Evaluation of HTGR Cogeneration Plant Load-Follow Operations Capability

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ABSTRACT

HTGR as a high temperature (950°C) nuclear heat source can efficiently generate variable energy products including electricity, hydrogen, and process heat. This paper describes the plant design of a modular (600MWt) HTGR system cogenerating electricity and process heat and discusses its operational feasibility of electric load follow using a new control scheme. The system generates electricity by direct cycle gas turbine and process heat through a topping high temperature intermediate heat exchanger. The process heat is transported via a secondary heat transport loop to such an industrial plant as hydrogen or steam production plant. The electricity generated supplies external grid output while meeting in-house power consumption in the reactor and the production plant. The load follow operations are performed by controlling the reactor coolant inventory while keeping the primary system thermal conditions including reactor power, reactor temperature, and turbine temperatures unchanged. This control strategy is designed to achieve high thermal efficiency in a wide range of part electric load and, by minimizing thermal transient of the reactor, to enable response to rapid load follow demand. The newly proposed control strategy is evaluated by simulation of a bounding load-follow event. The results of the simulation are discussed.

1. INTRODUCTION

High temperature gas reactor (HTGR) is a helium-cooled, graphite-moderated, and thermal-neutron reactor with various fuel cycle options [1-4]. The commercial reactor designs are generally rated in small size of up to several hundred megawatts per unit and with full passive nuclear safety. The reactor has the ability of delivering 950°C nuclear heat, in contrast to about 300°C by existing commercial reactors. The technology is well developed and near-term deployable. Due

to these technology characteristics, the HTGR mission is widely seen to be dedicated cogeneration of electricity and high temperature process heat or hydrogen, which serves to expand the role of nuclear energy beyond power generation [5-11]

The HTGR offers an attractive energy option for those process industries that consume significant power and heat. For steel mills, for instance, the HTGR could supply hydrogen for direct thermochemical reduction of iron ore and electricity for charging steel furnace. For chemical and petroleum industries, the HTGR would supply large amounts of process steam and hydrogen for hydrogenation and oil refining. Being small and passively safe, the HTGR is equally well suited to energy supply in remote areas or developing countries without large electric grid. Besides electricity, these areas have a wide range of process heat demands. Japan Atomic Energy Agency is researching and developing HTGR cogeneration systems for industrial applications in Japan [12] and in developing markets [13].

Cogenerating high temperature heat and power represents a new mission for nuclear energy and presents design challenges. Can an HTGR match the energy supply performance afforded by fossil-fired combined heat and power plant in the markets of interest? For instance, is the HTGR cogeneration flexible enough to follow load demands such as daily peak electricity, which is essential to remote users? In general, it is neither technically simple nor economically desirable to vary thermal operating parameters of a nuclear reactor both rapidly and widely to engage in considerable load changes.

This study evaluates the Gas Turbine High Temperature Reactor of 300 MWe Cogeneration (GTHTR300C) system design for load following. Section 2 discusses the potential load requirements for the design. Section 3 describes the plant design of GTHTR300C including control system based

on newly-proposed control methods. Section 4 discusses simulation results of the whole plant performance against a bounding load following event. The conclusions of the study are given in Section 5.

2. LOAD-FOLLOW REQUIREMENT

Industries like steel and oil producers consume intensive heat and power and are looking for more efficient and cleaner energy sources to cut costs and CO₂ emissions. A 4,000 ton/day direct reduction steelmaking plant, currently the world's largest scale, is estimated to consume about 800 MWt of heat and 200 MWe of electricity in the furnaces and operation utilities. Two HTGRs suffice to supply all energy and hydrogen needs of the process while making it free of CO₂ emission.

In both developed and developing economies, small-sized nuclear reactors are increasingly considered to help meet industrial and remote energy needs that can involve significant load following. In 2009, electric demand in Japan peaks in summer by 50% over winter while daily peak is even more pronounced. The load can climb by about 1% of base load per minute during early hours of a business day. On the other hand, the winter electricity demand in Kazakhstan is 50% more than in it consumes summer. In arid regions, electricity demand is both seasonal and diurnal.

Nuclear reactor plants are capital intensive such that construction expense makes up one third or more of cost of energy production. Economics would thus prescribe a combined base load even in frequent load following. Assuming that historical or anticipated load curves for industrial or remote user are known, it is possible to size a cogeneration plant to generate maximum electricity, since it must be supplied in real time, and use the balance of plant thermal capacity to generate heat. Any shortfall and surplus of thermal energy in real time should be managed by stand-by heater or storage of heat-processed product to ensure supply. Note that this strategy certainly has ramification on the economics of a specific cogeneration site beyond the scope of this general study. Moreover, it is necessary for the cogeneration plant to follow the rate of electricity peaking in the load curves. The rates typically include $\pm 5\%$ per minute and $\pm 10\%$ step of the base electric load.

3. HTGR PLANT DESIGN

JAEA developed and has, since 1998, been operating the 30MWt and 950oC high temperature engineering test reactor [14, 15]. It is based on the know-how gained in the HTTR and additional development of nuclear plant technologies including power conversion and heat process equipment that JAEA has developed the basic design for the commercial GTHTR300C, a Generation-IV HTGR system to cogenerate electricity and heat or hydrogen at high thermal efficiency [16-17]. As schematically shown in Figure 1, the GTHTR300C consists of a 600MWt HTGR, an intermediate heat exchanger (IHX) for 900oC process heat supply to a high-temperature hydrogen production plant, a direct-cycle recuperated gas turbine for reactor coolant circulation and power conversion, and a precooler to discharge the waste heat of the power conversion cycle. Although not shown, the waste heat of 160oC removed in the precooler can supply

desalination and district heating without penalty to power generation. The closed intermediate helium loop circulates hot helium from IHX to the distant hydrogen plant and completes necessary environmental and material separation between the nuclear and chemical plants.

The helium gas turbine is a single-shaft, axial-flow design having six turbine stages and twenty compressor stages. The gas turbine is rated at 280 MWe and 3,600 rpm and drives a synchronous generator from shaft cold end. The machine design mostly complies with established industrial practice in heavy-duty combustion gas turbine. The hydrogen production plant is ideally based on a thermochemical iodine sulfur (IS) process or a steam electrolysis process. The IS process involves three inter-cyclic thermochemical reactions for the decomposition of water molecules into hydrogen and oxygen gas products. The process consumes water as the only material feedstock and all other process materials used are chemical reagents. The heat and electricity consumed by the process are drawn in-house as shown in Figure 1. The heat supports the endothermic decomposition reactions and the electricity drives the electrolyzers, gas circulators, pumps and other utilities.

The GTHTR300C design includes a new proposal of control strategy to accomplish cogeneration load following. Two prerequisites of the proposal are 1) that the reactor temperature and thermal power remain unchanged in order to permit rapid and frequent control including daily peak electricity generation and 2) that the efficiency of the power generation remains constant. The cogeneration ratio is adjusted by varying the heat rate through the variable speed circulator in the IHX secondary loop and by simultaneously regulating turbine power output to follow electric load but without changing vital gas turbine aerodynamic performance parameters such as gas velocity, temperature, and pressure ratio. This is found to be achievable by regulating turbine mass flow rate indirectly by monitoring and controlling turbine inlet temperature, T_t , constant through flow valve CV4 and by regulating turbine inlet pressure, P_r , to follow electric load through primary coolant inventory control by flow valves IV1 and IV2, which connects to helium storage and supply tanks.

In terms of equipment sizing, the greater the controllable range of cogeneration load following is required, the larger the size of flow valve CV4 will be. On the other hand, the faster the load following is desired, the larger the inventory control valves IV1 and IV2 would be. While the inventory valves are found to be of small in all practical control needs, the flow valve CV4 can be large in a large plant with extensive range of load following because of the low pressure head or large flow coefficient associated with the specific installation arrangement. In this case, multiple units of smaller size operating in parallel have installation and operation advantages over a large-size single valve unit, including control sequencing and redundancy as well as that the number of valves in the multi-valve unit can be added or subtracted according to the extent of load following as required by the plant user.

HTGR core thermal power will in general respond to change in coolant flow due to resulting temperature change from affected coolant cooling and further negative reactivity

Figure 1: Cycle process and control of the GTHT300C, an HTGR plant designed for cogeneration for electricity and high-temperature heat or further hydrogen.

feedback of temperature. The good performance of this design feature has been obtained in the tests of the HTTR. As a result, GTHT300C takes the same approach to controlling the core power during load following, that is, through coolant control and reactivity feedback. Use of control rods is only necessary in startup and shutdown, in long-term operation at reduced core temperature, and to compensate fuel burnup.

4. SIMULATION RESULTS

A plant system simulation model is constructed by building the component models and material database specific to the GTHT300C and then merging them with the standard models and solver of the RELAP5 MOD3. Description on the development of the simulation model can be found elsewhere [19, 20] and is not repeated here. The reactor is represented by nuclear fission of point neutron kinetics with various sources of reactivity feedback, fuel blocks with power generation and heat transfer in hot and average coolant channels, the reflector blocks with coolant channels, reactor upper and lower gas plena, control rod flow channels, core support cooling flow path, and RPV and vessel cooling flow path. The recuperator model includes the high pressure fluid, low pressure fluid, and metal plate surface. The precooler model includes the helium side, cooling water side, and helical-coil metal tube surface. The IHX model contains the primary coolant side, the intermediate loop helium side, and metal tubular surface. The flow of the intermediate helium loop can be controlled by varying the helium circulator speed with variable speed motor to regulate the process heat rate of the IHX. Heat transfer correlations

are incorporated corresponding to the types of heat exchangers used in the plant. The major component physical models and material properties for the reactor, the heat exchangers, and the helium gas turbine have been validated by the HTTR operations and additional mock-up tests [11, 13].

Table 1. Base heat and power cogeneration parameters

	Reactor	IHX heat rate	Gas turbine
Power	600 MWt	170 MWt	203 MWe
Temperature	950°C outlet	900°C heat sent out	850°C turbine inlet
Pressure	5 MPa	5 MPa	5 MPa
Gas flow	325 kg/sec	81 kg/sec	325 kg/sec

The base heat and power ratio, which is application specific, sets maximum heat rate of the plant. The base cogeneration parameters are summarized in Table 1. In this cogeneration mode, the reactor outlet coolant of 950°C enters the primary side of the IHX and heats the secondary helium to 900°C. About 170 MWt of heat is transferred in the IHX and carried by the intermediate loop to the hydrogen process, which produces 0.64 million Nm³ (58 tonnes/day) hydrogen per day. The balance of the reactor thermal power is converted to electric power in the direct cycle gas turbine plant. About 12% of gross electricity generated is used in-house to supply the reactor plant and hydrogen plant uses.

Figure 2 shows the results of following electric demand increase, Ld, at 5% of base load per minute. Starting from the

Figure 2: Simulation results of electric load following at 5%/min.

base cogeneration parameters in Table 1, power generation is raised by opening inventory control valve IV1 to increase helium inventory in the primary circuit, which raises the turbine inlet pressure, P_t , to 7 from 5 MPa. This is accompanied by reducing the hydrogen plant heat rate through reducing the intermediate loop flow circulation rate by the variable speed gas circulator. This causes the primary exit temperature of the IHX to increase. The load follow valve, CV4, is activated to maintain turbine inlet temperature constant by directing colder helium flow from the recuperator to mix with the hotter gas exiting the IHX so that the turbine inlet temperature is maintained closely to the rated 850°C as shown in Figure 2. The maximum power generated increases to 280 MWe, which is achieved in around 7 minutes. In the mean time, use of flow valve CV1 can effectively control the stability of turbine rotational speed with only minimum valve modulation. To return to the base cogeneration parameters, the above process is reversed by reducing helium inventory with IV2 in the primary coolant circuit and closing the load follow valve CV4 while increasing the hydrogen plant heat rate through the IHX. This has similarly been confirmed by simulation..

5. CONCLUSION

The results discussed in this paper lead to the conclusion of several salient features of the GTHTR300C. First, the reactor is operated near full power, as shown in Figure 2, during load follow such that the reactor control rod position is not changed. Second, the fuel temperature is not affected despite change in coolant pressure. This feature results from the core heat transfer that remains in a fully-developed turbulent flow regime in the load range of interest. Third, the reactor outlet coolant temperature, as well as reactor inlet coolant temperature (not shown in Figure 2), is kept constant, because rapid temperature transients are neither feasible, because of the large thermal inertia of the reactor core, nor desirable, because they cause thermal stress to the reactor equipment. The above three features show that any effect on reactor operation conditions is kept to minimum despite the considerable range of load following.

The last important feature is that the key gas turbine operating parameters including turbine inlet temperature (shown in Figure 2) and pressure ratio, which determine the operating point of the gas turbine, are unchanged such that the aerodynamic performance of both the turbine and compressor remains at their optimum design conditions. This means that the plant power generation efficiency remains constant. The GTHTR300C is thus shown to have the technical feasibility and economical advantage of performing flexible energy production including load following.

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