Condition monitoring of steam generator by estimating the overall heat transfer coefficient

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Abstract: This study develops a technique for monitoring in on-line the state of the steam generator of the fast-breeder reactor (FBR) “Monju”. Because the FBR uses liquid sodium as coolant, it is necessary to handle liquid sodium with caution due to its chemical characteristics. The steam generator generates steam by the heat of secondary sodium coolant. The sodium-water reaction may happen if a pinhole or crack occurs at the thin metal tube wall that separates the secondary sodium coolant and water/steam. Therefore, it is very important to detect an anomaly of the wall of heat transfer tubes at an early stage. This study aims at developing an on-line condition monitoring technique of the steam generator by estimating overall heat transfer coefficient from process signals. This paper describes simplified mathematical models of superheater and evaporator to estimate the overall heat transfer coefficient and a technique to diagnose the state of the steam generator. The applicability of the technique is confirmed by several estimations using simulated process signals with artificial noises. The results of the estimations show that the developed technique can detect the occurrence of an anomaly.

Keyword: status diagnostics; overall heat transfer coefficient; heat transfer tube; steam generator; fast-breeder reactor

1 Introduction

The fast-breeder reactor (FBR) “Monju” uses liquid sodium as coolant. It is necessary to handle liquid sodium with caution due to its chemical characteristics. The steam generator that consists of evaporator and superheater generates steam by the heat of sodium coolant. Because the secondary coolant of liquid sodium faces to water/steam across a thin metal tube wall in the steam generator, the sodium-water reaction may happen if a pinhole or crack occurs at the wall of a heat transfer tube. Therefore, it is very important to detect an anomaly of the wall of heat transfer tubes at an early stage.

Inspection techniques [1]-[4] such as Eddy Current Testing (ECT) are widely applied for inspecting the wall of heat transfer tubes. However, an inspection by the techniques takes much time and many processes such as cool-down process, coolant drain, inspection preparations, inspection, heating-up process and coolant filling. Although they give detailed inspection results, they are not applicable to detect the happening of an anomaly during plant operation.

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This study aims at developing an on-line technique for condition monitoring of the steam generator by estimating overall heat transfer coefficient that is an unobserved important state variable from process signals such as temperature, pressure and flow rate in various portions of plant. This technique can monitor the state of the steam generator during operation and doesn’t need much time and processes.

When a pinhole, a crack, or erosion-corrosion wastage occurs at the wall of a heat transfer tube, the overall heat transfer coefficient increases due to the decrease in thermal resistance. So, an anomaly of the wall of heat transfer tube can be detected at an early stage by estimating and monitoring the overall heat transfer coefficient. On the other hand, the overall heat transfer coefficient decreases due to the increase in thermal resistance by adherence of water stain or scale to the wall of a heat transfer tube. So, it is possible to grasp a degradation of heat-transfer efficiency with estimating and monitoring the overall heat transfer coefficient.

This paper describes simplified mathematical models of superheater and evaporator to estimate the overall heat transfer coefficient and a technique to diagnose the state of the steam generator. The applicability of the technique is examined by several estimations using simulated process signals with artificial noises for the cases of a normal operation and the happening of an anomaly such that water stain adheres to the wall of heat transfer tube of evaporator.

2 Simplified models of superheater and evaporator

2.1 Superheater

The superheater of Japanese prototype FBR “Monju” consists of a cylindrical vessel with a helical heat transfer tube bundle inside as shown in Fig. 1. The number of helical heat transfer tubes is 147. The liquid sodium flows through the vessel outside the helical heat transfer tubes and the steam flows inside the helical heat transfer tubes [5][6].

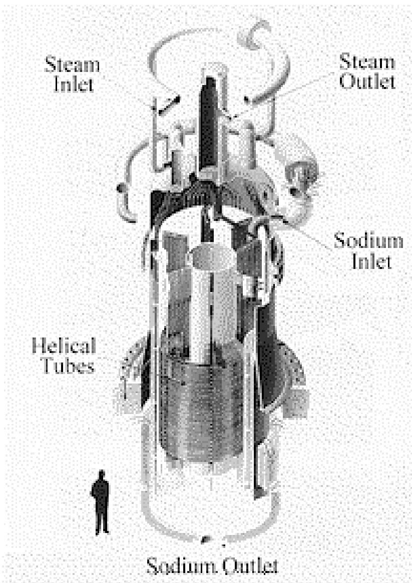

Fig. 1 Structure of superheater [5].

Although the superheater has a complicated structure, the superheater is expressed in a simplified model of countercurrent type as shown in Fig. 2 due to the small number of process signals available to estimate the overall heat transfer coefficient. In addition, the heat exchange between the vessel and the gas around the superheater is ignored and all steam flowing into the superheater is assumed to be superheated steam.

The overall heat transfer coefficient can be estimated from few process signals based on the simplified mathematical model. This simplified mathematical model is applicable to a heat exchanger of various plants because the basic structure of them is similar to the structure of “Monju” superheater.

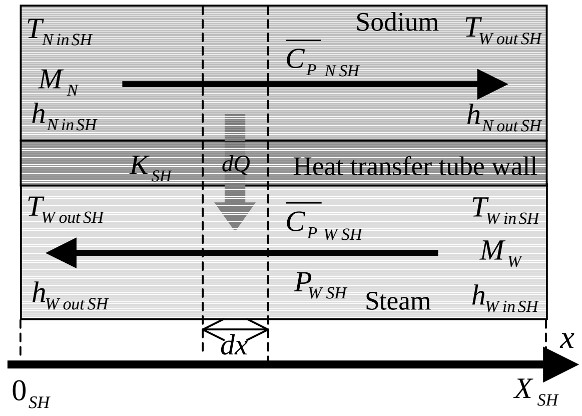

Fig. 2 Schematic of a simplified model of superheater.

2.2 Evaporator

The structure of the evaporator of Japanese prototype FBR “Monju” is similar to that of the superheater as shown in Fig. 3. The number of helical heat transfer tubes is 140. The liquid sodium flows through the vessel outside the helical heat transfer tubes and the steam flows inside the helical heat transfer tubes [6][7].

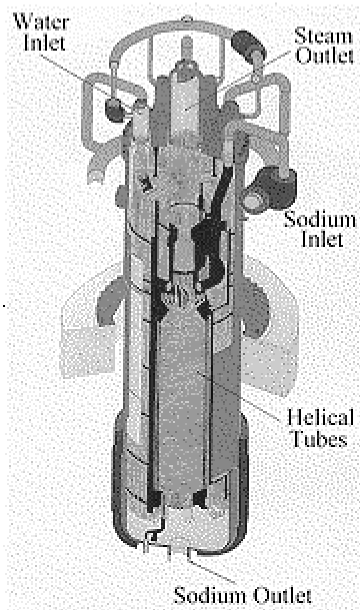

Fig. 3 Structure of evaporator [7].

The complicated structure of the evaporator is expressed in a simplified model of countercurrent type as shown in Fig. 4 for deriving mathematical equations to estimate the overall heat transfer coefficient of evaporator. The heat exchange between the vessel and the gas around the evaporator is ignored and the inner volume of the evaporator tubes and cylindrical vessel is divided into compressed water region, saturated water region and superheated steam region depending on the state of water.

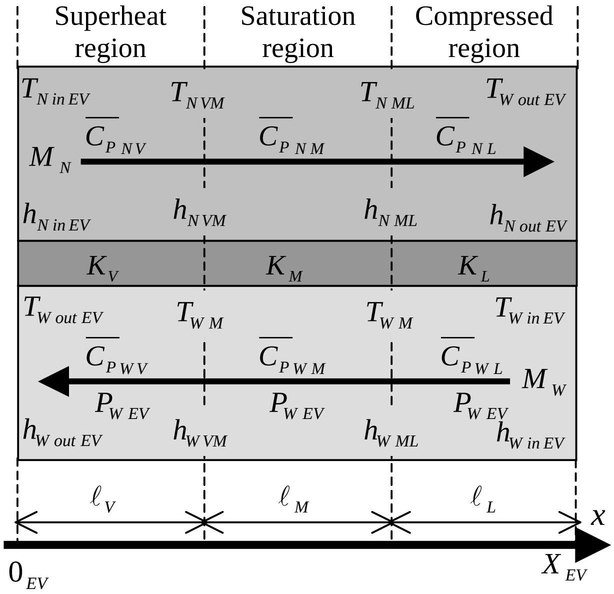

Fig. 4 Schematic of a simplified model of evaporator.

3 Mathematical expressions of simplified models for estimating overall heat transfer coefficient

3.1 Superheater

The mathematical expressions of the simplified model of superheater to estimate overall heat transfer coefficient of superheater K_{SH} are derived by considering the heat balance in minute interval dx as shown in Fig. 2. Two mathematical expressions are derived from the energy balance equations of secondary sodium and superheated steam [8]. The final mathematical expressions for estimating overall heat transfer coefficient of superheater K_{SH} are shown as Eq. (1) and (2).

$$K_{SH} = \frac{M_N \left(h_{N\,in\,SH} - h_{N\,out\,SH}\right)\left(\log \Delta T_{X_{SH}} - \log \Delta T_{0_{SH}}\right)}{R_{SH} X_{SH} \left(\Delta T_{X_{SH}} - \Delta T_{0_{SH}}\right)} \quad (1)$$

$$K_{SH} = \frac{M_W \left(h_{W\,out\,SH} - h_{W\,in\,SH}\right)\left(\log \Delta T_{X_{SH}} - \log \Delta T_{0_{SH}}\right)}{R_{SH} X_{SH} \left(\Delta T_{X_{SH}} - \Delta T_{0_{SH}}\right)} \quad (2)$$

As seen in Eq. (2), the overall heat transfer coefficient K_{SH} is estimated from the quantities of mass flow rate of steam M_W, inlet and outlet specific enthalpy of steam $h_{W\,in\,SH}$, $h_{W\,out\,SH}$, total heat transfer area of superheater $A_{all\,SH} = R_{SH} X_{SH}$ and temperature difference between liquid sodium and steam at both ends of superheater $\Delta T_{0_{SH}}$ and $\Delta T_{X_{SH}}$.

3.2 Evaporator

In the case of evaporator, the inner volume of the evaporator tubes and cylindrical vessel is divided into compressed water region, saturated water region and superheated steam region as shown in Fig. 4. The overall heat transfer coefficient of compressed water region, saturated water region and superheated steam region of evaporator are denoted as K_L, K_M and K_V, respectively. In the same way as deriving the mathematical expressions for estimating overall heat transfer coefficient of the superheater, the following mathematical expressions are obtained for estimating overall heat transfer coefficients of the regions of evaporator as shown in Eq. (3) ~ (5) [8].

$$K_V = \frac{M_W \left(h_{W\,out\,EV} - h_{W\,VM}\right)\left(\log \Delta T_{VM} - \log \Delta T_{0_{EV}}\right)}{R_{EV}\, \ell_V \left(\Delta T_{VM} - \Delta T_{0_{EV}}\right)} \quad (3)$$

$$K_L = \frac{M_W \left(h_{W\,ML} - h_{W\,in\,EV}\right)\left(\log \Delta T_{X_{EV}} - \log \Delta T_{ML}\right)}{R_{EV}\, \ell_L \left(\Delta T_{X_{EV}} - \Delta T_{ML}\right)} \quad (4)$$

$$K_M = \frac{M_W \left(h_{W\,VM} - h_{W\,ML}\right)\left(\log \Delta T_{ML} - \log \Delta T_{VM}\right)}{R_{EV}\, \ell_M \left(\Delta T_{ML} - \Delta T_{VM}\right)} \quad (5)$$

Equations (3) to (5) include the lengths of the three regions ℓ_V, ℓ_M and ℓ_L which are not actually observed. The equations that do not include the lengths of the three regions must be derived to estimate the overall heat transfer coefficient of each region. However, it is difficult to derive these equations because the number of relational equations is smaller than the number of unknown variables.

We make the following assumptions because it is considered that the adherence of water stain and scale to the wall of a heat transfer tube tends to occur in not superheated steam region but compressed water region. One of the assumptions is that the overall heat transfer coefficient of superheated steam region of evaporator is calculated from that of superheater and the value of it is treated as known. In addition, in the saturated water region of evaporator, it is assumed that saturated steam and saturated water have contact with the wall of a heat transfer tube in the proportion of specific volume of saturated vapor a to that of saturated water b. Then, the overall heat transfer coefficient of saturated water region K_M is given by

$$K_M = \frac{aK_V + bK_L}{a+b}. \tag{6}$$

The total heat transfer area of the evaporator $A_{all\,EV}$ is given by

$$A_{all\,EV} = R_{EV} X_{EV} = R_{EV}\left(\ell_V + \ell_M + \ell_L\right). \tag{7}$$

By substituting Eq. (3) ~ (6) into Eq. (7) and solving it for K_L, the following equation is obtained:

$$K_L = \frac{\begin{bmatrix} -K_V\left(aA_{all\,EV}K_V - a\alpha_1 - b\alpha_2 - c\alpha_3\right) \\ + K_V\sqrt{\begin{matrix}\left(aA_{all\,EV}K_V - a\alpha_1 - b\alpha_2 - c\alpha_3\right)^2 \\ + 4ab\alpha_2\left(A_{all\,EV}K_V - \alpha_1\right)\end{matrix}} \end{bmatrix}}{2b\left(A_{all\,EV}K_V - \alpha_1\right)}, \tag{8}$$

where α_1, α_2 and α_3 are given by the following equations.

$$\alpha_1 = \frac{M_W\left(h_{W\,out\,EV} - h_{W\,VM}\right)\left(\log\Delta T_{VM} - \log\Delta T_{0_{EV}}\right)}{\left(\Delta T_{VM} - \Delta T_{0_{EV}}\right)} \tag{9}$$

$$\alpha_2 = \frac{M_W\left(h_{W\,ML} - h_{W\,in\,EV}\right)\left(\log\Delta T_{X_{EV}} - \log\Delta T_{ML}\right)}{\left(\Delta T_{X_{EV}} - \Delta T_{ML}\right)} \tag{10}$$

$$\alpha_3 = \frac{M_W\left(h_{W\,VM} - h_{W\,ML}\right)\left(\log\Delta T_{ML} - \log\Delta T_{VM}\right)}{\left(\Delta T_{ML} - \Delta T_{VM}\right)} \tag{11}$$

In Eq. (8), the overall heat transfer coefficient of superheated steam region is calculated from that of superheater. The thermal resistance of superheater $1/K_{SH}$ is given by

$$\frac{1}{K_{SH}} = \frac{1}{\gamma_{N\,SH}} + \frac{d_{SH}}{\lambda_{SH}} + \frac{1}{\gamma_{W\,SH}}, \tag{12}$$

where $\gamma_{N\,SH}$, $\gamma_{W\,SH}$, d_{SH} and λ_{SH} are mean heat transfer coefficient between liquid sodium and wall of heat transfer tube of superheater, heat transfer coefficient between steam and wall of heat transfer tube of superheater, and thickness and thermal conductivity of heat transfer tube of superheater, respectively.

The thermal resistance of superheated steam region of evaporator $1/K_V$ is given by

$$\frac{1}{K_V} = \frac{1}{\gamma_{NV}} + \frac{d_V}{\lambda_V} + \frac{1}{\gamma_{WV}}, \tag{13}$$

where γ_{NV}, γ_{WV}, d_V and λ_V are mean heat transfer coefficient between liquid sodium and wall of heat transfer tube of evaporator in superheated steam region, heat transfer coefficient between steam and wall of heat transfer tube of evaporator in superheated steam region, thickness and thermal conductivity of heat transfer tube of evaporator in superheated steam region, respectively. It is assumed that

$$\gamma_{NV} \approx \gamma_{N\,SH} \tag{14}$$

and

$$\gamma_{WV} \approx \gamma_{W\,SH}. \tag{15}$$

By substituting Eqs. (12), (14), and (15) to into Eq. (13) and solving for K_V, the following equation is obtained:

$$K_V = \frac{K_{SH}\lambda_{SH}\lambda_V}{\lambda_{SH}\lambda_V - K_{SH}\lambda_V d_{SH} + K_{SH}\lambda_{SH}d_V}. \tag{16}$$

As the results of manipulation, the mathematical expressions of the simplified model for estimating overall heat transfer coefficient of superheated steam region, compressed water region and saturated water region are Eq. (16), (8) and (6), respectively.

By the assumptions mentioned above, the estimated values of overall heat transfer coefficient of superheated steam region vary in the same way as that of superheater. For the same reason, the estimated values of overall heat transfer coefficient of saturated water region vary in the same way as that of superheated steam region and compressed water region. In this study, we monitor the estimated values of overall heat transfer coefficient of compressed water region K_L for diagnosing the state of evaporator.

4 Condition monitoring of steam generator by the estimation of overall heat transfer coefficient

4.1 Evaluation method

According to experts of "Monju" staffs, it is desirable to be able to monitor 0.5% variation in overall heat transfer coefficient for diagnosing the abnormality of the steam generator. The monitoring accuracy is required because the variation of heat transferred to evaporator should be less than 0.5 % to ensure the output steam from evaporator to be superheated.

Because the overall heat transfer coefficient stays fairly constant in a steady operation, it is considered to be able to judge steam generator as normal if the variations, the so-called relative errors, in estimated values of overall heat transfer coefficient are less than ±0.5%. The relative error of an estimated value of overall heat transfer coefficient is calculated from the following equation:

$$e_i = \frac{K_i - \overline{K}}{\overline{K}} \times 100 , \tag{18}$$

where e_i, K_i, $\overline{K}$ are relative error, estimated value of overall heat transfer coefficient and average of all estimated values of overall heat transfer coefficient, respectively.

4.2 Estimation at steady operating condition

We estimate overall heat transfer coefficient by the derived mathematical expressions using simulated process signals for confirming whether or not the relative errors in estimated values of overall heat transfer coefficient are less than ±0.5%. The simulated process signals are generated from the calculated process signals by a plant dynamics analysis code NETFLOW++ [9] for a steady operating test of "Monju" at 40% electrical power output. The process signals are obtained every one second. The characteristics of sensor noises and specific fluctuations of process signals are analyzed using the measured process signals of "Monju" during steady operating tests at 40% electric power output. Autoregressive models (AR models) are used to express dynamic characteristics of noises and specific fluctuations for observed signals. Artificial noises are generated by the AR models and added to the calculated process signals by NETFLOW++ to imitate to the real process signals. The similarity of the artificial noises generated by the AR models is confirmed by comparing the frequency-domain characteristics between the artificial noises and real noises observed.

Butterworth type digital low pass filters are used to reduce the influence of the noises. The cut-off frequencies are determined by considering the frequency-domain characteristics of the noises. The time averaging process is also applied for the filtered process signals. The overall heat transfer coefficient is estimated by changing the number of observed signals in time averaging process. The estimation using time averaged process signals for 5 minutes (300 samples) show that all relative errors of estimated values are less than ±0.5% [8].

4.3 Condition monitoring technique

Considering the request by experts that the overall heat transfer coefficient should be estimated within 0.5% variation, the state of steam generator is judged as an anomalous one when the estimated value of overall heat transfer coefficient is more than ±0.5%. However, we may misjudge the state of steam generator as an anomalous state by big noises included momentary in the process signals.

In order to avoid the misjudgment, two evaluation indicators shown in Table 1 and 2 are defined and a confidence value that expresses the self-evaluation result of the reliability of condition monitoring is calculated. The evaluation indicator 1 expresses the degree of deviation from the normal value. However, the deviation sometimes becomes large due to big noises of observed signals resulting in a diagnosis error. Big noises rarely happen in consecutive sampling times. The evaluation indicator 2 relates with consecutive number of times of deviation from the normal value. It is effective to avoid the diagnosis error. Therefore, the confidence value in anomaly diagnosis is given by multiplying both evaluation indicators.

Table 1 Evaluation indicator 1 related with the degree of deviation from the normal value

Absolute value of relative error of overall heat transfer coefficient	Evaluation indicator 1
|K| < 0.55%	0
0.55% <= |K| < 0.60%	0.1
0.60% <= |K| < 0.65%	0.2
0.65% <= |K| < 0.70%	0.3
0.70% <= |K| < 0.75%	0.4
0.75% <= |K| < 0.80%	0.5
0.80% <= |K| < 0.85%	0.6
0.85% <= |K| < 0.90%	0.7
0.90% <= |K| < 0.95%	0.8
0.95% <= |K| < 1.00%	0.9
1.00% <= |K|	1.0

Table 2 Evaluation indicator 2 related with the consecutive number of times of deviation from the normal value

Consecutive number of times of deviation from normal state	Evaluation indicator 2
0	0
1	0.1
2	0.2
3	0.3
4	0.4
5	0.5
6	0.6
7	0.7
8	0.8
9	0.9
10	1.0

4.4 Condition monitoring using simulated process signals

For confirming whether or not the developed technique can detect the occurrence of an anomaly, we estimate overall heat transfer coefficient by the mathematical expressions using simulated process signals at the happening of a small anomaly.

The simulated process signals are calculated using plant dynamics analysis code NETFLOW++. The "Monju" operation condition in the calculation is in the steady operation at 40% electrical power output for first 999 seconds and in the condition with an anomaly happened at 1000 seconds. The anomaly is the water stain of 0.1mm that adheres in a stepwise manner to the wall of heat transfer tube of evaporator. The adherence of stain induces the degradation of heat transfer of evaporator. The process signals are obtained every one second. The sensor noises and specific fluctuations of process signals are generated by AR models considering the analysis results of them using the measured observed signals of "Monju" during steady operating tests at 40% electric power output. The generated artificial noises are added to the calculated process signals by NETFLOW++.

The overall heat transfer coefficients are estimated using the process signals with the artificial noises after filtering noises by the digital filters and time averaging for 5 minutes to reduce the sensor noises of the process signals. Figures 5 and 6 show the estimated results of overall heat transfer coefficient and the calculated confidence values for evaporator and superheater, respectively.

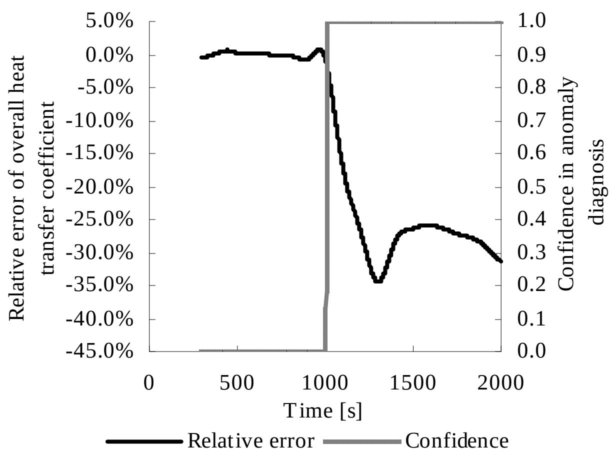

Fig. 5 Estimated results of overall heat transfer coefficient of evaporator and calculated confidence in condition monitoring.

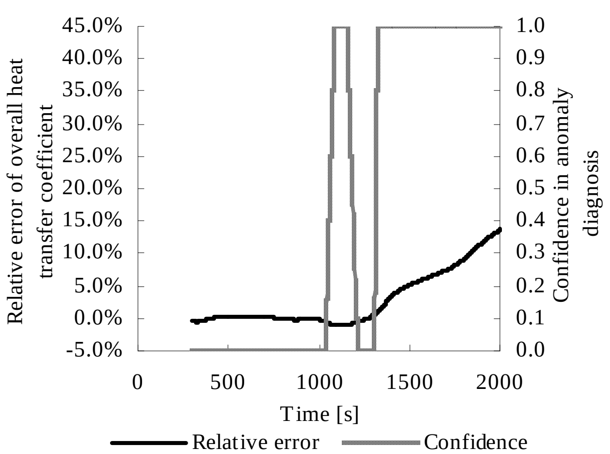

Fig. 6 Estimated results of overall heat transfer coefficient of superheater and calculated confidence in condition monitoring.

As the result of the estimation of overall heat transfer coefficient of evaporator, the developed technique can detect the occurrence of the anomaly. The anomaly is detected after 4 seconds since it occurs. The confidence value in condition monitoring becomes 1.0 after 13 seconds since the anomaly occurs.

While, as the result of the estimation of overall heat transfer coefficient of superheater, the developed technique also can detect the occurrence of the anomaly. This result is thought that the reduction of inlet steam temperature of superheater by the reduction of overall heat transfer coefficient of evaporator influences that of superheater. The anomaly is detected after 38 seconds since it occurs. The confidence value in anomaly diagnosis becomes 1.0 after 86 seconds since the anomaly occurs. The time to detect the anomaly by estimating overall heat transfer coefficient of superheater is later than the time of evaporator.

The reason why the confidence value in Fig. 6 shows the sharp drop at around 50 seconds is explained in the following. As shown in Fig. 6, the overall heat transfer coefficient slightly decreases by increasing the temperature difference between the inlet steam of superheater and outlet sodium of superheater when the anomaly happens. Then, the overall heat transfer coefficient gradually increases because of the decrease of the temperature difference. Because the overall heat transfer coefficient becomes a value in the normal range, the evaluation indicator 1 becomes to zero for a while resulting in the sharp drop of the confidence value.

5 Conclusions

In this study, an on-line technique has been developed for condition monitoring of the steam generator of the FBR “Monju”. The condition of steam generator is diagnosed from the estimated overall heat transfer coefficient, which is an unobserved important state variable, from observed process signals such as temperature, pressure and flow rate. Monitoring the fluctuation of estimated values of overall heat transfer coefficient enables to detect an anomaly of the wall of heat transfer tube at an early stage. This technique can diagnose the steam generator during operation and doesn’t require much time and processes.

The superheater and evaporator, which constitute the steam generator, are expressed in simple models of countercurrent type. The mathematical expressions for estimating the overall heat transfer coefficient are derived considering the heat balances in the simple models of superheater and evaporator.

The applicability of the technique is examined by several estimations of overall heat transfer coefficient using simulated process signals with artificial noises. As the result of the estimation of overall heat transfer coefficient of evaporator, the developed technique can detect the occurrence of the anomaly at an early stage after the happening of the anomaly.

The overall heat transfer coefficient will change when the flow conditions of secondary sodium and steam/water change. This means that the developed technique will apply the detection of the anomaly that influences the flow conditions of steam generator.

Nomenclature

x : Distance from inlet [m]
dx : Minute interval of heat transfer tube [m]
$\overline{C_p}$: Averaged specific heat under constant pressure [J/kg °C]
M : Mass flow rate [kg/s]
T : Temperature [°C]
ΔT : Difference in temperature between liquid sodium and water/steam [°C]
P : Pressure [MPa]
h : Specific enthalpy [J/kg]
X : Length of heat transfer tube [m]
ℓ : Length of region [m]
R : Circumferential length of heat transfer tube [m]
A : Heat transfer area in dx [m^2]
A_{all} : Total heat transfer area [m^2]
Q : Total amount of heat transfer [W]
K : Overall heat transfer coefficient [W/ (m^2 °C)]
$\overline{K}$: Averaged Overall heat transfer coefficient [W/ (m^2 °C)]
r : Heat transfer coefficient [W/ (m^2 °C)]
λ : Thermal conductivity [W/ (m °C)]
d : Thickness of heat transfer tube [m]

Subscripts;
N : Liquid sodium
W : Water/Steam

SH : Superheater
EV : Evaporator
L : Compressed water region in evaporator
M : Saturated water region in evaporator
V : Superheated water region in evaporator
VM : Boundary between superheated steam region and saturated water region in evaporator
ML : Boundary between saturated water region and compressed water region in evaporator
in : Inlet
out : Outlet

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References

[1] ONOUE, A., and YAMADA, F.: Development of Inspection Technique for future Commercialized FBRs, Japan, Japan Nuclear Cycle Development Institute, 2002.

[2] ONOUE, A., and YAMADA, F.: Development of Inspection Technique for future Commercialized FBRs, Japan, Japan Nuclear Cycle Development Institute, 2003.

[3] ONOUE, A., NISHI, H., YAMADA, F., TERUYAMA, H., ISHIBASHI, J., KAGEYAMA, T., and KINJO, H.: Elemental Technology Development of the FBR (3) –Study of Inspection Technique and MA Incineration Technique for the Improvement of FBR Economy–, JNC Technical Review, 2004, 24 separate volume: 107-118.

[4] TAKAHASHI, K., SHIINA, A., ONIZAWA, T., IBAKI, S., YAMAGUCHI, T., and TAGAWA, A.: Inspection of the Steam Generator Heat Transfer Tubes for FBR Monju Restart, Proceedings of ICONE17, 2009.

[5] Technical information of Monju -Auxiliary Building & Secondary Loops- Superheater, http://www.jaea.go.jp/04/monju/EnglishSite/contents02-3-2.html#AB3.

[6] Technical information of Monju -Basic specification-, http://www.jaea.go.jp/04/monju/EnglishSite/contents02-1.html#BS7.

[7] Technical information of Monju -Auxiliary Building & Secondary Loops- Evaporator, http://www.jaea.go.jp/04/monju/EnglishSite/contents02-3-2.html#AB2.

[8] FURUSAWA, H. and GOFUKU, A.: Diagnosis of steam generator by estimating an unobserved important state variable, Journal of Nuclear Science and Technology (submitted to).

[9] MOCHIZUKI, H.: Development of the plant dynamics analysis code NETFLOW++, Nuclear Engineering and Design, 2010, 240: 577-587.