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A simplified mathematical model of a U-tube steam generator under variable load conditions

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Abstract A steam generator in a nuclear power plant with a light water reactor is a heat exchanger, in which the heat is being transferred from the primary to the secondary loop (it links the primary and secondary loops). When the power plant is running, the inlet parameters (temperatures and mass flow rates) on both sides of the steam generator can change. It is important to know how the changes of these parameters affect the steam generator performance. The complexity of the processes taking place in the steam generator makes it difficult to create a simulator reflecting its performance under changed conditions. In order to simplify the task, the steam generator was considered as a ‘black box’ with the aim of examining how the changes of the inlet parameters affect the changes of the outlet ones. On the basis of the system (steam generator) response, a simple mathematical model of the steam generator under variable load conditions was proposed. In the proposed model, there are two dimensionless parameters and three constant coefficients. A linear relation between these dimensionless parameters was obtained. The correctness of the model was verified against the data obtained with a steam generator simulator for European Pressured Reactor and AP-600 reactors. A good agreement between the proposed model and the simulator data was achieved.

Keywords: Steam generator; Mathematical model under variable load conditions

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Nomenclature

A_1, A_2, A_3, A_4	– constant coefficients
a_1, a_2, a_3, a_4	– constant coefficients
\dot{m}_{in}	– mass flow rate (primary loop), kg/s
\dot{m}_s	– mass flow rate (secondary loop), kg/s
M	– dimensionless quantities
p_{in}	– pressure at the inlet to the steam generator (primary loop), Pa
p_s	– water supply pressure (secondary loop), Pa
p_{sat}	– saturation pressure, Pa
T_{in}	– temperature at the inlet to the steam generator (primary loop), K
T_s	– water supply temperature (secondary loop), K
T_{sat}	– saturation temperature, K
T_{out}	– temperature at the outlet of the steam generator (secondary loop), K

Greek symbols

Π	– dimensionless quantities
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Subscripts

in	– inlet
o	– reference state
out	– outlet
s	– supply
sat	– saturation

1 Introduction

In power plants with pressurised water reactors (PWR), a steam generator is an important component that links the primary and secondary loops. In European pressured water reactor (EPR) and AP-600 reactors, the steam generator is a U-tube shell-and-tube heat exchanger. In the primary loop, the pressurized water flows through the reactor core to collect the energy from the uranium fission, and then inside the tubes of the steam generator to transfer the heat to the secondary side fluid. On the secondary side, the heat is collected by feed water which evaporates [1,2]. The generated steam is sent to a turbine where it expands, and work is performed. A diagram of the power plant with the PWR and the steam generator [3] is shown in Fig. 1. On the primary side, the fluid at the inlet and outlet of the steam generator is water; on the secondary side, however, there is water at the inlet and the almost saturated steam at the outlet. An example of temperature distribution in the PWR steam generator is shown in Fig. 2 (the

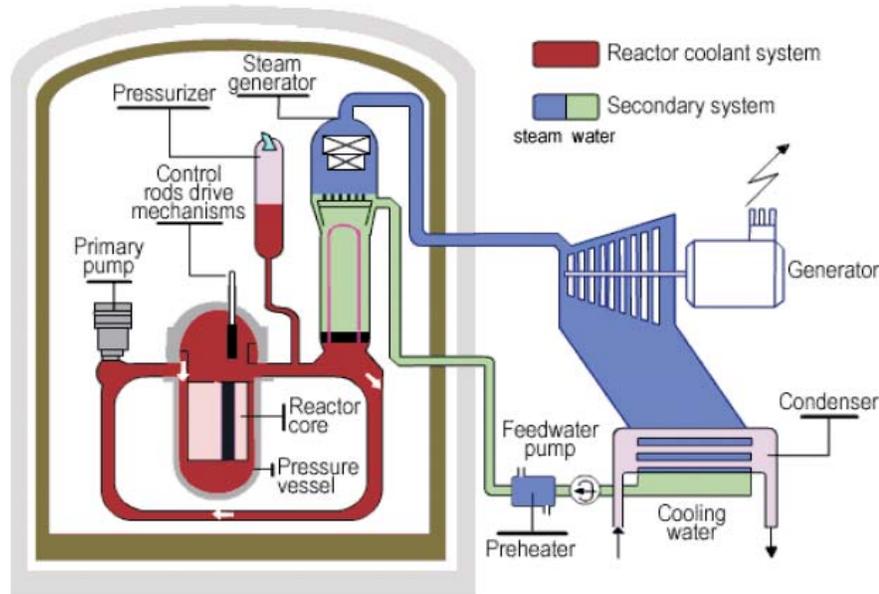


Figure 1. The diagram of the system with a PWR [3].

pressure drop in the secondary loop was not considered). On the secondary side in the latest steam generators, economizers are used, in which the water is heated to reach the state of saturation. Using the economizer makes it possible to raise the steam generator outlet pressure and achieve a higher enthalpy rise in the turbine.

While the PWR power plant is operating, the variations in the turbine load or the reactor power can cause the change of working parameters at the steam generator inlet on the primary and secondary sides. For safety reasons, it is essential to know what effect the changes of the inlet parameters have on the steam generator performance. This can be done by creating a steady-state steam generator simulator. Nevertheless, this task is not easy, which stems from the complexity of phenomena in the steam generator, complex structure, phase change of one of the fluids, and varying direction of the flow of both fluids. In the lower part of the steam generator, the heat is transferred from water to water, while in the upper part from water to the water and steam mixture. On the secondary side, the feed water first flows down, and then it flows up, collects the heat and evaporates (Fig. 3). Non-evaporized water droplets are separated in cyclones

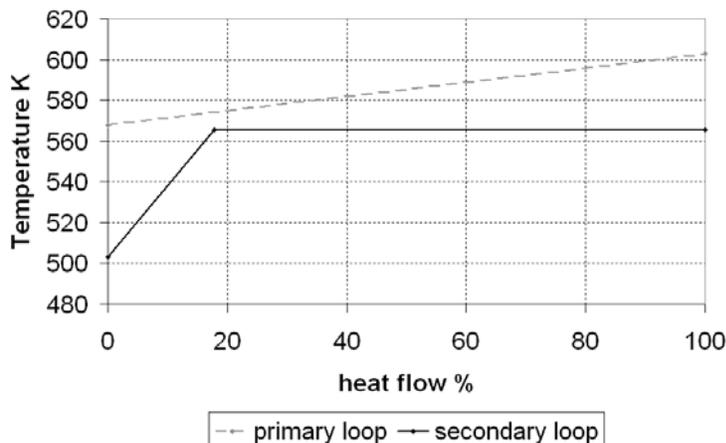


Figure 2. Temperature distribution in the steam generator.

and separators, and flow down for reheating. The dehumidified steam flows to the turbine. On the primary side, the direction of the fluid flow is also changeable. The water from the primary loop flows through the steam generator in the tubes first cocurrently with the steam and water mixture, and then countercurrently. To describe the phenomena in the steam generator, the mass, momentum and energy balance, the Péclet equation and criteria relations are used. In the literature, static [4] and dynamic models [5] employing these relations can be found, as well as models using neural networks [6] and fuzzy models [7,8] of steam generators. The complexity of the processes taking place in the steam generator makes it intricate to create its accurate simulator, and the geometry of the whole assembly and its components has to be known (getting the geometrical dimensions from the manufacturer is very difficult, if not possible at all). Due to these limitations, it was decided that the steam generator should be considered as a 'black box' with the aim of examining how the changes of the inlet parameters affect the changes of the outlet ones. Based on the response of the system defined in this way, creating a mathematical model of the steam generator under changed conditions was proposed. Six variables can be found in the steam generator model: water flow rate in the primary loop, the inlet and outlet temperature on the primary side, the feed water mass flow rate and temperature on the secondary side, and the steam pressure (temperature). We have two equations: the energy balance and Péclet equation.

Hence, we have four independent variables. The inlet mass flow rates were assumed to be equal to the outlet mass flow rates in the simulators. At the beginning, the independent variables were assumed to be: the mass flow rates and temperatures of both fluids at the inlets to the steam generator. Steam saturation temperature and the water temperature at the outlet on the primary side will be determined.

2 The mathematical model

Using the data obtained with the steam generator simulator for an EPR power plant, a relation was obtained describing the steam generator performance under changed conditions. Figure 3 is a diagram of the steam generator [9], illustrating the notation used and the flow directions of both fluids. In the first case, the effect of the primary side inlet water temperature on the secondary side saturation temperature was examined. The secondary side feed water temperature and mass flow rate, and the primary side mass flow rate were constant; only the temperature at the inlet to the steam generator on the primary side varied. The system (steam generator) response to the change of the water temperature at the inlet was linear (Fig. 4)

$$T_{sat} = a_1 T_{in} + a_2 . \quad (1)$$

In the second case, it was examined what effect the change of the mass flow rates on the primary and secondary sides has on the steam generator performance. Dimensionless quantities were introduced:

$$\Pi = \frac{T_{sat} - T_s}{T_{in} - T_s} , \quad (2)$$

and

$$M = \frac{\dot{m}_s}{\dot{m}_{in}} . \quad (3)$$

The inlet temperatures of both fluids were constant; firstly, the primary side water mass flow varied (the secondary side feed water mass flow rate was constant); secondly, the mass flow rate on the primary side was constant, while the one on the secondary side varied. A linear relation between the two dimensionless parameters was obtained (Fig. 5)

$$\Pi = 1 - A_4 M . \quad (4)$$

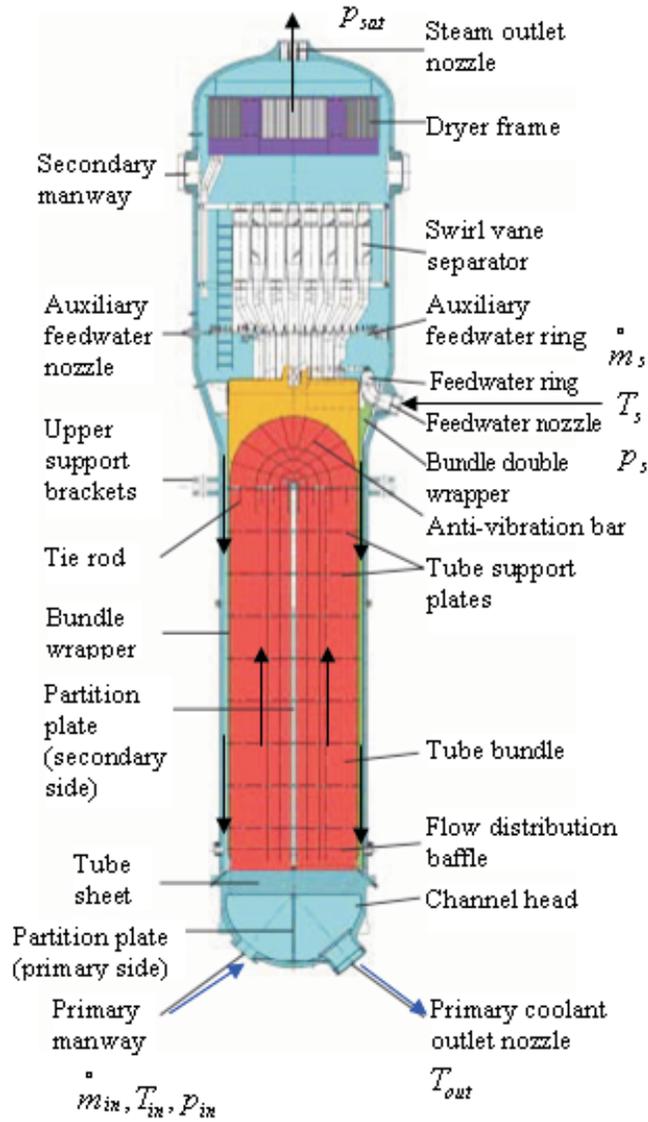


Figure 3. The diagram of the EPR steam generator [9].

Similar formula for the heat transfer effectiveness of the steam condenser was observed as the function of the cooling water mass flow rate [13–16]. No adequate data were available to examine the effect of the feed water temperature on the steam saturation temperature with constant mass flow rates of both the fluids and constant inlet water temperature on the primary side. It is known that when the feed water temperature decreases while the mass flow rate and temperature at the inlet on the primary side remain constant, the steam temperature will also decrease, since the system receives less energy. In line with the analogy of the change of steam temperature following the change of inlet temperature on the primary side Eq. (1), a linear relation between the saturation temperature and the feed water temperature was also assumed.

$$T_{sat} = a_3 T_s + a_4 . \quad (5)$$

A simultaneous effect which the inlet water temperature on the primary side and the feed water temperature on the secondary side have on the steam temperature, with constant mass flow rates of both these fluids, can be illustrated in the following form:

$$T_{sat} = a_1 T_{in} + a_2 + a_3 T_s + a_4 . \quad (6)$$

The relation (6) can be transformed to a form involving a dimensionless parameter Π ,

$$\Pi = 1 - \frac{(A_1 T_{in} + A_2 T_s + A_3)}{T_{in} - T_s} . \quad (7)$$

Comparing the relation (4) for constant inlet temperatures with varying mass flow rates, and the relation (7) for constant mass flow rates and varying inlet temperatures, the effect of all the inlet parameters (the two inlet temperatures and two mass flow rates) on the steam saturation temperature can be written in the form

$$\Pi = 1 - \frac{(A_1 T_{in} + A_2 T_s + A_3)}{T_{in} - T_s} M . \quad (8)$$

In the relation (8), there are three constant coefficients which have to be determined using the measurement data from the real system or from the steam generator simulator. Knowing the three coefficients, one can examine how the steam saturation temperature changes with varying inlet parameters. The water outlet temperature on the primary side can be determined using the energy balance.

3 Results

The correctness of the proposed relation (8) was verified against the data obtained with the EPR steam generator simulator. Firstly, it was examined how the saturation temperature changes while the water temperature at the steam generator inlet on the primary side changes. The other parameters of both fluids at the inlet to the steam generator were constant. The system (steam generator) response was linear (Fig. 4).

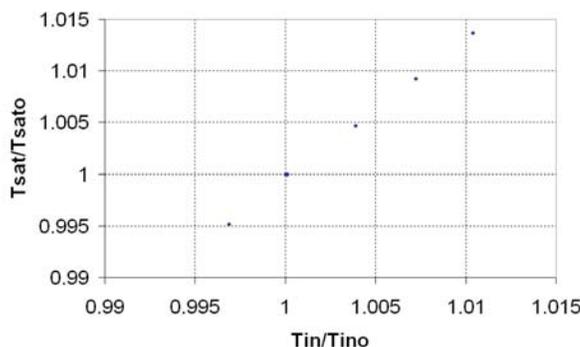


Figure 4. The relation between the steam temperature and the inlet temperature on the primary side of the EPR steam generator.

In further consideration, the relation between the dimensionless parameter Π , Eq. (2), and the dimensionless parameter M , Eq. (3), was examined. The temperatures of both fluids at the inlet to the steam generator were assumed to be constant; the mass flow rates on the primary and secondary sides were changed. For the dimensionless parameters defined in this way, a linear relation was obtained (Fig. 5).

Figure 6 illustrates a comparison between the dimensionless parameters determined from the definition (2) and the one from the proposed relation (8). The points in Fig. 6 are located along a straight line, which proves a very good agreement between the dimensionless parameter Π determined from the definition (2) and the one from the proposed relation (8).

The difference between the dimensionless parameter Π determined from the definition (2), based on the data from the EPR simulator, and the one from the proposed relation (8) as shown in Fig. 7. The differences are within ± 0.025 , which should be considered a satisfactory result. Figure 8 illustrates the difference between the steam temperature obtained with the

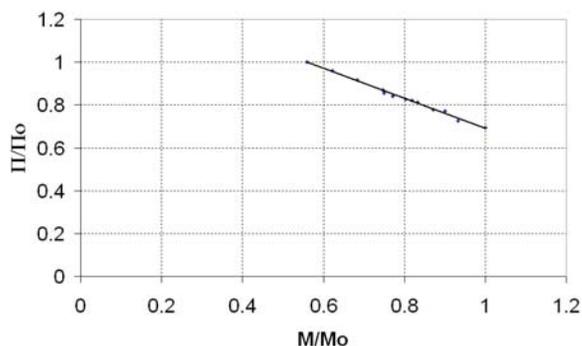


Figure 5. The relation between two dimensionless partameters Π and M for the EPR steam generator.

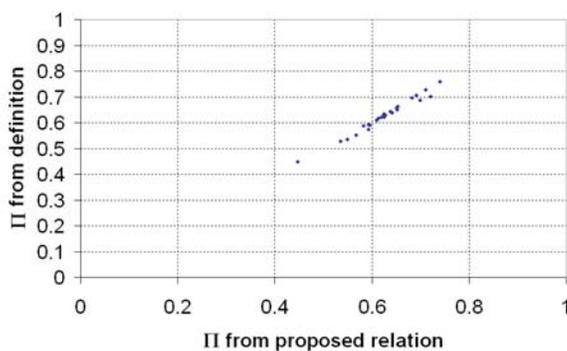


Figure 6. A comparison between the dimensionless parameters determined from the definition (2) and the proposed relation (8) for the EPR steam generator.

EPR simulator and the one calculated from the proposed relation (8). For most data, the differences are within ± 2 K. Only for one analyzed steady state, the difference exceeds this range.

The relation (8) was also verified against the data obtained with the simulator of the AP-600 unit's steam generator [10]. The diagram of the steam generator in the power plant with the AP-600 reactor [11,12] is shown in Fig. 9. In this simulator, the secondary side pressure was kept constant due to the turbine operation. The feed water mass flow rate and temperature on the secondary side, and the water inlet and outlet temperature on the primary side varied. The water pressure and mass flow rate on the primary side were kept constant.

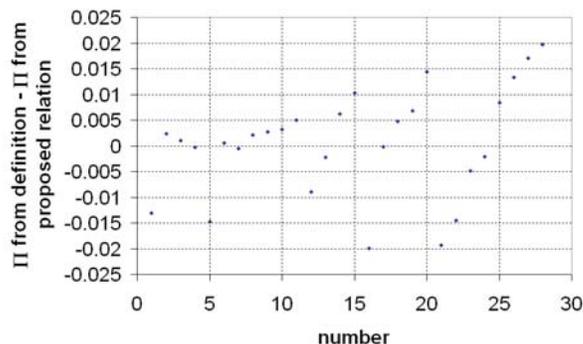


Figure 7. The difference between the dimensionless parameter Π determined from the definition (2) and the one from the proposed relation for the EPR steam generator (8).

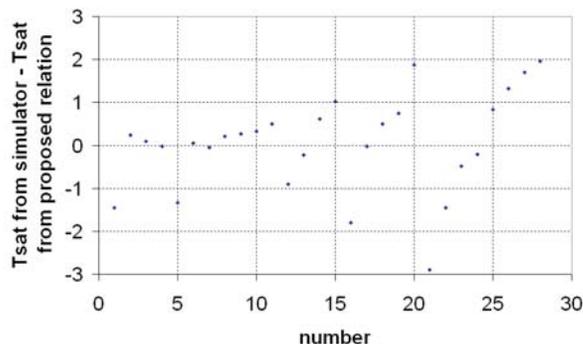


Figure 8. The difference between the steam temperature obtained with the EPR simulator and the one calculated from the proposed relation (8).

In Fig. 10, the relation between the dimensionless parameter Π , Eq. (2), and the dimensionless parameter M , Eq. (3), is shown. Similarly to the EPR steam generator, the linear relation was also obtained for the AP-600 steam generator. Figure 11 illustrates a comparison between the dimensionless parameter determined from the definition (2) and the one from the proposed relation (8) for the AP-600 steam generator. The points in Fig. 11 are located along a straight line, which proves a very good agreement between the dimensionless parameter Π determined from the definition (2) and the one from the proposed relation (8). The difference between the dimensionless parameter Π determined from the definition (2) based on the data from the AP-600 simulator and the one from the proposed relation (8)

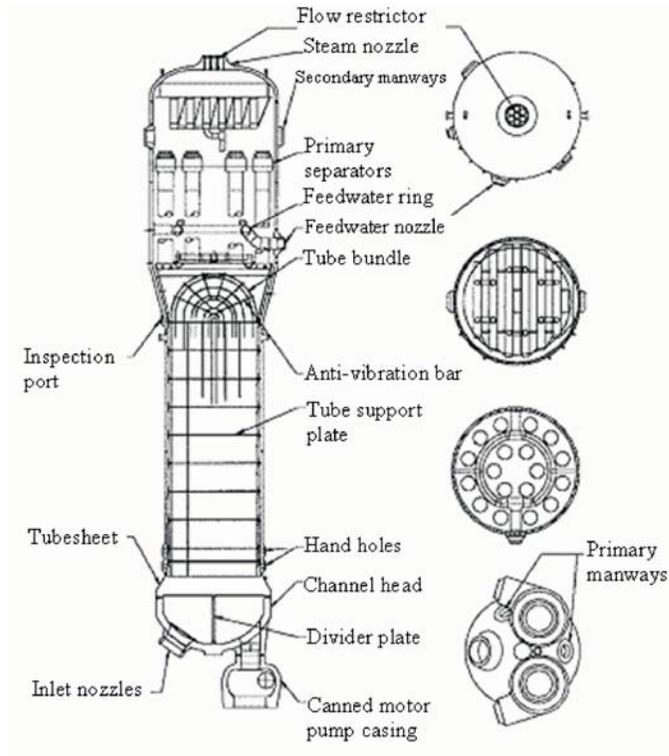


Figure 9. The diagram of the steam generator in the power plant with the AP-600 reactor [11].

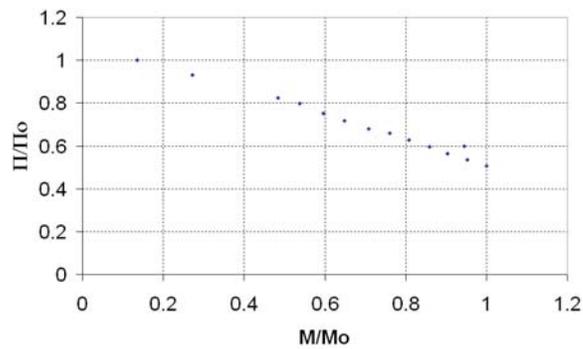


Figure 10. The relation between two dimensionless parameters Π and M for the AP-600 steam generator.

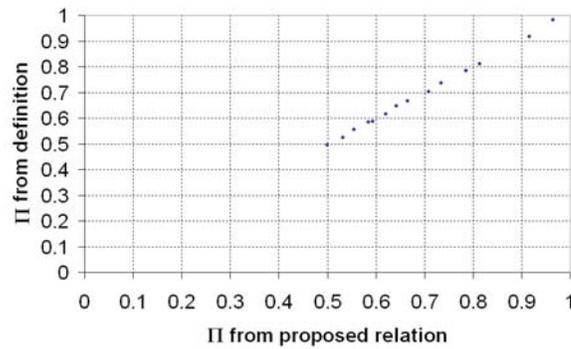


Figure 11. A comparison between the dimensionless parameter determined from the definition (2) and the one from the proposed relation (8) for the AP-600 steam generator.

is shown in Fig. 12. For most data, the differences are within ± 0.01 , which should be considered a good result. Only for one analyzed steady state, the difference exceeds this range.

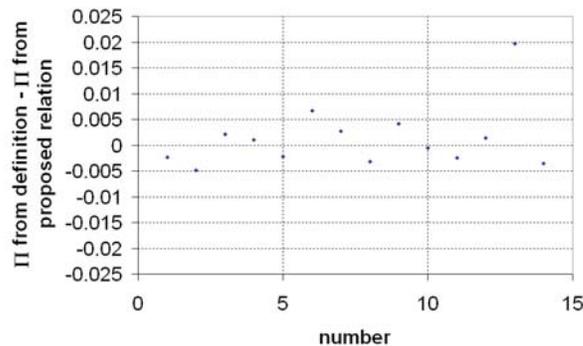


Figure 12. The difference between the dimensionless parameter Π determined from the definition (2) and the one from the proposed relation (8).

Figure 13 illustrates the differences between the steam temperatures obtained with the simulator of the AP-600 steam generator and the one calculated from the proposed relation (8). For most data, the differences are within ± 1 K. Only for one analyzed steady state, the difference exceeds this range.

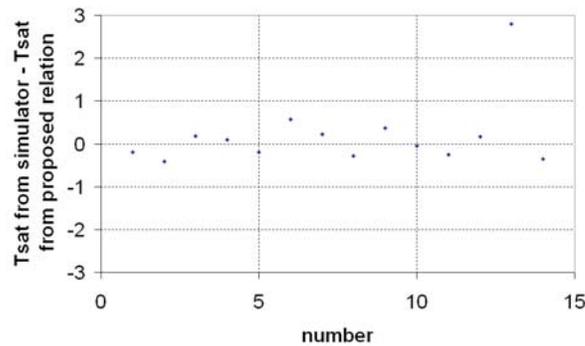


Figure 13. The difference between the steam temperature obtained with the AP-600 simulator and the one calculated from the proposed relation (8).

4 Conclusions

The changed working conditions of the steam generator, linking the primary loop with the secondary loop, were analyzed. While the nuclear power plant is operating, variations in the parameters can occur at the steam generator inlet on the primary and secondary sides. It is essential to know how the variations in the primary side parameters affect the secondary side parameters and vice versa. It is not straight forward to create an accurate mathematical model of the system under variable load conditions, capable of illustrating the effect of all the phenomena occurring in the steam generator. The exact geometry of all its components has to be known in such case. Therefore, an alternative approach was proposed, consisting in considering the steam generator as a ‘black box’ with inlets and outlets.

The system (steam generator) responses to the changes of each inlet parameters were examined. Using the data obtained with a simulator of the EPR steam generator, a simple mathematical model of the steam generator performance under variable load conditions was proposed. In the model, there are two dimensionless parameters: one dependent on temperatures Eq. (2), and the other on the ratio of the mass flow rates of both fluids Eq. (3). The correctness of the proposed model was verified against the data obtained with the simulator of the EPR and AP-600 steam generator. In both cases, a good agreement was achieved between the data obtained with the proposed model and the simulators (Figs. 6, 8, 11, and 13).

In the proposed model, there are three constant coefficients which have to be determined using the measurement data or manufacturer specifica-

tions at least for three different operating conditions of the steam generator. When the three constant coefficients have been determined, the working parameters of the steam generator under changed conditions can be approximately calculated, using the proposed relation (8).

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