat supply rates, which are shown in y-axis of Fig.11, are defined as percentages of maximum available rates. In case of Almaty, daily variation amount is large and exceeds the maximum load-following capability which is determined by design pressure of components in the GTHTR300C. Hence, increase in heat supply rate from rated value is scheduled in order to increase the options of operation mode. Notice that the maximum load-following capability can be increased in proportion to the design pressure of the components in the system.

Helium coolant of 0.1 MPa is injected to primary cooling system in order to provide a margin for turbine speed control through CV_{PS} before the start of load-following operation. The injection can be completed within 2 minutes, which is a reasonable length of time for the preparation. Primary cooling system pressure is controlled in order to control turbine flow rate corresponding to the load schedule from a power-feeding direction center, as shown in **Fig. 12**. Helium supply and discharge are conducted through CV_{PS} and CV_{PD} and the maximum injection and discharge rates are only 0.35 kg/s and 0.36 kg/s, respectively.

Electricity generation rate varies corresponding to the planned load schedule, while IHX heat rate is controlled to assign the generated heat in reactor appropriately, as can be seen in **Fig.13**. Firstly, electricity generation rate is reduced down to 170 MWe and IHX heat rate is increased up to 186 MW simultaneously. After 4 hours of the reduction, electricity generation rate is increased up to 283 MWe while IHX heat rate is reduced to zero.

The increase and decrease of IHX heat rate initiate the decrease and increase in turbine inlet temperature, respectively, as can be seen in **Fig.14**. Although, the turbine inlet temperature decrease of 10°C results in cycle pressure ratio decrease, the variation is less than 1 %, which is negligible as seen in Fig.14. On the other hand, increase in turbine inlet temperature initiates CV_{RB} actuation in order to maintain the turbine inlet temperature, and the coolant flow bypasses the reactor as shown in **Fig.15**. The bypass flow rate up to 133 kg/s enables to mitigate the reactor flow increase within 2 % of the rated value. As a result, the reactor power is almost stable and the variation is within 5 %, which is negligible, as can be seen in **Fig.16**. The reactor outlet temperature is also well controlled whose variation is only 0.6 % of the rated value.

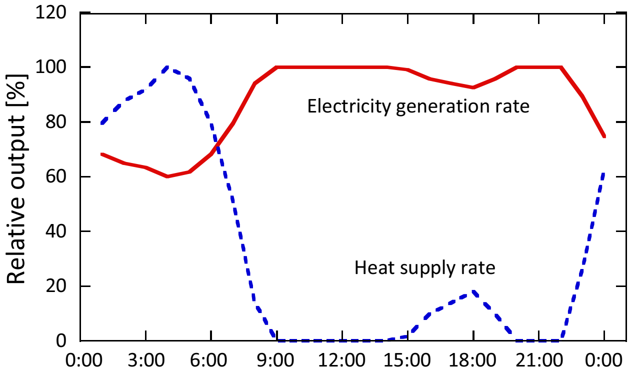

Fig.11 Scheduled load curve for load-following operation in Almaty

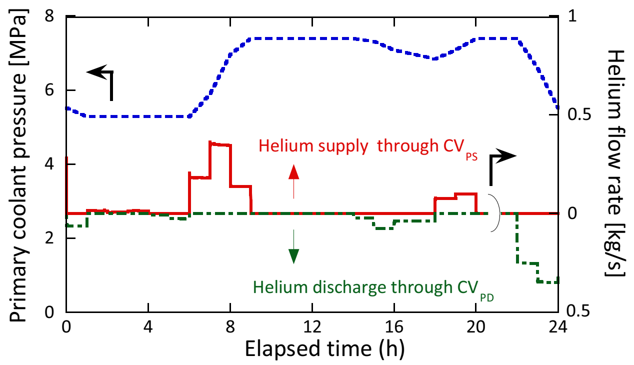

Fig.12 Transient response of primary coolant pressure and flow rate at primary helium supply flow rate control valve during the load-following operation for Almaty

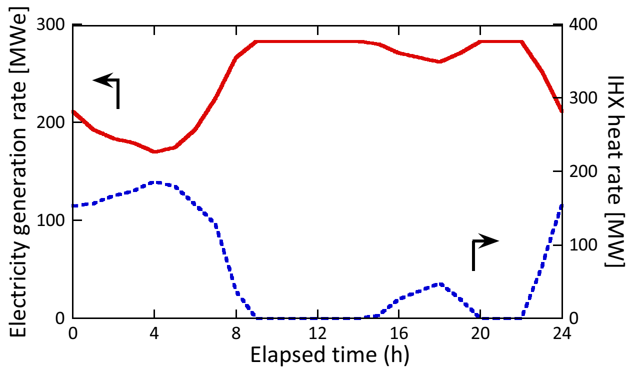

Fig.13 Transient response of electricity generation rate and IHX heat rate during the load-following operation for Almaty

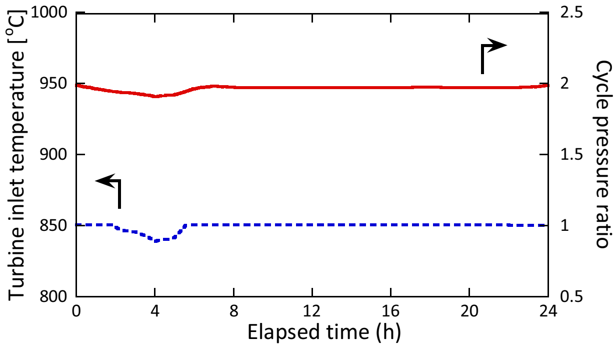

Fig.14 Transient response of turbine inlet temperature and cycle pressure ratio during the load-following operation for Almaty

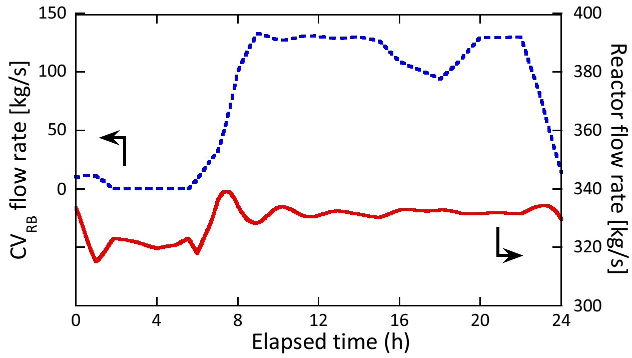

Fig.15 Transient response of flow rate at reactor bypass flow rate control valve and reactor flow rate during the load-following operation for Almaty

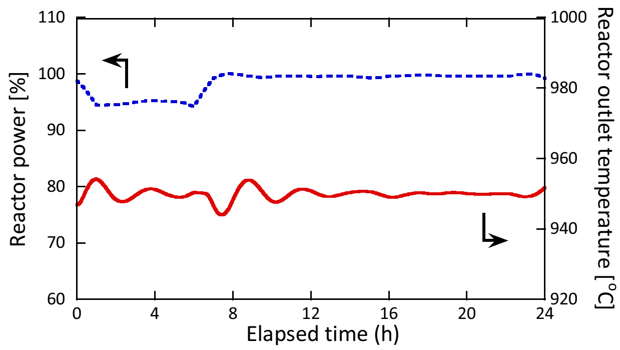

Fig.16 Transient response of reactor power and reactor outlet temperature during the load-following operation for Almaty

Daily Load-following Operation in Saudi Arabia

In Saudi Arabia, massive increase in electric demand has been seen due to the improvement of life quality and increase in population. Thus, major power shortfall is concerned in the near future. Also, there is increased concern of serious water shortage since 95 % of the land is desert and rocky hills. In addition, preservation of fossil fuel used for power generation is crucial since the economics of country depends heavily on exports of crude oil and petroleum products [17]. VHTR gas-turbine cogeneration systems are expected to contribute to solve these problems because of the capability of simultaneous power and water production with employing load-following operation.

In the present study, Jeddah, which locates on the coast of Red Sea and belongs to a relatively small grid named Western Operation Area, is selected for an example. **Figure 17** shows the daily load curve in Jeddah on February 1, 2006 [18]. As can be seen, the maximum load of the day is approximately 3000 MW and the daily variation amount is approximately 25 % of the maximum load.

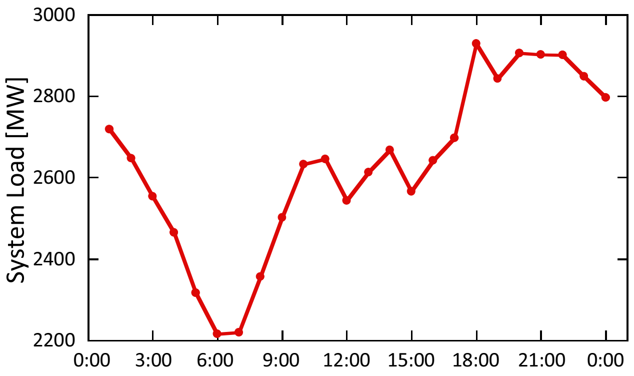

Fig.17 Daily load curve in Jeddah on February 1, 2006 [18]

Based on the daily load curve, scheduled operation curve is created as shown in **Fig. 18**. For the simplification, the data is reordered to be started from 6 a.m. assuming the load from 1 a.m. to 5 a.m. in the next day is same as the current day. Relative electricity generation and heat supply rates, which are shown in y-axis of Fig.18, are defined as percentages of maximum available rates.

Before the start of load-following operation, helium coolant of 0.1 MPa is injected to primary cooling system in order to provide a margin for turbine speed control through CV_{PS}. The injection can be completed within 2 minutes, which is a reasonable length of time for the preparation. Primary cooling system pressure is controlled in order to control turbine flow rate corresponding to the load schedule from a power-feeding direction center, as shown in **Fig. 19**. Helium supply and discharge are conducted through CV_{PS} and CV_{PD} and the maximum injection and discharge rates are only 0.18 kg/s and 0.12 kg/s, respectively.

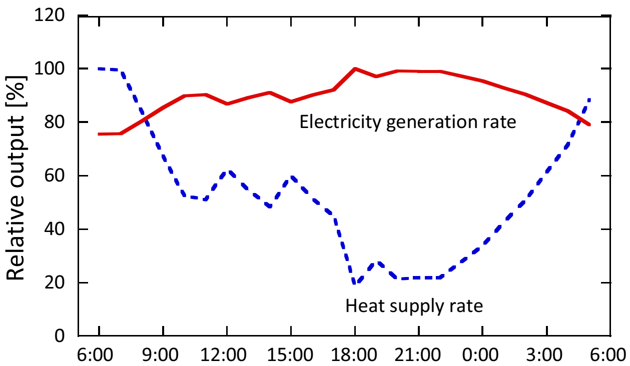

Fig.18 Scheduled load curve for load-following operation in Jeddah

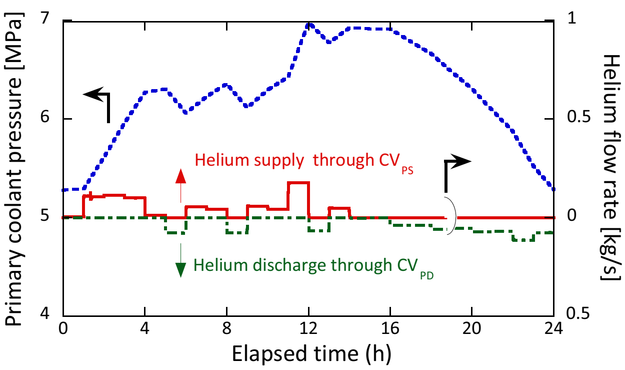

Fig.19 Transient response of primary coolant pressure and flow rate at primary helium supply flow rate control valve during the load-following operation for Jeddah

Electricity generation rate varies corresponding to the planned load schedule, while IHX heat rate is controlled to assign the generated heat in reactor appropriately, as can be seen in **Fig.20**. The maximum electricity generation rate is 267 MWe while IHX heat rate is reduced down to 36 MW.

The decrease of IHX heat rate initiate the CV_{RB} actuation in order to maintain the turbine inlet temperature, and the coolant flow bypasses the reactor as shown in **Fig.21**. Small fluctuation of the reactor flow appears at the initiation time of CV_{RB} actuation due to the limiter circuit of control, and the increase is within 6 kg/s. During the load-following operation, the reactor bypass flow rate reaches approximately 103 kg/s and the reactor flow rate is maintained virtually constant. The maximum variation of reactor flow is approximately 6 kg/s, that is 2 % of the rated value. As a result, reactor power variation is sufficiently small, and reactor outlet temperature is maintained stable as shown in **Fig. 22**. Simultaneously, turbine inlet temperature, which assumed to be increase due to the IHX heat rate reduction, is almost kept constant and its maximum variation is within 7°C as can be seen in **Fig.23**. In addition, the cycle pressure ratio is kept constant, and therefore electricity generation efficiency is maintained high.

CONCLUSION

The control system design for the GTHTR300C cogeneration system is shown to offer effective load-following capability by taking full advantage of the unique operation features of the VHTR, the closed Brayton cycle and most importantly the direct thermodynamic gas interface of the nuclear heat source and the gas turbine cycle.

The control simulation following scheduled daily load curves representative of relatively small grids in developing countries are carried out using a system analysis code. The results of the simulation show that the design goal can be effectively met by monitoring and controlling constant a few of selected operating parameters of the reactor and gas turbine such as reactor outlet temperature, turbine inlet temperature and speed. The original control methods proposed are shown technically feasible to allow load-following operation while maintaining constant reactor power and high thermal efficiency in a VHTR power and heat cogeneration system, which also benefits the plant economics.

The load-following capability from such cogeneration system would greatly improve the stability of electricity grid when an increase in the share of nuclear power productions is sought in remote regions and in developing countries that are characteristic of small electric grid connection.

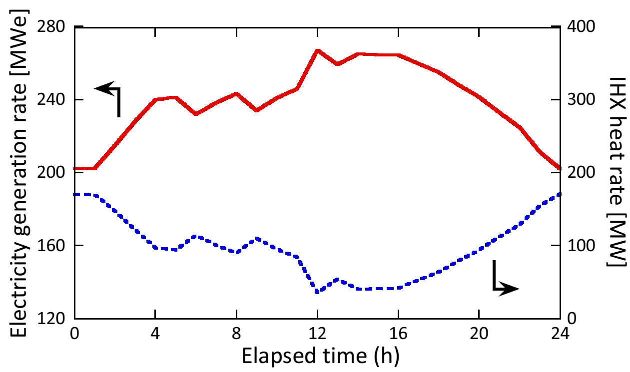

Fig.20 Transient response of electricity generation rate and IHX heat rate during the load-following operation for Jeddah

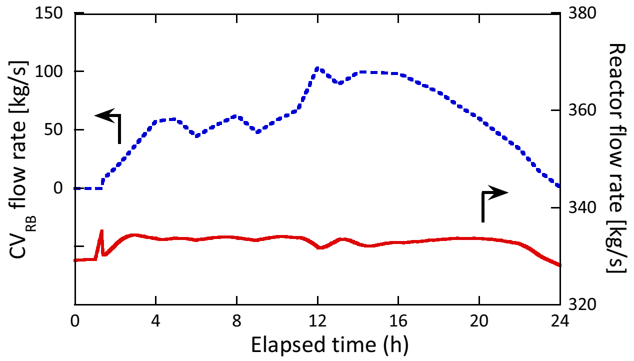

Fig.21 Transient response of flow rate at reactor bypass flow rate control valve and reactor flow rate during the load-following operation for Jeddah

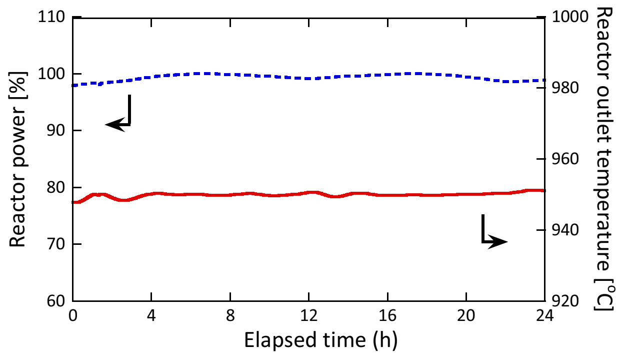

Fig.22 Transient response of reactor power and reactor outlet temperature during the load-following operation for Jeddah

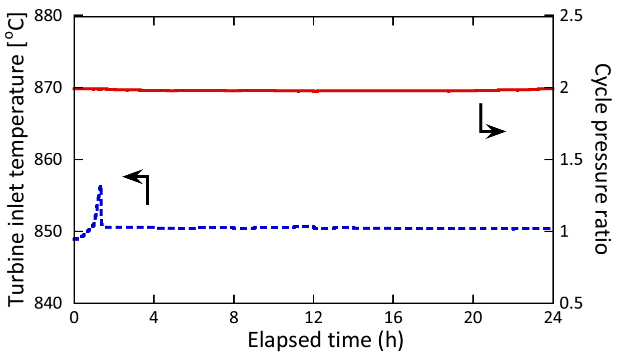

Fig.23 Transient response of turbine inlet temperature and cycle pressure ratio during the load-following operation for Jeddah

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