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ARTICLE

Study on load following of a molten salt fast reactor

Hiroyasu Mochizuki * and Masahiko Nakase

Laboratory for Zero-Carbon Energy, Institute of Innovative Research, Tokyo Institute of Technology
2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550 Japan

The load-following operation of the 700 MWt molten chloride salt fast reactor (MCSFR) is studied using the RELAP5-3D code and the FLUENT code with the neutronics and thermal-hydraulic coupling model. It is assumed that the fuel salt composition is $NaCl$-$MgCl_2$-$HMCl_3$, and the cooling salt composition is $NaCl$-KCl-$MgCl_2$. When the pump rotation speed changes, the average core temperature changes, and the fuel density changes accordingly. This results in a change in reactor thermal power. The pump revolution was reduced to 34% and 39% of the rated condition in one hour to reduce the reactor power to 50% in cases of RELAP5-3D and FLUENT, respectively. The change in temperature is 17.6 K when the rotation speed is reduced to 34% in 1 hour, and the rate of change of the outlet temperature is 0.293 K/min. Furthermore, a governor-free operation and a load frequency control operation can be achieved using two heat storage tanks without changing the flow rate in the primary and secondary heat transport system.

***Keywords:** molten chloride salt fast reactor; daily load-following; load frequency control; governor free; neutronics-thermalhydraulics coupling; RELAP5-3D code; FLUENT code*

Nomenclature

α_T	salt temperature reactivity coefficient (δk/k/K)	ρ	reactivity (δk/k)
α_D	Doppler reactivity coefficient (δk/k/K)	ρ_a	applied reactivity (δk/k)
$\beta_{s,i}$	delayed neutron fraction under static conditions (-)	ρ_{loss}	reactivity loss by fuel circulation (δk/k)
$\beta_{loss,I}$	fraction of delayed neutron loss of group i (-)	τ_C	transit time of the fuel in the core (s)
ΔT	temperature difference (K)	τ_L	transit time of the fuel in the exterior loop (s)
λ_i	decay constant of precursor of group i (1/s)		
$\lambda_{T,I}$	decay constant considering the transit times (1/s)		

1. Introduction

As previous research has shown, in the future it will be problematic for nuclear power to be solely responsible for the base load [1]. Up to now, thermal power plants have played an important role in balancing the supply and demand of electricity. As photovoltaic power generation and wind power generation increase, it becomes more difficult to balance supply and demand. As a result, regardless of the type of reactor, it will be required to supply the necessary power when necessary. Although not explicitly stated in Generation IV goals, this ability will be needed. When a nuclear reactor with this capability is built, thermal power plants that emit carbon dioxide can be closed.

Among the candidates for next-generation reactors, i.e., Gen IV reactors, that are expected to bear the future of nuclear energy, molten salt reactors (MSRs) have been attracting attention in recent years, and many design and construction plans have been announced by venture business companies and national institutes [2]. It has been clarified from researches that a molten chloride salt fast reactor (MCSFR) has inherent safety for any transients and accidents, and long-term safety can be achieved by a fully passive decay heat removal system (DHRS) [3]. It has also been found through the above analyses that in a transient event where all fuel pump trips, the reactor power automatically drops to the decay heat power level, and in the case of a single pump trip, the power shifts smoothly to the partial power. This indicates that the reactor can omit control rods and power can be controlled by changing the pump speed of the MCSFR, and the purpose of this study is to investigate the load-following operation.

Figure 1 illustrates changes in electricity consumption in Japan for one day in January 2022. This curve is an average, and there are fine variations on the actual curve. The evolution from 0 to 12 o'clock in this figure is shown in a cartoon way in the same figure, and it can be seen that it is composed of three basic components. In response to

*Corresponding author. E-mail: mochizuki.h@zc.iir.titech.ac.jp

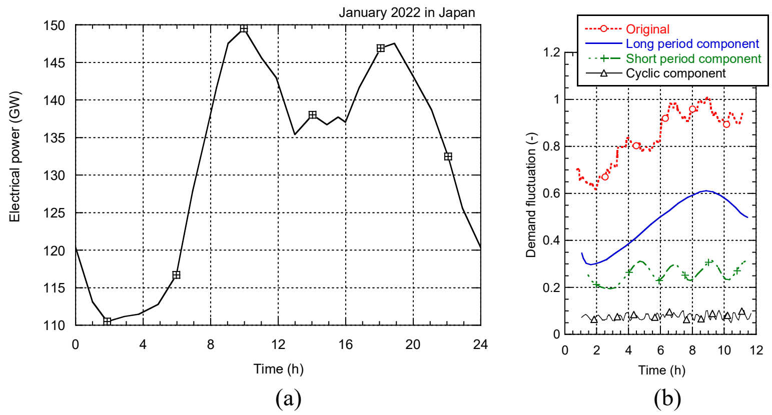


Figure 1. Electrical power demand curve (a) in Japan and (b) its three components.

Table 1. Three types of load-following operation.

Operation	Power change rate	Remark
Daily load-following operation	100% to approx. 50% in 1 hour	
Load frequency control (LFC) operation	Approx. 5% of rated power or more in 1 min.	Operation for a period of several min. to a dozen min.
Governor free (GF) operation	Approx. 5% of the rated power within 3.33 s	Operation for a period of several sec. to several min.

such fluctuations in power demand, nuclear power plants have been operating daily load following (DLF) operations, as shown in **Table 1**. DLF is the most widely known mode, and some nuclear power plants have changed the reactor power in the range of 100% to 50% of the rated thermal power (RTP) as DLF. The typical example is 100-50-100% RTP in 14-2-6-2 hours. DLF can be achieved by changing the reactor power on an hourly basis and generating electricity that is proportional to the reactor power. Since the finer fluctuations overlap with the daily electricity demand change, the frequency of the grid system is controlled to be constant by control from the power supply command center. This operation is called the load frequency control (LFC) operation. LFC is a control that targets short-period fluctuations from a few minutes to a dozen minutes. It is important that the generator has the capability to operate at an appropriate rate of change. For even shorter cycle fluctuations, governor-free (GF) operation is applied to suppress frequency fluctuations. In GF operation, the power generator output is adjusted by detecting the change in the rotation speed of the generator with respect to the load fluctuation of the frequency from several seconds to several minutes.

In the present study, DLF operation with pump speed change is investigated using both the RELAP5-3D code and the FLUENT code. The LFC operation and the GF operation are investigated without changing the flow rate in the primary and secondary heat transport system using the RELAP5-3D code. Although the void fraction of helium bubbles injected to remove fission product gases increases with decreasing core flow, this effect is neglected in the present study.

2. Analysis model

The conceptual MCSFR in the present study is illustrated in **Figure 2**. In this study, a four-loop configuration of MCSFR is assumed. The reactor is an empty cylinder (2.3m ID, 2.4m height) without control rods and with bent hot legs provided at the top of the reactor core. One primary loop consists of the reactor core, gas treatment equipment, a fuel pump, and a fuel salt-to-coolant salt heat exchanger (FCHX). The inlet pipe is offset counterclockwise by 10 cm. The heat exchanger flow path is a rectangular channel with a cross section width of 10 mm and a height of 7 mm, and the flow direction is sine-shaped. The total length is approximately 5m, and the effective heat transfer part fits in 3m. The heat transfer coefficient of FCHX for RELAP5-3D has been proposed through the validation of FLUENT model which was validated by the experimental data using supercritical carbon dioxide [4]. In the present study, the polyhedral mesh has been used to shorten the calculation time. The secondary heat transport system (HTS) consists of a secondary FCHX, a coolant pump, two heat storage tanks (HSTs) with 785 m^3, a gas heat exchanger (GHX) and a decay heat removal system (DHRS) with an air cooler. The tertiary HTS consists of a secondary side of GHX, and a gas turbine system with a generator. In the present analysis model for the RELAP5-3D code illustrated in **Figure 3**, DHRS is omitted because this system is not used during the load-following operation. In the analysis model, it is treated as two loops, that is, single loop A and loop B that integrates three loops. The tertiary system is simplified and the boundary conditions are imposed at the inlet and outlet of the system. Calculations in the core are also performed using the FLUENT code

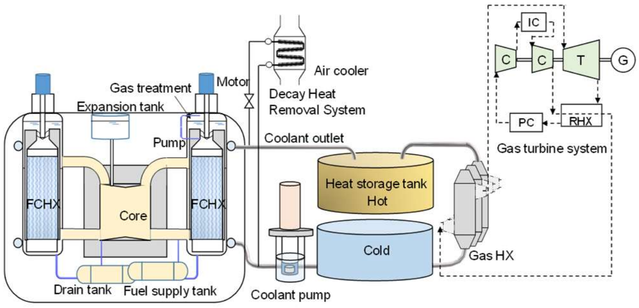


Figure 2. Schematic of the conceptual MCSFR system.

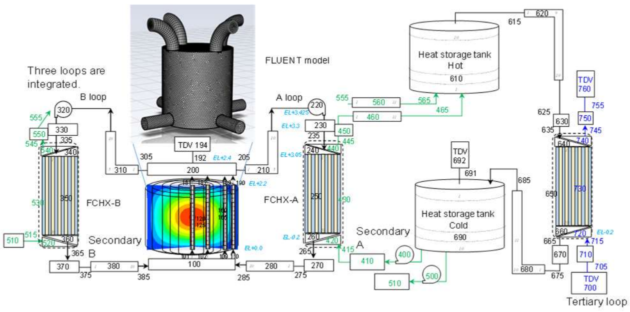


Figure 3. Analysis model using the RELAP5-3D code and FLUENT code.

with boundary conditions calculated by RELAP5-3D.

Although a partial loss-of-fuel flow (LOFF) event and an unprotected station blackout (USBO) event have already been analysed using a similar analysis system [3], the analysis system has been slightly modified. The composition of the chloride molten fuel salt is 40NaCl-30$MgCl_2$-20$UCl_{3/4}$-10($PuCl_3$-$MACl_3$) and the composition of the molten coolant salt is 27.5NaCl-32.5KCl-40$MgCl_2$. MA stands for minor actinide.

3. Code validation

3.1. Code-to-code validation

The analysis in this study using the RELAP5-3D code requires a neutronics and thermal-hydraulics coupling analysis of the molten salt reactor. Up to now, in the molten salt reactor system, the FLUENT code with the user defined function (UDF) which incorporates discretized one-point kinetic equations has been verified using the operation data of MSRE [5]. Regarding the RELAP5-3D code, the benchmarks that analyze partial LOFF due to one-pump trip, etc. in an MCSFR have shown that the analysis results are almost the same as the verified FLUENT code as shown in **Figure 4**. The important thing in this analysis is that the reactor power decreases as the decreasing fuel flow rate. This is because the average fuel temperature increased with decreasing flow rate and negative reactivity was applied. In the comparison of partial LOFF, the reactor power calculated by RELAP5-3D is higher than that by FLUENT by approximately 10%. However, the similar evolution is shown in two codes. The difference in reactor power between FLUENT and RELAP5-3D is mainly due to the difference in the thermal-hydraulic calculation methods of both codes. Since the FLUENT code analyzes the vortex flow in the core almost faithfully, the average temperature in the core under the steady state condition tends to be calculated high as much as 853.4 K. On the other hand, the RELAP5-3D code can calculate one-dimensional flow, and the average temperature is 839.0 K. The average temperature change after the flow rate decreases to approximately 75% is approximately 1.6 K higher for the FLUENT calculation, although the FLUENT outlet temperature after the transient is slightly lower than the result of RELAP5-3D. Furthermore, the one-point kinetics model of the RELAP5-3D code is based on the theory of static fuel and is not a complete model for the system in which fuel flows in and out. Therefore, in the analysis that requires precision, the exterior loop is calculated by RELAP5-3D, and the inside of the core is calculated by FLUENT. However, when analyzing the operating characteristics of load-following, it is difficult to use the FLUENT code all the time considering the calculation time. The above comparison shows that there is no major problem in using the RELAP5-3D with the knowledge that it contains a small error in reactor power.

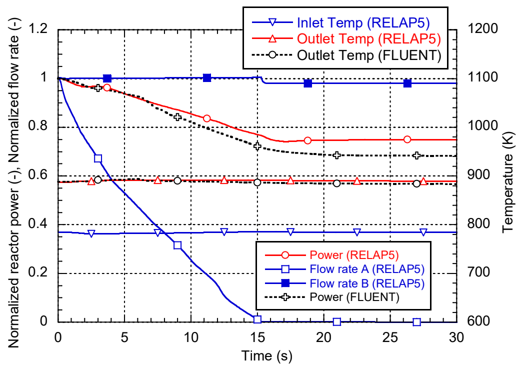
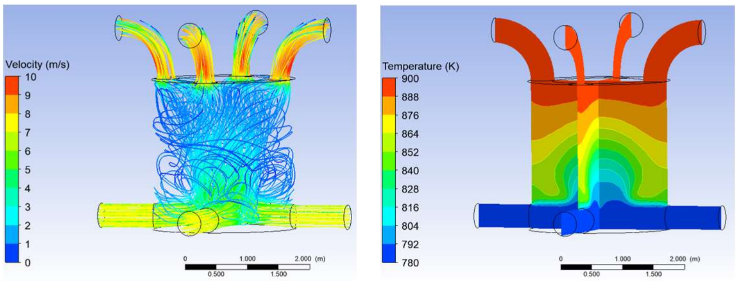


Figure 4. Comparison of calculated reactor power and outlet temperature between FLUENT and RELAP5-3D for one pump trip conditions (rated reactor power: 700 MWt, loop flow rate: 3075 kg/s), (reproduced from Mochizuki, [3]).

3.2. Validation of RELAP5-3D using MSRE data

Since we have test results of reactivity insertion measured using the MSRE at 1, 5, 8 MW thermal power [6], the direct validation of RELAP5-3D was conducted [7]. The analysis model included all HTSs of MSRE from the primary HTS to the air heat sink. The primary system was a molten fluoride fuel salt and the secondary cooling system was a molten fluoride salt. Therefore, two types of fluid property files for RELAP5-3D were generated in advance using the ATHENA code [8]. Good agreement was obtained between the test results and calculated results. Therefore, RELAP5-3D can be applied to channel type MSRs without problems. The application of the neutronics and thermal-hydraulics coupling model of RELAP5-3D to the molten salt reactor has been validated.



(a) Steam line and velocity contour (b)Temperature contour

Figure 5. Stream line and temperature distribution in the core under steady state condition.

4. Steady state calculation

In the present study, the core with 700 MWt rated thermal power (RTP) is cooled by setting the rotational speed of the fuel pump to 800 rpm. The loop flow rate under the steady state conditions is 3075 kg/s. The cooling salt flow rate of the secondary system is set to 3000 kg/s per loop. The tertiary system is a nitrogen gas, and electrical power is generated using the Brayton cycle. However, because the dimensions of GHX is under consideration, the molten salt heat exchanger that has been studied up to now is used for the tertiary system instead of GHX. The tertiary system flow rate is set at 15700 kg/s and the inlet temperature is set at 656 K. As a result, the temperature of the molten coolant salt of the secondary system that flows into FCHX is 710 K, and the temperatures of the molten fuel salt at the inlet and outlet of the core are 784 K and 888 K, respectively. It took about 2 hours for the convergence calculation of RELAP5-3D due to the HST model although the size of the HST is intermediate. The position of the inlet pipe is shifted 10 cm to the right of the line toward the center of the core to generate a weak vortex. From this configuration, as shown in **Figure 5**, it can be seen that the molten fuel salt from the inlet pipes flow towards around the core. It can be seen that the temperature of the core is uniformed by weak vortices. When the inlet pipe is directed toward the center, the temperature in the peripheral region tends to rise, and when the inlet pipe shifts significantly, the temperature in the center region tends to rise.

5. Load-following calculations

It is necessary to use the lambda represented by the following equation in the one-point kinetics equations for molten salt reactors.

$$\lambda_{T,i} \equiv \lambda_i + \frac{1-\exp(-\lambda_i \tau_L)}{\tau_C} \qquad (1)$$

The effective delayed neutron fraction is calculated considering the fraction of delayed neutron loss of group i caused by fuel recirculation as follows.

$$\beta_{eff} = \sum_{i=1}^{6} \beta_i = \sum_{1=1}^{6} (\beta_{s,i} - \beta_{loss,i}) \qquad (2)$$

$$\beta_{loss} = \sum_{i=1}^{6} \beta_{loss,i} = \sum_{i=1}^{6} \beta_{s,i} \left[1 - \frac{\lambda_i}{\lambda_{T,i}}\right] \qquad (3)$$

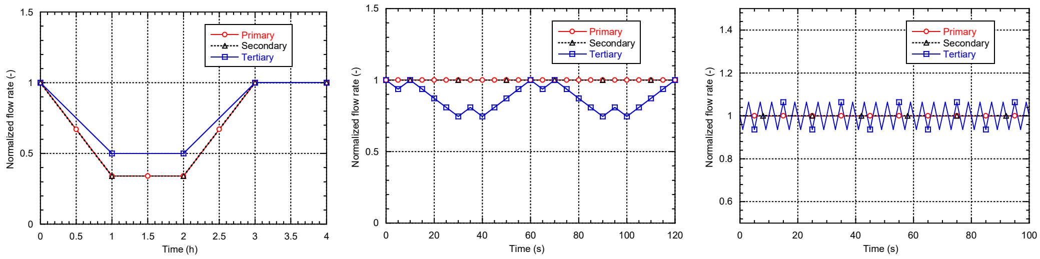
For the derivation of the above equation, refer to the previous study [9]. The reactivity with respect to the temperature of the molten salt reactor and the loss of reactivity as a result of flow are considered as follows.

$$\rho = (\alpha_T + \alpha_D)\Delta T + \rho_a - \rho_{loss} \qquad (4)$$

When shifting from steady-state to transient calculation, small disturbances may be introduced due to changes in the calculation methods. In the steady-state calculation, the constant reactor power is given to the code using a table. On the other hand, in transient calculations, the initial total power is given to the code in consideration of reactivity values such as temperature reactivity, etc. In order to avoid these disturbances, a null-transient computation is conducted before the event starts, and then the disturbance due to the transient is added. This interval is set to 100 s, and it is confirmed that the initial conditions have completely converged to the set values before the transient event is applied. The operating conditions for three types of load-following operations are listed in **Table 2**. **Figure 6** is a diagram of the flow rate change patterns explained in the above table. The power change pattern in the figure was adopted in this study because LFC, in particular, is a typical control pattern when power utilities check their operations.

Table 2. Changes in temperature and power through load-following operation.

Case	Target reactor power change initial/reduced (MWt)	Condition
DLF	700/350	DLF-1: The primary and secondary flow rate change to 34% in 60 min. Tertiary flow rate change to 50 % in 60 min., DLF-2: Primary and secondary flow rate change to 39% in 60 min.
LFC	700/693.7	Constant primary and secondary flow rates. Tertiary flow rate change to 75% in 0.5 min.
GF	700/700	Constant primary and secondary flow rates. Change in the tertiary flow rate to ±5% in 4 or 20 s.



(a) DLF (b) LFC (c) GF

Figure 6. Flow rate change patterns in load following operation of DLF, LFC and GF. operation.

5.1. Daily load-following operation

Among the load-following operations already introduced, the daily load-following (DLF) operation with slow response will be examined first. We need to know how much the reactor power changes when the flow rates of the fuel pump, the cooling salt, and the tertiary system change. The change in the required output of the tertiary system is given under the assumption that it is proportional to the flow rate. This assumption is considered correct because the heat capacity of the molten salt is constant in the present study.

The real operating pattern of 100-50-100% RTP in 14-2-6-2 hours introduced before requires a long CPU time to obtain the result. Considering the characteristics of the molten salt reactor, it is possible to change the reactor power in a shorter time, and to save CPU time, the pattern of 100-50-100% RTP is calculated in 1-1-1-1 hours. The reactor power is changed in 1 hour and increased in 1 hour is illustrated in **Figure 7**. In this case, the flow rates of primary and secondary HTS decrease from 100% to 34%, and the flow rate of the tertiary system decreases from 100% to 50%. If flow rates of primary and secondary are decreased to 50% in the case of RELAP5-3D, the reactor power did not decrease to 50%. The core inlet flow rate and temperature, which are the calculation results of RELAP5-3D, are given as boundary conditions to FLUENT, and the same transient process is calculated by FLUENT. The calculation of FLUENT takes a very long time. Therefore, the computation time is accelerated by a factor of 25 and aborted when the flow rate recovers. It has been confirmed in advance that the results of computation time accelerated by a factor of 25 are consistent with the results computed in real time as shown in the figure. The reactor power calculated by FLUENT has decreased to 44% of RTP. The outlet and inlet temperatures of the reactor are changing in a slight curved manner in the calculated results with both codes, and it is considered that the average temperature also deviates from the straight line. For this reason, the reactor power changes slightly later than the energy demand change of the tertiary system, even though the flow rate is changed linearly. The rate of temperature change is also important in load-following operation. The reduced reactor power is also shown in the same table.

In light-water reactors, there is a limitation to cooling with a temperature change of 55 K/h or less [10], and this speed is 0.916 K/min. Since the outlet temperature change rates for the DLF operation evaluated by FLUENT and RELAP5-3D are 0.293 K/min (17.6 K/h) and 0.598 K/min (35.9 K/h), respectively, there is still a margin for the limit, and it is possible to change at a slightly faster speed. The reason for the difference of the reactor power between two codes is the same as explained in Section 3.1. The average temperatures calculated by RELAP5-3D and FLUENT change from 837.5 K and 853.4 K to 842.7 K and 860.1 K one hour after transient, respectively. The average temperature changes for both codes are 5.2 K and 6.7 K, respectively, although the outlet temperature of FLUENT is low. When the flow rate is reduced to 39% of the initial flow rate for FLUENT, the reactor power in this case is approximately 50% of the RTP. The temperature at the reactor outlet changes by about 15 K in one hour, that is, 0.25 K/min. In this way, there is a difference in reactor power due to the flow rate change between the detailed code and the system code. However, since such temperature changes occur every day, it is necessary to investigate in detail whether there is a structural problem. In this way, it

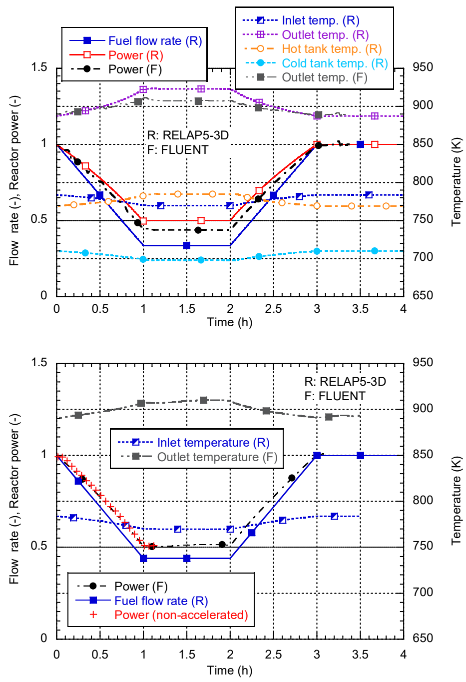


Figure 7. Evolution of daily load following for case DLF-1 (above) and case DLF-2. (bottom).

has been clarified that reactor power can be changed from rated power to about half in one hour by changing the flow rates in the primary and secondary HTSs. Therefore, RELAP5-3D is effective for rough investigation, but nuclear thermal coupling analysis using CFD code such as FLUENT is necessary for detailed design. We understand that in the future the ratchet effect must also be evaluated because of daily temperature changes.

5.2. Load frequency control (LFC) operation

In LFC operation, a change in power generation is requested from the power supply command center. When the request is received at the MCSFR power plant, it is investigated whether the power change can be done only by the change in flow rate in the tertiary system. It is also necessary to confirm whether the thermal-hydraulic change in the tertiary system affects the primary system through the temperature change in the secondary system. The flow rate in primary system and the secondary system will not change. In this study, it can be assumed that the change in power generation is proportional to the change in flow rate in the tertiary system based on thermodynamic theory.

Figure 8 illustrates the evolution of the plant parameters when the generator load demand changes by about 25% from the rated electrical output (REO) under constant flow rate conditions in the primary and secondary HTS in 30 s. The average reactor power in this operation is approximately 88 %. It is assumed that the LFC signal is transmitted to the plant every 5 s, and the electrical output power is controlled. The flow rate in the figure shows that the flow rate of the tertiary system is changed depending on the change in power demand. Because it is equipped with heat storage tanks, it can be seen that there is almost no temperature change at the core inlet and outlet. Therefore, the reactor power does not change significantly, but it decreases slightly because it is controlled in the direction of suppressing the power to approximately 88% of REO. In this study, the behavior of changing the rotation speed of the pump and the behavior of changing the load are analyzed separately, and it is shown that LFC operation is possible. In reality, the LFC signal is received while the reactor power is changed significantly, so these two methods will be performed at the same time.

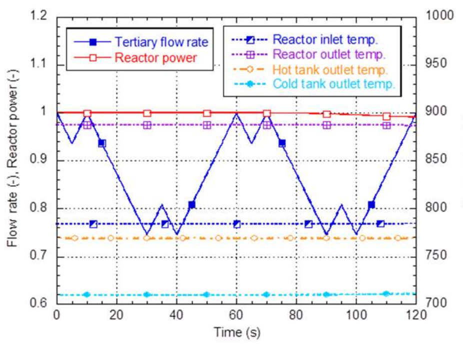


Figure 8. Evolution of load frequency control operation with constant flow rate in primary and secondary HTS.

5.3. Governor-free operation

Since governor-free (GF) operation needs to be dealt with very quickly, it is impossible to respond by changing the reactor power. HSTs are required to support this operation, and in this research, two tanks, hot and cold, are provided. The dimensions of the tank must be adjusted according to the purpose, but the purpose of this study is to show that GF operation is possible. **Figures 9 (a)** and **(b)** illustrate the behavior of the plant when the required output of the tertiary system is changed by 5% REO in 4 and 20 s, respectively. It can be seen that the temperature of the primary and secondary systems hardly changes depending on the capacity of the HST, i.e., 0 or 785 m^3. Therefore, it is shown that the operation can be continued without changing the reactor power.

6. Discussion on load-following operation

HSTs are provided especially for responding to changes with a short cycle, and the behavior of DLF operation when these tanks are removed is evaluated as shown in **Figure 10** using RELAP5-3D. The pattern of load change is for 100-50-100% RTP in 1-1-1-1 hours, and the flow change pattern is the same as that in Figure 7. This result is almost the same as the case where HSTs are provided, and it can be seen that the tanks are not required for the DLF operation. Since the amount of reduction in reactor power is slightly smaller than when the tanks are provided, a slightly lower pump speed should result in the same power reduction.

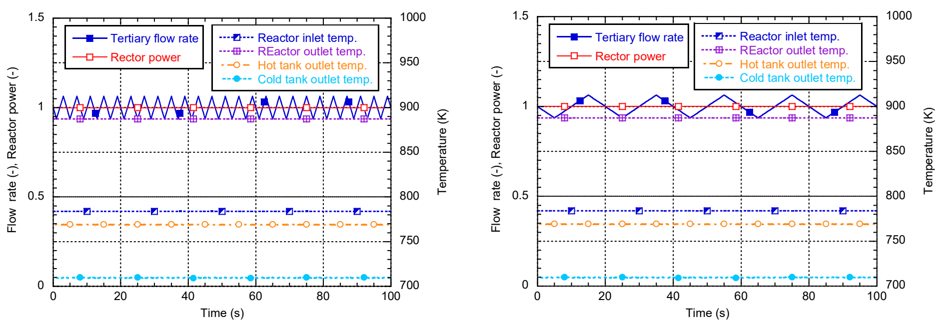


Figure 9. Evolutions of governor-free operations with constant flow rate in primary and secondary HTS (a): frequency of 4s, (b): frequency of 20 s.

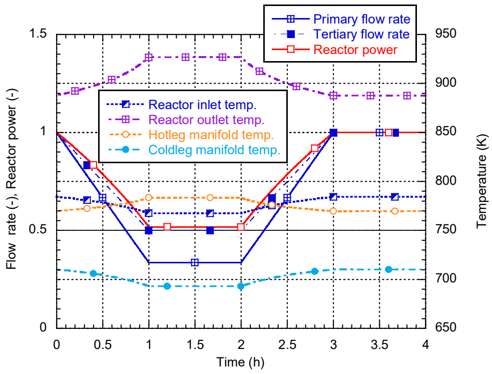


Figure 10. Evolution of daily load-following without heat storage tanks (100% to 34% flow rate for the primary and secondary heat transport system, and 100% to 50% flow rate for the tertiary system in 1 hour).

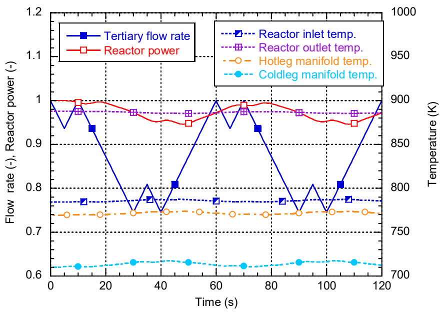


Figure 11. Evolution of load frequency control operation with constant flow rate in primary and secondary HTS without heat storage tanks.

In the case of LFC operation, as shown in **Figure 11**, if there is no HST, the reactor inlet and outlet temperatures change according to the change in the energy requirement of the tertiary system, and the reactor power also changes. Such a change in the temperature of the molten salt is not preferable because the temperature changes repeatedly in the structural material. Therefore, in the LFC operation, it is necessary to have HSTs to reduce the variation of the plant temperature.

The characteristics of the load-following operation shown above differ slightly depending on the type of molten salt. However, the basic characteristics are the same, and similar results can be obtained with any composition of molten fuel salt.

7. Conclusions

As a result of neutronics and thermal-hydraulics coupling analysis using the RELAP5-3D code and the FLUENT code for the transient of load-following operation in a molten chloride salt fast reactor, the following conclusions were obtained.

1) The daily load-following operation, in which the rated thermal power is halved in one hour and returned to the rated power in one hour, can be realized with a safety margin in temperature change rate by changing the rotation speeds of the fuel pump and the coolant pump.
2) The change in reactor power in response to the request for a load change from the power supply command center, i.e., LFC operation, can be achieved by the change in flow rate in the tertiary heat transport system. The heat storage tank is necessary for this operation and has the effect of reducing changes in temperature and reactor power.
3) Load-following for demand load fluctuations in seconds can be handled by governor-free operation that keeps the turbine speed constant using the stored heat in heat storage tanks.

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