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Recirculation Operation in a Liquid Metal Reactor with a Superheated Steam Cycle

Sim Yoon Sub, Eoh Jae Hyuk, Song Soon Ja, and Wi Myung Hwan
Korea Atomic Energy Research Institute
150 Dukjin-dong Yuseung-gu, Daejeon 305-353, Korea
yssim@kaeri.re.kr

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Abstract

The characteristics of the recirculation operation of LMR which are different from the conventional plants such as PWR and fossil fuel plants were investigated using a computer code TSGS developed in this study. For simulating the transient behavior of the steam generation system, a water level control algorithm utilizing digital control hardware features was introduced. By investigation, the function of the recirculation operation was defined, the major features of the operation were found. Also good performance of the level control algorithm was confirmed.

Key Words : recirculation operation, LMR, KALIMER, superheated steam, level control, operation target, once-through operation

1 Introduction

The recirculation operation of SG in a LMR with a superheated steam cycle is quite different from that in PWR. In PWR, the recirculation is to reheat the water liquid separated from the mixture by the moisture separator and is made through the whole power operation range. However, the recirculation operation in LMR with a superheated steam cycle is an intermediate operation mode and made only at a low power range. Also the operation in LMR has different features compared to the operation in a fossil fuel plant and the difference comes from the following basic differences in the plants.

- Fossil fuel plant : The steam condition can be controlled directly by the fuel supply rate of the fire boiler and the heat from the fuel is directly transferred to the steam through the heat transfer tube.
- LMR plant with a superheated cycle : The heat for producing the steam is from the nuclear core and is transferred to the steam via the two coolant loops in series such as the PHTS (Primary Heat Transport System) and IHTS (Intermediate Heat Transport System).

From the differences described above, the recirculation operation in LMR with superheated steam cycle such as KALIMER[1] comes to have unique features, which have been generally not known domestically in detail. The domestic technology level on the LMR NSSS design has been improved pretty much through development of the conceptual design of KALIMER[1]. Understanding on the details of the unique features in the LMR recirculation operation is now required for further development of the LMR NSSS design technology since NSSS is closely related to and supported by the SGS operation and the domestic system technology has arrived at a level to be able to consider key features of the interaction between NSSS and the SGS operation. To meet the necessity, the characteristics of the recirculation operation in LMR with a superheated steam cycle are investigated in this paper. Also a computer code TSGS is developed for the investigation.

2. The Steam Generation System of the Analysis

The recirculation operation performance is generally a function of the whole plant system features but its main features are determined by the steam generation system (SGS) which consists of the steam generator(SG), SGAWT(SG Auxiliary Water Tank), SGAWT level control and recirculation pump. Fig. 1 shows the structure. In this study, the analysis is focused on the SGS and the effects of other systems are considered as boundary conditions by plant operation targets. This approach simplifies the analysis without loosing both of generality and practicality.

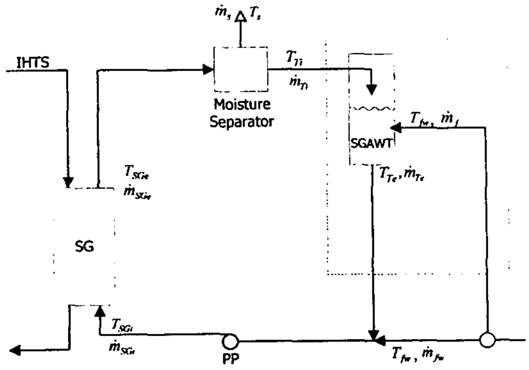


Fig. 1. Structure of the Steam Generation System

In the recirculation operation, feedwater is inserted to the SGAWT and mixed with the water that enters the SGAWT from the moisture separator. The mixed water is pumped to the steam generator and heated by the heat from IHTS. Then it is fed to the separator and separated into liquid and vapor.

When the power level is high, once-through operation is made. In the once-through operation, SGAWT is isolated from SG and feedwater. The feedwater is inserted directly to the steam generator and the exit flow from the steam generator is sent to the turbine.

3. Mathematical Description of the System

3.1. Governing Equations

The governing equations for the operation in the SGS are as follows.
In the SGAWT,

$$\frac{\partial E_{Ti}}{\partial t} = Avg_t(\dot{m}_{fw} h_{fw}) + Avg_t(\dot{m}_{Ti}\, h_{Ti}) - Avg_t(\dot{m}_{Te}\, h_{Te}) \tag{1}$$

$$\frac{\partial M_{Ti}}{\partial t} = Avg_t(\dot{m}_{fw}) + Avg_t(\dot{m}_{Ti}) - Avg_t(\dot{m}_{Te}) \tag{2}$$

In the steam generator,

$$\frac{\partial E}{\partial t} = -\frac{\partial}{\partial x}(\dot{m} h) + \int U(T_s - T)\,dA \tag{3}$$

$$\frac{\partial \rho A}{\partial t} = -\frac{\partial}{\partial x}(\dot{m}) \tag{4}$$

The used nomenclature is as the following.
$Avg_t(\phi)$: the time average of ϕ, E: energy, M: mass, m: mass flow rate, h: enthalpy, A:flow area.
subscript: fw:feedwater, i: inlet, e:exit, T:tank, t:total(liquid and vapor), s: surrounding.
Eq. (1) and (2) are converted to the difference equations Eq. (5) and (6) for numerical computation.

$$E_{Ti}^{j+1} = E_{Ti}^{j} + \Delta t(Avg_t(\dot{m}_{fw}h_{fw}) + Avg_t(\dot{m}_{Ti}\, h_{Ti}) - Avg_t(\dot{m}_{Te}\, h_{Te})) \tag{5}$$

$$M_{Ti}^{j+1} = M_{Ti}^{j} + \Delta t(Avg_t(\dot{m}_{fw}) + Avg_t(\dot{m}_{Ti}) - Avg_t(\dot{m}_{Te})) \tag{6}$$

From the definition of the internal energy u,

$$u_T = \frac{E_{Ti}}{M_{Ti}} \tag{7}$$

$$h_{Te} = h_T = f(u_T, P_T) \tag{8}$$

The rate of the recirculation flow which flows from the SGAWT to the steam generator is expressed as Eq. (9).

$$\dot{m}_{Te} = a_{f1}\,\dot{m}_f + a_{f2} \tag{9}$$

where a is a model coefficient.

The relation between the volume V_f and mass M_{Ti} of the fluid in the tank is described by Eq. (10).

$$V_f = v_f(P_T, u_T)M_{Ti} \tag{10}$$

where v_f is the specific volume of the fluid.

From the geometrical restriction that the fluid volume can not exceed the tank volume for the fluid V_{Tf}, Eq. (10) for the fluid volume is modified as Eq. (11)

$$\begin{aligned} V_f &= V_f \text{ of Eq.(10)} && : V_f \le V_{Tf} \\ V_f &= V_{Tf} && : V_f \ge V_{Tf} \end{aligned} \tag{11}$$

3.2. Auxiliary Descriptions

Equations for describing the characteristics of the equipment and control parameter are derived here.

3.2.1. Feedwater Flow Rate and SGAWT Level Control

The feedwater flow rate depends on the control logic of the fluid in the tank and there can be two alternatives for the control. One is controlling the tank pressure and the other is water level control. The pressure control can be made when the water in the tank is at a saturated condition and the level control is for a subcooled condition.

As it will be found later, the water in SGAWT becomes a subcooled state during the recirculation operation and the level control is used in this study.
The change of the level is expressed by Eq. (12).

$$L(t_2) = L(t_1) + \int_{t_1}^{t_2} (\dot{m}_i - \dot{m}_e)\frac{v}{A}dt \tag{12}$$

The level error at time t e_L^t is,

$$\varepsilon_L^t = L(t) - L_{targ} \tag{13}$$

where L_{targ} is the target level for the control.

In setting up the level control logic, the conventional control logic of the PID logic[3] was tested but its performance was not satisfactory and a new control logic which utilizes digital control and employs the physical characteristics of the system is used.

For the level to be satisfactorily controlled, the following requirements need to be satisfied.

$$L = L_{targ} \quad , \quad \dot{m}_i = \dot{m}_e \tag{14}$$

From this, the following logic is deduced. When the sign of the level error is maintained at the same value continuously, it means the level has not reached the target level and the compensation flow rate is set in proportion to the error. When the sign is, however, reversed, it means the level has surpassed the target and the inflow rate is set to be equal to the outflow rate. This logic is expressed mathematically as Eq. (15).

$$
\begin{aligned}
\Delta \dot{m}_i &= k\left(\frac{A}{v\Delta t}\right)\varepsilon_L^l && :\varepsilon_L^l.\varepsilon_L^{l-1} > 0 \\
\Delta \dot{m}_i &= -\sum \dot{m}^l && :\varepsilon_L^l.\varepsilon_L^{l-1} \le 0
\end{aligned}
\tag{15}
$$

where υ is the specific volume of the fluid in the tank and k is a constant. Additionally, a deadband and a limiter are used for stable operation and equipment protection of the control system.

3.2.2. Moisture Separator

In the SGS, the mixture from the steam generator during recirculation is fed into the moisture separator as shown in Fig. 1 and is separated into liquid and vapor groups as shown in Fig. 2.

Since a moisture separator generally does not separate vapor from liquid completely, the group of vapor (steam) comes to also contain liquid and vice versa. To quantify the effectiveness of the separator, performance indexes f_f and f_g are defined as Eq. (16).

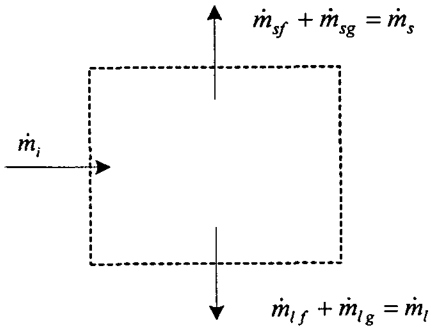


Fig. 2. Flows in the Separator

$$
f_f \equiv \frac{\dot{m}_{lf}}{\dot{m}_l} \ , \ f_g \equiv \frac{\dot{m}_{sg}}{\dot{m}_s} \tag{16}
$$

The parameters have the following meaning.

$\dot{m}_l$: the flow rate of the liquid group, $\dot{m}_{lf}$: liquid flow rate in $\dot{m}_l$,

$\dot{m}_s$: flow rate of the vapor(steam) group $\dot{m}_{sg}$, : vapor (steam) flow rate in $\dot{m}_s$

The performance indexes f_f and f_g are modeled as Fig.3. The model was set up using the approach of the simple model in RELAP [2]. Specifically speaking, they were derived from the following requirements to the separator and the energy balance between the inlet and exit flows.

- For x_i >=1, f_g=1. For x_i <=0, f_f=1
- As x_i increases, f_f decreases and f_g increases.
- f_f and f_g should be continuous at x_i change.

where x_i is the steam quality of the fluid at the separator inlet.

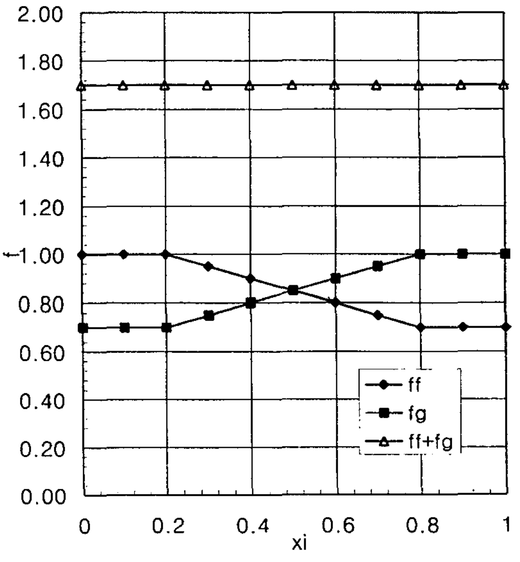


Fig. 3 Separator Performance Indexes f_f and f_g

The separated flow components from the separator model of Fig.3 are shown in Fig. 4 as a function of the inlet quality.

3.2.3. Boundary Condition for the SGS Operation

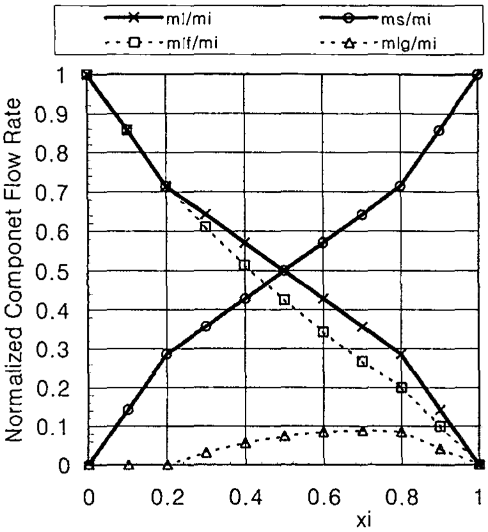


Fig. 4. Separated Flow Components from the Separator Performance Model of Fig.3

The boundary conditions of the SGS such as the temperature and flow rate of the IHTS sodium to the SGS and the feedwater temperature are assigned from the target values of the system parameters for plant operation. The operation target values [4] are shown as a function of the plant power in Fig. 5.

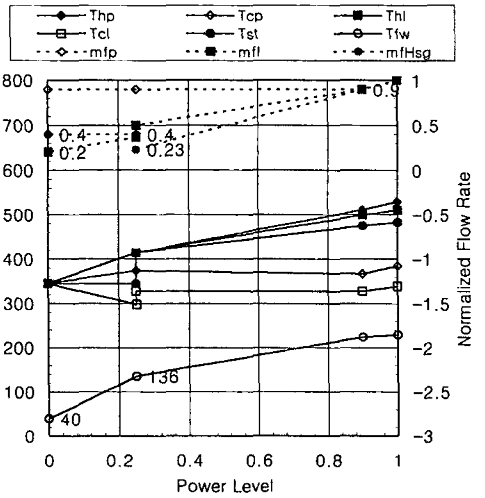


Fig. 5. The Target Values of the System Parameters for Plant Operation

In the legend of Fig. 5, *h*, *c*, *P*, and *I* respectively denote hot, cold, PHTS and IHTS. *Tst* denotes the steam temperature and *mfHsg* is for the SG flow rate of the water (H_2O) side.

In the target values, the switching between the recirculation and once-through operations is made at the power level of 25% as will be explained in Article 5.1. The target values were set up somewhat iteratively with the analysis results of this study so that the boundary condition of the SGS analysis can be reasonable.

During the transition operation between the recirculation operation and the once-through operation, the system parameters of the SGS boundary condition are changed by Eq. (17) to reduce the thermal impact on the system.

$$\phi(t) = \phi_{RC} + (\phi_{ot} - \phi_{RC})\frac{t - t_{sw}}{dt_{sw}} \qquad (17)$$

In Eq. (17), $\boldsymbol{\Phi}$ stands for the SG inlet temperature of the IHTS sodium, feedwater temperature and recirculation flow rate. The scuscripts *RC*, *ot* and *sw* respetively mean recirculation operation, once-through operation and switching. Specifically speaking, *tsw* is the time when the switching starts and *dtsw* is the time period for the transition. The switching starts when the target power reaches the switching power level, i.e., 25%.

4. Development of the Code for the Analysis of SGS

4.1. Overall Description of the Code

A computer code TSGS was written for analyzing the performance of the SGS described mathematically by the derived equations of Article 3.

In the code, the analysis of the steam generator is made by another code BoSupSG-SS [2] as one of the modules in the code developed in this study TSGS. The code BoSupSG-SS is a steady state analysis code for a superheated steam generator and the governing equations Eq. (3) and (4) for the steam generator are modeled as Eq. (18) and (19) in the code.

$$\frac{\partial}{\partial x}(\dot{m}h) = \int U(T_s - T)dA \tag{18}$$

$$\dot{m} = uniform \tag{19}$$

In Eq. (18), U is the overall heat transfer coefficient and the integration is taken for the calculation cell surface where the heat transfer occurs across the wall between the fluids of calculation and the surrounding medium. Eq. (18) and (19) are solved using analytic solutions for each calculation cell and the calculation results are free from the truncation error in a numerical solution.

SGS is applied for steady and transient operation to find out the characteristics of the recirculation operation. Since the SG analysis module in TSGS which is BoSupSG-SS is a steady state analyzer, some caution may be needed in interpreting the TSGS results. The results come to have a tendency of having less transient damping effects at a transient operation analysis. Using a steady state analyzer for the steam generator, however, can be interpreted as bringing in a more generality in the calculation results for studying the SGS operation characteristics themselves since the transient effects of the PHTS and IHTS which are not the characteristics of the SGS itself will be involved in the analysis results when a transient analysis is fully made for a plant.

4.2. Reliability Assessment of the Developed Code

The developed code was applied for various conditions and the results were checked with the following view points. From the checking, the developed code was evaluated to produce reliable calculation results for investigating the recirculation operation characteristics.

- Error in the energy balancing between the hot fluid and cold fluids.
  - In all the tested condition, the error was less than 0.00005%
- Convergence of the solution in the final iteration
  - As the solution passes all the internal iteration criteria, the numbers of calculations in various iteration levels became 1
- Smooth convergence and calculation trend
  - During the iteration, the change of the calculation results were smooth.
  - When time dependent boundary conditions were applied, the calculation results showed smooth follow to the boundary condition change.

As the representative results, the process reaching the steady state solution at the

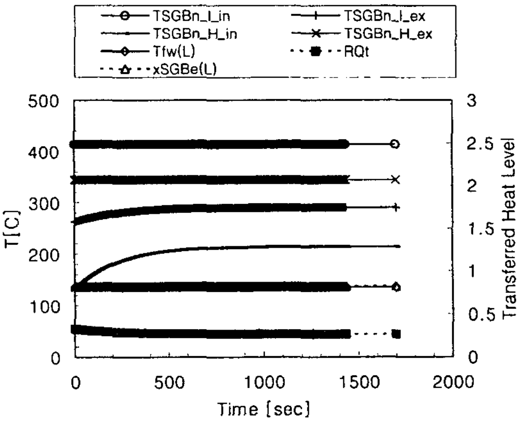


Fig. 6. Reaching the Steady State at a 25% Recirculation - TH Parameters

recirculation operation with a 25% power level is shown in Fig. 6, 7 and 8.

In Fig. 6, *I*, *H*, SGB_n, *RQt* and *x* mean respectively IHTS, water(H2O), steam generator tube bundle (The bundle is a subregion of a steam generator but can be interpreted as the same meaning of the steam generator in this paper.), power actually transferred and steam quality. The calculated parameters which were started from arbitrary values show convergence to the steady state values without any abnormality.

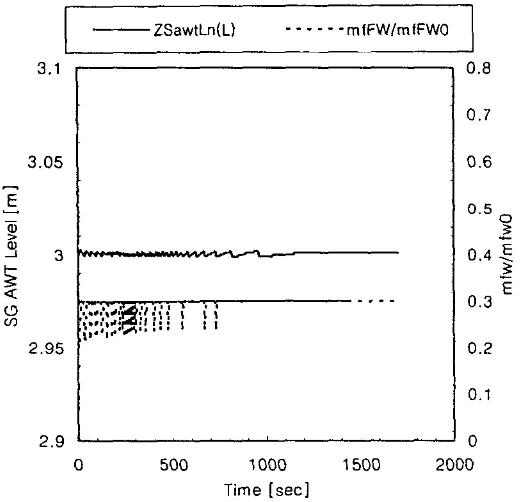


Fig. 7. Reaching the Steady State at a 25% Recirculation - Water Level Control

Fig. 7 of the water level control shows also smooth convergence. In the figure, the feedwater flow rate is shown as the ratio to that of 100% power operation condition.

Fig. 8 shows the convergence parameters. In the code TSGS, iterative calculation is made until the converged solution is reached at each time step. The parameters *dhmaxS_I* and *dhAWTe* represent the convergence performance in that iterative calculation and they respectively mean the maximum enthalpy change in the SG calculation and that in the SGAWT calculation. *ERQSGB_I%* denotes the energy balance error in the final solution at each time step.

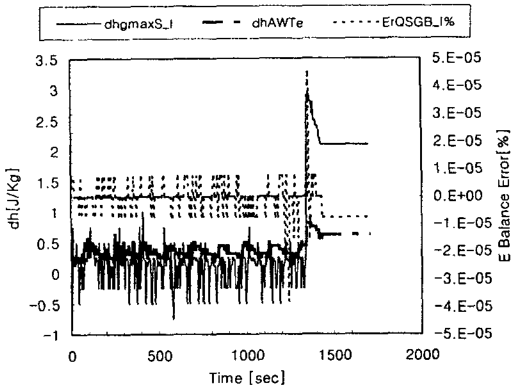


Fig. 8. Reaching the Steady State at a 25% Recirculation - Convergence Parameters

The figure shows that enthalpy calculation is converged up to 3 J/kg (equivalent to 0.0006 °c (=3/5000) approximately) and the energy balance error is less than 0.00005% throughout the whole calculation.

5. Recirculation Operation Characteristics

5.1. Function of the Recirculation Operation and the Requirements to the Recirculation Flow Rate

Consideration of the requirements to the recirculation flow rate is first made from the reason for the need of and the requirement to the recirculation operation at a low power level.

- When the power level is low, the exit fluid condition from a steam generator may not be good enough for the steam to be inserted to the turbine. Depending on the condition, the exit flow state can be even liquid if recirculation operation is not made.
- The transition between the recirculation and once-through operation should be smooth to

reduce the thermal impact on the system.

From this, it is deduced that the role of the recirculation operation is not for the transition of the SGS itself but the support of SGS to the plant so that the plant status can be progressed from the zero power operation level to a turbine operation power level or from a turbine operation power level to the zero power operation level. Hereafter only one side change, that is, plant power increase is mentioned for brevity of the description unless comments on the change in the other side, that is, power decrease is specifically required.

Specifically speaking, the fuctions that SGS needs to perform during the recirculation operation are as follows.

- Treatment of the heat produced in NSSS
- Generation of the steam for plant operation such as feedwater heating.

The exit condition of the fluid from a steam generator needs to meet the following reauirements.

- The steam from SG during recirculation operation period should not be superheated.

If the steam is superheated, there is no more recirculation and the SGS operation mode comes to change into an once-through operation mode. It means the plant status is deviated from the planned route and problems can occur in controlling the plant.

- It is desirable to avoid a subcooled condition at the SG exit.

Having an subcooled condition at the exit itself does not cause a problem but can make the switching to the once-through operation unnecessarily long or result in a rapid temperature change to the system at the switching.

From the points made above, the fluid at the SG exit needs to be saturated and that is mathematically expressed by Eq. (20).

$$0 < x_{SGe} < 1 \tag{20}$$

The analysis to the requirement of Eq. (20) is made for a steady state and perfect separator. At this condition, the energy balance to the system is like the one shown in Fig. 9 at $0 \leq x_{SGe} \leq 1$.

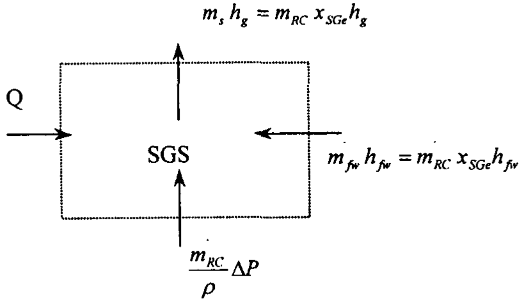


Fig. 9. Energy Balance in the SGS at a Steady State with a Perfect Moisture Separator

When perfect separation is made, the steam flow rate $\dot{m}_s$ becomes the product of recirculation flow rate $\dot{m}_{RC}$ and the fluid quality at the x_{SG} exit ΔP. The term containing ΔP in the figure denotes the recirculation pumping heat. Q is the heat from IHTS.

In the control volume of Fig. 9, the energy balance is expressed by Eq. (21)

$$\dot{m}_{RC}\, x_{SGe} h_g = \dot{m}_{RC}\, x_{SGe} h_{fw} + Q + \frac{\dot{m}_{RC}}{\rho}\Delta P \tag{21}$$

where h_g is the saturated vapor enthalpy of water. From Eq. (21),

$$x_{SGe} = \frac{\dfrac{Q}{\dot{m}_{RC}} + \dfrac{\Delta P}{\rho}}{h_g - h_{fw}} \tag{22}$$

Eq. (22) says that the quality is always larger than 0 and which is natural since there is no outflow of energy from the control volume at a steady state when the quality is less than 0.

From Eq. (22), the required recirculation flow rate for the exit fluid not to become a superheated condition is specified by Eq. (23).

$$\dot{m}_{RC} > \frac{Q}{h_g - h_{fw} - \frac{\Delta P}{\rho}} \qquad (23)$$

Eq. (23) is applied to the feedwater temperature which was changed at power change by the operation target values shown in Fig. 5, and Fig. 10 shows the results.

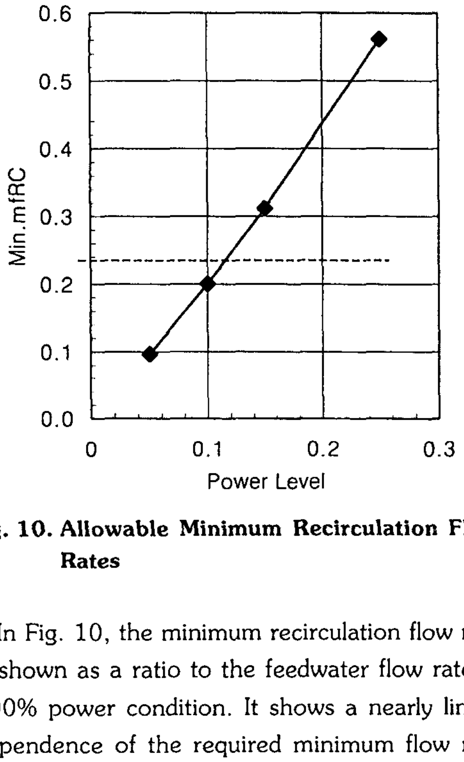


Fig. 10. Allowable Minimum Recirculation Flow Rates

In Fig. 10, the minimum recirculation flow rate is shown as a ratio to the feedwater flow rate at 100% power condition. It shows a nearly linear dependence of the required minimum flow rate on the power level. In selecting the flow rate, consideration on the flow stability in SG needs to be made since phase changes occur in the water which flows inside the tube. For the KALIMER SG design, an analysis was made for the stability and the results[5] showed that there will not be flow instability at the flow rate of 23.5% of the nominal flow rate in the condition of 25% power. It means the flow will be stable when the flow rate is larger than the analyzed condition flow rate at a power level less than 25%. The dotted horizontal line in the figure represents the analyzed flow rate.

From this, the switching to the once-through operation can be made at the power above 15% with the analyzed flow rate of 23.5%. However, the switching power level is selected as 25% and the recirculation fow rate is set at 40% for the further analysis, i.e., af_1 in Eq. (9) is set as 0, considering the margin for stable operation and the uncertainty involved in the perfect separation assumption.

5.2. Operation Characteristics

The characteristics of the operation was analyzed using the developed code TSGS with the plant operation target values of Fig. 5 as the boundary conditions. In the analysis, the models of the level control and moisture separator in Article 3 were used.

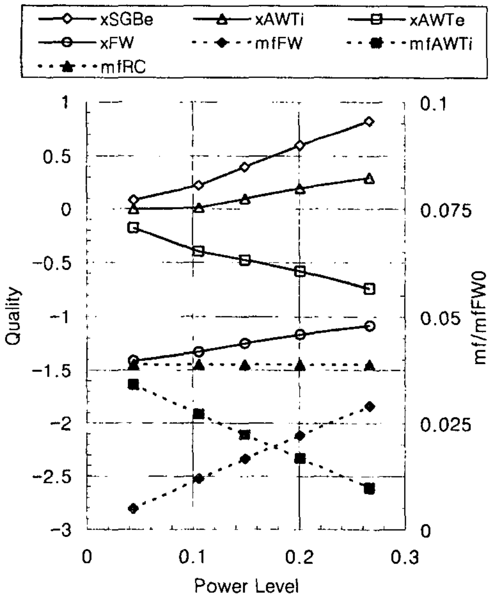


Fig. 11. Qualities and Flow Rates at a Steady State

Fig. 11 shows the results of the analysis for steady states at different power levels. The qualities are for those at the SGAWT exit *xAWTe* (which is close to the quality at the SG inlet), SG outlet *xSGBe(L)* and at the SGAWT inlet *xAWTi*. The curve of *mfAWTi* represents the flow rate to the SGAWT from the separator.

In the figure, the quantitative definition of Eq. (24) is used for the quality.

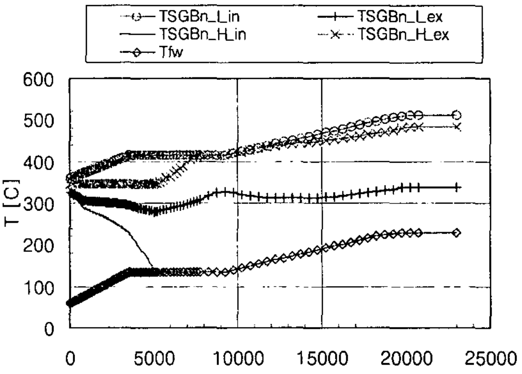
$$x = \frac{h - h_f}{h_g - h_f} \tag{24}$$

where h_f is the saturated liquid enthalpy of water.

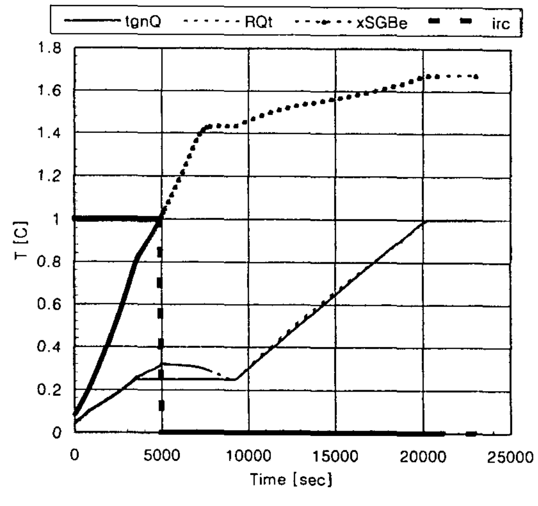
The quality at the SGAWT exit *xAWTe* which is the same as the average quality of the SGAWT fluid decreases as the power increases. This is because that the power increase makes the enthalpy difference between the inlet and exit of the steam generator increase since the recirculation flow rate is maintained constant and the flow rate of the feedwater which is cooler than the SGAWT liquid increases while the quality of the inflow to the SGAWT *xAWTi* increases only slightly as the power increases.

Figures from Fig. 12 to Fig. 15 are the results for the analysis at a plant power change transient. The power level changes first from 5% to 25% power at the rate of 1% per 3minutes and stays at 25% for 90minutes during the transition period for the operation mode switching. Then again the level changes to 100% power level at 1% per 3.7minutes. The rates were chosen considering that the most severe requirement to the transient operation capability in the EPRI URD [6] is 2% per minute for a 10% power change as the load follow capability.

Fig. 12 shows the profiles of the system temperatures, heat actually transferred by the steam generator *RQt*, the target power level *tgnQ* and the operation status indication paramter *irc*. The parameter *irc* is 1 when the operation mode is the recirculation and 0 when the mode is the once-through. In the names of the temperatures curves, the letters I and H respectively mean the temperature of IHTS and water (H_2O). In the figure, the temperature changes are generally smooth and the most rapid change among them is made at the steam temperature(*TSGBn_H_ex*) for the period from *t*=5,000 second to about 7,500 second. This period belongs to the operation switching period which was from *t*=3,500 second to 8,900 second. If a thermal load analysis turns out to be that the change in this period is too severe, the following two measures can be



A. Temperatures



B. Power, SG Exit Quality and Operation Status

Fig. 12. SGS Parameter Changes at the Power Change from 5% to 100% - Heat Related Parameters

considered for reduction of the thermal load.

- Extending the switching period
- If the extending is not practical, then reduce the recirculation flow rate so that the steam quality from the steam generator at the time entering the switching becomes higher.

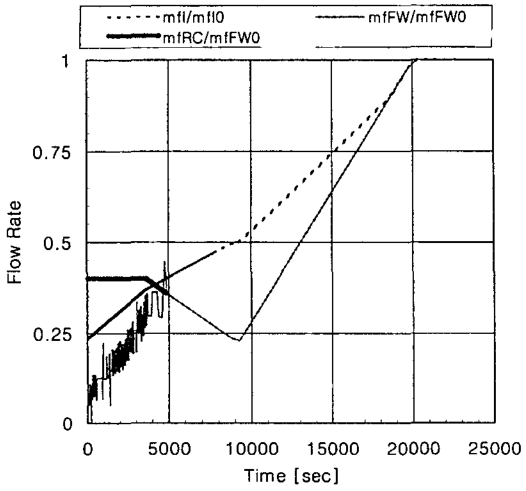


Fig. 13. Flow Rates Change at the Power Change from 5% to 100%

Fig. 13 is for the flow rates. In the figure, the IHTS sodium flow rate *mfI* is shown as the ratio to its value at 100% power and other flow rates are shown as the ratio to the feedwater flow rate at 100% power. The parameter *mfI* is the boundary condition and changed by the operation target. During the recirculation period the reccirculation flow rate *mfRC* is fed to the SG. When the plant power level reaches the switching power (at *t*=3,500sec), *mfRC* decreases by Eq. (17) to match the planned feedwater flow rate at the end of the transition period. After the transition period, the plant is operated at a complete once-through mode and the feedwater flow rate *mfFW* gradually increases as power increases. During the recirculation operation period, the feedwater flow rate increases since the steam quality at the SG exit increases as shown in Fig. 12-B and more steam flows out from SG as the power increases. The fluctuation in the feedwater comes from the fact that its rate is determined by the water level control.

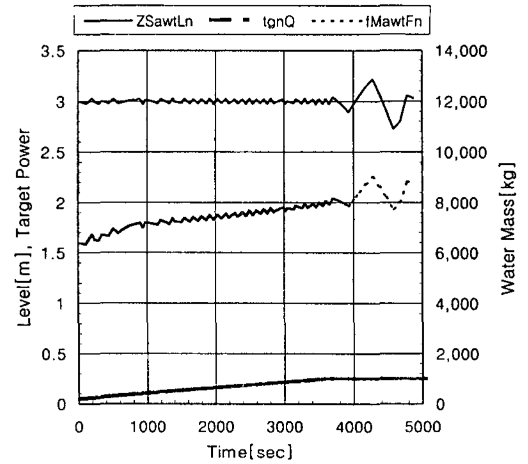


Fig. 14. Water Level and Mass Changes During the Recirculation Operation

Fig. 14 shows the changes of the water level *ZSawtLn* and water mass *fMawtFn* in SGAWT and the target power level *tgnQ* during the recirculation operation period. The level is well controlled up to about 3,600 second and then it shows relatively large fluctuation. This is because the system enters the transition operation mode at t=3,500sec and the transient profiles of the IHTS temperature, feedwater temperature and recirculation flow rate become different from the previous time period as shown in Fig. 12 and explained by Eq. (22). This change in the boundary conditions causes a relatively severe load to the control and fluctuation occurs. The magnitude of the fluctuation, however, is still less than 0.3m and that can not be a practical problem and it can be said the level control algorithm introduced in this study performs well. The water mass increases since the quality of the water in the tank decreases with the power increase as explained in Fig. 11.

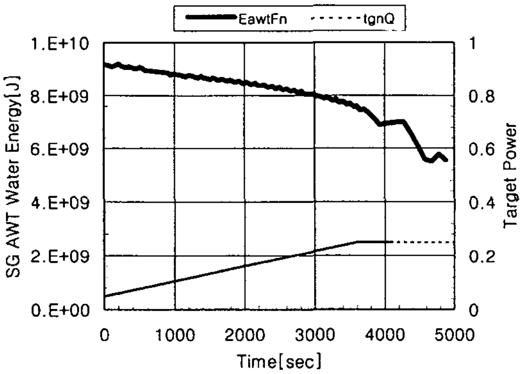


Fig. 15. Water Energy Change During the Recirculation Operation

Fig. 15 is for the energy of the SGAWT water *EawtFn* and shows the energy decreases when the power level increases. As the power increases, the water mass increases as shown in Fig. 14 but the water quality decreases as shown in Fig. 11 but the quality increase rate is more rapid and consequentially the energy in the tank comes to decrease. This trend also supports the discussion on the function of the recirculation operation of Article 5.1, i.e., 'The role of the recirculation operation is not for the transition of the SGS itself but the support of SGS to the plant so that the plant status can be progressed from a zero power operation level to a turbine operation power level.'

As an additional remark, the use of the steady state analyzer for the SG in the transient analysis shown here does not give any significant influence to the findings from the analysis since what were taken from the analysis results are not the quantities but the trend and general features of the plant operation with the recirculation operation.

6. Conclusions

The features of the recirculation operation in LMR with a superheated steam cycle which are different from those of PWR and a fossil plant were investigated. The major findings and works made by this study are summarized as the following.

1. The features of the trends in the temperatures and flow rates changes when the plant power increases from low power to 100% have been found.
2. The qualitative requirements to the recirculation flow rate have been derived.
3. The plant operation target values need to be set in conjunction with the recirculation operation characteristics of SGS and the plant operation targets used in this study are good for the plant power operation including the recirculation operation.
4. The basic algorithm of the water level control logic utilizing digital control features performs well for the control.
5. The code TSGS developed in this study for the analysis of SGS performance performs well.

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