Parameter Estimation of a Simple Primary Circuit Model of a VVER Plant

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***Abstract*—A simple dynamic model in physical coordinates (an improved version of our model reported in [1]) and the corresponding parameter estimation procedure for the primary circuit dynamics of VVER-type pressurized water reactors is presented in this paper. The primary uses of the model are control oriented dynamic model analysis and high level controller design. The most important requirements of the simple physical model are that it should contain the possible minimal number of differential equations and it should be capable of describing important dynamic phenomena such as load change transients between day and night periods. Furthermore, the estimated parameter values should fall into physically meaningful ranges. The parameter estimation method is based on the decomposition of the overall system model into separably identifiable subsystems. The identification of the subsystems is followed by the fine-tuning of the model parameters with the parameter estimation of the entire system model. The constructed model satisfies the predefined requirements and its response shows good fit to the measurement data that were obtained from three units of the Paks Nuclear Power Plant in Hungary.**

I. INTRODUCTION

THE gradually changing operating requirements, the ever stringent regulations related to performance, effectiveness and safety often necessitate the retuning or the redesign of different subsystems in nuclear power plants. These important tasks are supported by the improving quantity and quality of dynamic measurements as a result of developing hardware-software environment and modern sensor devices. It is well known from theory and engineering practice that the application of advanced feedback control can dramatically improve dynamical system properties often without the need to introduce significant changes in the technology. Recently, applied modern control methods in nuclear power plants include linear robust control [2], model predictive control [3], [4] and adaptive neural control [5].

However, most of the aforementioned model analysis and controller design methods require that the original mathematical model of the system is in the form of (a preferably low number of) ordinary differential equations. Unfortunately, the traditionally available and commonly used dynamic models [6], [7] for nuclear power plants are much too complex and detailed for control purposes. Therefore, one of the aims of this paper is to present such a simple dynamic model for the primary circuit of a VVER-type nuclear power plant in physical coordinates, and to describe the parameter estimation procedure for the model. The intended use of the model is control oriented system analysis and controller design.

The detailed dynamic modeling and simulation of thermal-hydraulic systems is an extensively studied area where reliable dynamic simulators can be found such as RELAP5 [6] or APROS [7]. However, the models obtained from these solutions are too detailed (i.e., the number of equations is too high) for our purposes. Of course, high fidelity simulation is indispensable later, particularly in the controller testing and tuning phase.

Relatively few publications can be found in the literature about the dynamic identification of simplified physical primary circuit models. In [8], the multidirectional search method is used for the parameter estimation of a 15 dimensional PWR model, where the training data were obtained from RELAP5. Effective particle filtering is used in [9] for the state estimation of a simple neutron flux dynamic model of 3 differential equations.

Our aim is to construct a model in the form of nonlinear ordinary differential equations with the following properties: 1) It should reproduce important dynamic phenomena such as load change transients in the thermal power interval of approximately 80–100%. 2) It should be able to acceptably describe the steady states in the neutron flux, primary circuit temperature and pressure. 3) The model parameters should fall into physically meaningful regions.

The model presented here is a modified version of the one that was described in [1], where the detailed modeling assumptions can be found. However, that model was not able to satisfy all three modeling requirements described above (see also [10]), therefore the need for model extension has been arisen. The main differences between [1] and the present model are that the old model has been extended with the energy (temperature) dynamics of the steam generator's tube-wall and an improved nonlinear heat transfer formula has been introduced in the new model. The methodology followed in this paper is also similar to that of a successful previous work, namely the control oriented modeling and identification of the pressurizer in the primary circuit [11]. Based on the developed model, an advanced dynamic inversion based pressure controller [12] was designed and implemented that is now working on all four units of the Paks Nuclear Power Plant in Hungary. However, the model structure and the identification procedure is more complex in the case of the present primary circuit model which contains the pressurizer as a subsystem.

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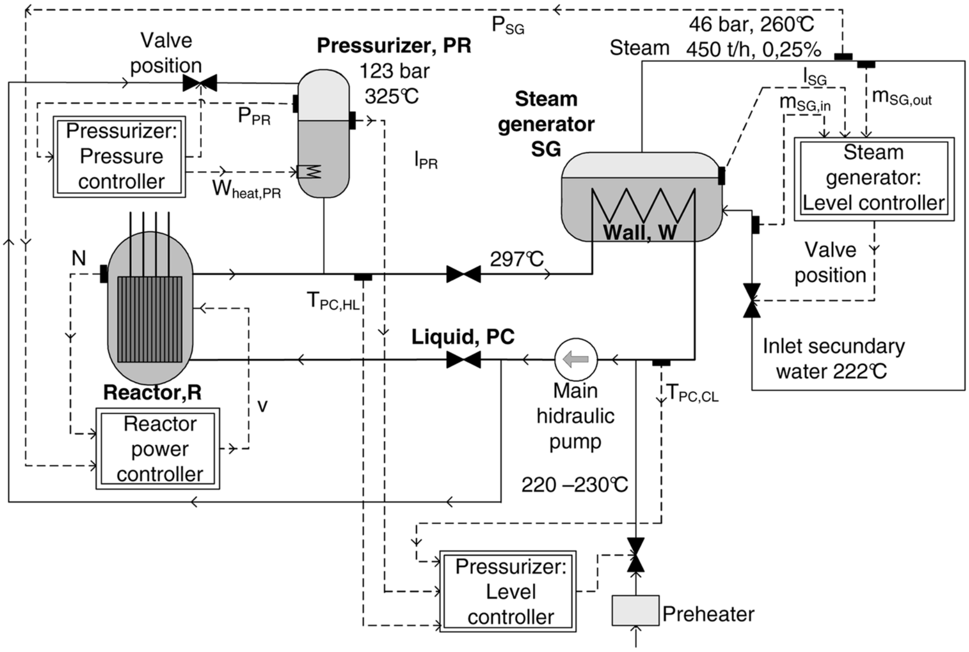

Fig. 1. Process flowsheet with the operating units of the simplified model. (R—reactor, PC—liquid in the primary circuit, PR—pressurizer, SG—steam generator and W—tube-wall).

The paper is organized as follows. In the Section II, the state-space model of the primary circuit is presented. The Section III describes the parameter estimation method and the measurements. The Section IV contains the results of the parameter estimation, while the conclusions can be found in the Section V.

II. SYSTEM MODELING

A. Modeling Setup and Assumptions

The set of operating units considered in our simple dynamic model includes the reactor (R), the primary circuit liquid (PC), the pressurizer (PR), the steam generator (SG), and the tube-wall in the steam generator (W) with their abbreviations between parentheses (see Fig. 1). Their dynamic models are derived from simplified mass, energy and neutron balances constructed for a single balance volume that corresponds to the individual unit. Each balance volume is considered a spatially homogeneous lumped parameter system. The considered controllers in the model are the pressure controller, the level controller of the pressurizer, the level controller in the steam generator and the power controller of the reactor, the dynamics of which has been neglected. The domain of the model includes the dynamic behavior in normal operating mode together with the load changes between the day and night periods.

The reactor model is a time-dependent, single-group neutron diffusion equation [13] model, with a single type of delayed neutron emitting nuclei whose concentration is in a quasi-steady state. The dependence of the nuclear physical mechanisms on the temperature is neglected, but the effect of the control rod position on the reactivity is approximated by a quadratic function.

The liquid in the primary circuit is assumed to be pure water, whose density depends on the temperature described by a second order polynomial, and its dependence on the pressure is neglected. The heat transferred from the primary circuit to the tube wall of the steam generator depends polynomially on the temperature difference between the average temperature of primary circuit liquid and the temperature of the tube-wall.

The dynamics of the primary side of the steam generators and the dynamics of the secondary side vapor phase are very quick compared to the dynamics of secondary water mass and temperature, therefore they are assumed to be in a quasi-steady state. Moreover, an equilibrium is assumed between the secondary liquid and the vapor phases. The heat transferred from the tube-wall of the steam generator to the secondary circuit water depends polynomially on the temperature difference between the temperature of the tube-wall and the temperature of the secondary liquid.

The liquid in the pressurizer is assumed to be pure water, and it is assumed to be part of the liquid in the primary circuit. The liquid mass in the pressurizer is computed as an excess to a nominal mass in the primary circuit. The density of the liquid is assumed to depend on its temperature according to a second order polynomial, and its dependence on the pressure is neglected.

The energy losses of operating units are supposed to be linear functions of their respective temperatures, except for the pressurizer where it is considered constant. The pressure in an operating unit is assumed to depend quadratically on the temperature in the operating unit.

B. State-Space Model

With the above simplifying modeling assumptions, the nonlinear state equations of the simple primary circuit dynamics are the following:

$$\frac{dN}{dt} = \frac{p_1 v^2 + p_2 v + p_3}{\Lambda} N + S \tag{1}$$

$$\frac{dM_{\mathrm{PC}}}{dt} = m_{\mathrm{in}} - m_{\mathrm{out}} \tag{2}$$

$$\begin{aligned}\frac{dT_{\mathrm{PC}}}{dt} = {} & \frac{1}{c_{p,\mathrm{PC}} M_{\mathrm{PC}}}[c_{p,\mathrm{PC}} m_{\mathrm{in}}(T_{\mathrm{PC},I} - T_{\mathrm{PC}}) + W_R \\ & + c_{p,\mathrm{PC}} m_{\mathrm{out}} 15 - 6 \cdot K_{T,\mathrm{SG},1}(T_{\mathrm{PC}} - T_W)^a \\ & - K_{\mathrm{loss,PC}}(T_{\mathrm{PC}} - T_{\mathrm{out,PC}})]\end{aligned} \tag{3}$$

$$\frac{dM_{\mathrm{SG}}}{dt} = m_{\mathrm{SG,in}} - m_{\mathrm{SG,out}} \tag{4}$$

$$\begin{aligned}\frac{dT_{\mathrm{SG}}}{dt} = {} & \frac{1}{c^L_{p,\mathrm{SG}} M_{\mathrm{SG}}}\left[c^L_{p,\mathrm{SG}} m_{\mathrm{SG,in}}(T_{\mathrm{SGSW}} - T_{\mathrm{SG}})\right. \\ & + c^L_{p,\mathrm{SG}} m_{\mathrm{SG,out}} T_{\mathrm{SG}} - m_{\mathrm{SG,out}} E_{\mathrm{evap,SG}} \\ & + K_{T,\mathrm{SG},2}(T_W - T_{\mathrm{SG}})^b \\ & \left. - K_{\mathrm{loss,SG}}(T_{\mathrm{SG}} - T_{\mathrm{out,SG}})\right]\end{aligned} \tag{5}$$

$$\begin{aligned}\frac{dT_W}{dt} = {} & \frac{1}{c_{p,W} M_W}\left[K_{T,\mathrm{SG},1}(T_{\mathrm{PC}} - T_W)^a\right. \\ & \left. - K_{T,\mathrm{SG},2}(T_W - T_{\mathrm{SG}})^b\right]\end{aligned} \tag{6}$$

$$\begin{aligned}\frac{dT_{\mathrm{PR}}}{dt} = {} & \frac{1}{c_{p,\mathrm{PR}} M_{\mathrm{PR}}}[\chi_{m_{\mathrm{PR}}>0} c_{p,\mathrm{PC}} m_{\mathrm{PR}} T_{\mathrm{PC,HL}} \\ & + \chi_{m_{\mathrm{PR}}<0} c_{p,\mathrm{PR}} m_{\mathrm{PR}} T_{\mathrm{PR}} - W_{\mathrm{loss,PR}} \\ & + W_{\mathrm{heat,PR}} - c_{p,\mathrm{PR}} m_{\mathrm{PR}} T_{\mathrm{PR}}].\end{aligned} \tag{7}$$

The output equations are as follows:

$$W_R = c_\Psi N \tag{8}$$

$$p_{\mathrm{SG}} = p^T_*(T_{\mathrm{SG}}) \tag{9}$$

$$\ell_{\mathrm{PR}} = \frac{1}{A_{\mathrm{PR}}}\left(\frac{M_{\mathrm{PC}}}{\varphi(T_{\mathrm{PC}})} - V^0_{\mathrm{PC}}\right) \tag{10}$$

$$p_{\mathrm{PR}} = p^T_*(T_{\mathrm{PR}}) \tag{11}$$

Note that the output variables determined by the above equations are the principal measured variables characterizing the state of the primary circuit: the reactor power W_R, the pressure in the steam generator p_{SG}, together with the level of and the pressure in the pressurizer (ℓ_{PR} and p_{PR}, respectively).

Other constitutive equations are

$$\varphi(T_.) = c_{\varphi,0} + c_{\varphi,1} T_. + c_{\varphi,2} T_.^2 \tag{12}$$

$$\begin{aligned}m_{\mathrm{PR}} = {} & \frac{dM_{\mathrm{PR}}}{dt} = m_{\mathrm{in}} - m_{\mathrm{out}} \\ & - V^0_{\mathrm{PC}}(c_{\varphi,1} + 2c_{\varphi,2} T_{\mathrm{PC}})\frac{dT_{PC}}{dt}\end{aligned} \tag{13}$$

where $\varphi(T_.)$ is the density of the liquid and . stands for PC or PR. These equations determine the mass flow rate m_{PR} between the pressurizer and the primary circuit that is induced by the variation of the density of the primary circuit liquid caused by the changes in the primary circuit temperature. It is important to note, that the change in the flow direction, i.e., the change in the sign of m_{PR} makes the model to exhibit a state-switching type hybrid behavior.

The definition of the variables and the parameters can be seen in Tables I and II, respectively.

As was noted in Section I, the model is largely based on the one presented in [1] with one additional differential equation that describes the effect of the tube wall energy dynamics [(6)] on the overall dynamics of the system. This has been necessitated by the difficulties in estimating the parameters appearing in the linear heat transfer term $K_{T,\mathrm{SG}}(T_{\mathrm{PC}} - T_{\mathrm{SG}})$ present in the former and simpler version [10] of our model. Because of the same reason, nonlinear heat transfer terms ($K_{T,\mathrm{SG},1}(T_{\mathrm{PC}} - T_W)^a$ and $K_{T,\mathrm{SG},2}(T_W - T_{\mathrm{SG}})^b$) have been applied in our present model in both of the primary circuit and the steam generator energy balance equations.

It is important to emphasize, that from a physical point of view, neglecting the reactivity feedback (i.e., the reactivity dependency on the temperatures) is a serious over-simplification that may influence significantly the system dynamics. However, the main reason for this neglect is to obtain a dynamic model with the simplest possible algebraic structure and a minimum number of parameters to be estimated, because a more complex model might unnecessarily complicate the process of nonlinear

TABLE I
VARIABLES WITH TYPE (STATE, INPUT, OUTPUT, DISTURBANCE)

Identifier	**Variable**	**Type**
N	R neutron flux	s
v	R control rod position	i
W_R	R reactor power	o
m_{in}	PC inlet mass flow rate	i
m_{out}	PC purge mass flow rate	d
M_{PC}	PC liquid mass	s
$T_{PC,I}$	PC inlet temperature	d
T_{PC}	PC temperature	s
M_{PR}	PR liquid mass	o
p_{PR}	PR pressure	o
T_{PR}	PR temperature	s
ℓ_{PR}	PR liquid level	o
$W_{heat,PR}$	PR heating power	i
M_{SG}	SG water mass	s
T_{SG}	SG steam generator temperature	s
$m_{SG,in}$	SG inlet mass flow rate	i
$m_{SG,out}$	SG steam mass flow rate	d
T_{SGSW}	SG inlet water temperature	d
p_{SG}	SG steam pressure	o
T_W	W temperature of the wall	s

TABLE II
ESTIMATED PARAMETERS OF THE PRIMARY CIRCUIT MODEL

Notation	**Definition**	**Op. unit**	**Domain**
(p_1, p_2, p_3)	Rod's parameters	R	-
S	Neutron source	R	-
$c_{p,PC}$	Specific heat	PC	$\approx 4900\ J/kg/K$
$K_{T,SG,1}$	Heat transfer coefficient	PC	-
$K_{T,SG,2}$	Heat transfer coefficient	SG	-
$K_{loss,PC}$	Energy loss coefficient	PC	-
$K_{loss,SG}$	Energy loss coefficient	SG	-
a, b	Powers of heat transfer	-	$\approx 1 - 2$
$c^L_{p,SG}$	Specific heat of water	SG	$\approx 4700\ J/kg/K$
$c_{p,W} \cdot M_W$	Specific heat and mass	W	$\approx 2 \cdot 10^7$
$c_{p,PR}$	Specific heat	PR	$> 5080\ J/kg/K$
$W_{loss,PR}$	Heat loss	PR	$\approx 10^5\ W$
V^0_{PC}	Volume of primary circuit	PR	$230 - 250\ m^3$
$E_{evap,SG}$	Evaporation heat (not estimated)	SG	$1658555\ J/kg$

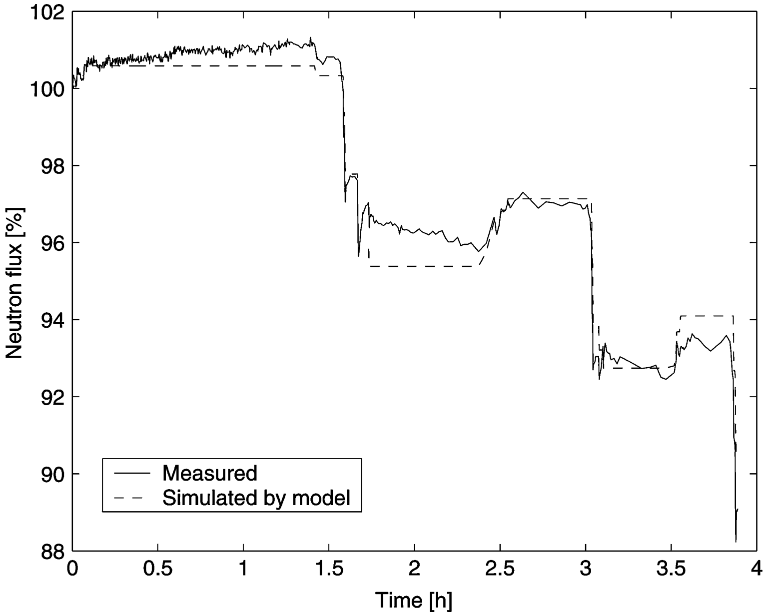

Fig. 2. The measured and model computed neutron flux in unit 1.

TABLE III
MEASURED VARIABLES

Reactor	Liquid in primary circuit	Steam generator	Pressurizer
N	m_{in}	$m_{SG,in}$	p_{PR}
v	m_{out}	$m_{SG,out}$	T_{PR}
W_R	$T_{PC,I}$	$T_{SG,SW}$	ℓ_{PR}
	$T_{PC,CL}$	p_{SG}	$W_{heat,PR}$
	$T_{PC,HL}$		

model analysis and controller design. It is expected that this approximation will cause a small difference between the measured and the model predicted neutron flux and primary circuit water temperature values, but this is still an acceptable simplification of reality in the investigated operating region, as it is clearly visible from the results of Section IV.

III. PARAMETER ESTIMATION

A. Measurements

Measured data (see Table III) from units 1., 3., and 4. of the Paks Nuclear Power Plant were collected for parameter estimation purposes. To extract as much dynamic information as possible, load change periods were selected for identification.

The time-span of the raw measurements was between 2 and 72 h. The selected data sequences had to contain steady-state values together with power increase/decrease without any significant disturbances and operating mode changes.

After the investigation of the measured data the following time intervals were chosen for parameter estimation. A time interval of 3.88, 2.5, and 2.5 h from unit 1, unit 3, and unit 4, respectively.

B. Parameter Estimation Method

The parameter estimation has been performed in two main steps. In the first step, three subsystems of the overall model—the reactor, the main thermo-hydraulic part of the circuit, and the pressurizer—have been identified separately in the following way. It is seen from the state equations (1)–(7) that the parameters in the neutron flux balance (1) can be estimated independently of the other operating units. Then the coupled (2)–(6) describing the dynamics of the liquid in the primary circuit, in the steam generator and the dynamics of the wall of the steam generator form another component that uses the reactor power as an input generated by the neutron flux dynamics. Finally, the third component is the pressurizer that depends heavily on the primary circuit water dynamics. The parameter estimation has been carried out sequentially and component-wise following the dependencies outlined above, i.e., the first is the reactor unit, the second one is the primary circuit water subsystem including the steam generator and finally, the pressurizer. For each subsystem, the measured variables were classified as manipulated inputs, nonmanipulable disturbances, and outputs.

The objective function of the identification measured the fit between the model computed (simulated) and measured output.

In the second step, the whole system model described by (1)–(7) was put together and identified using the parameter values obtained in the previous step as initial parameter values. Note that the classification of some variables has changed in this step compared to their previous role. Namely, the neutron flux, the primary circuit temperature, the pressurizer temperature, and the steam generator temperature that appeared as inputs or measurable disturbances for certain subsystems in the first step (and, therefore, their measured values were used for the simulations), now act as model computed state variables and the measurements are only used for objective function evaluation. Furthermore, the final output for the objective function of the whole model is composed as a linear combination of the outputs corresponding to the subsystems in the first step.

As it has been mentioned before, the value of the objective function to be minimized was the measure of the data fit in

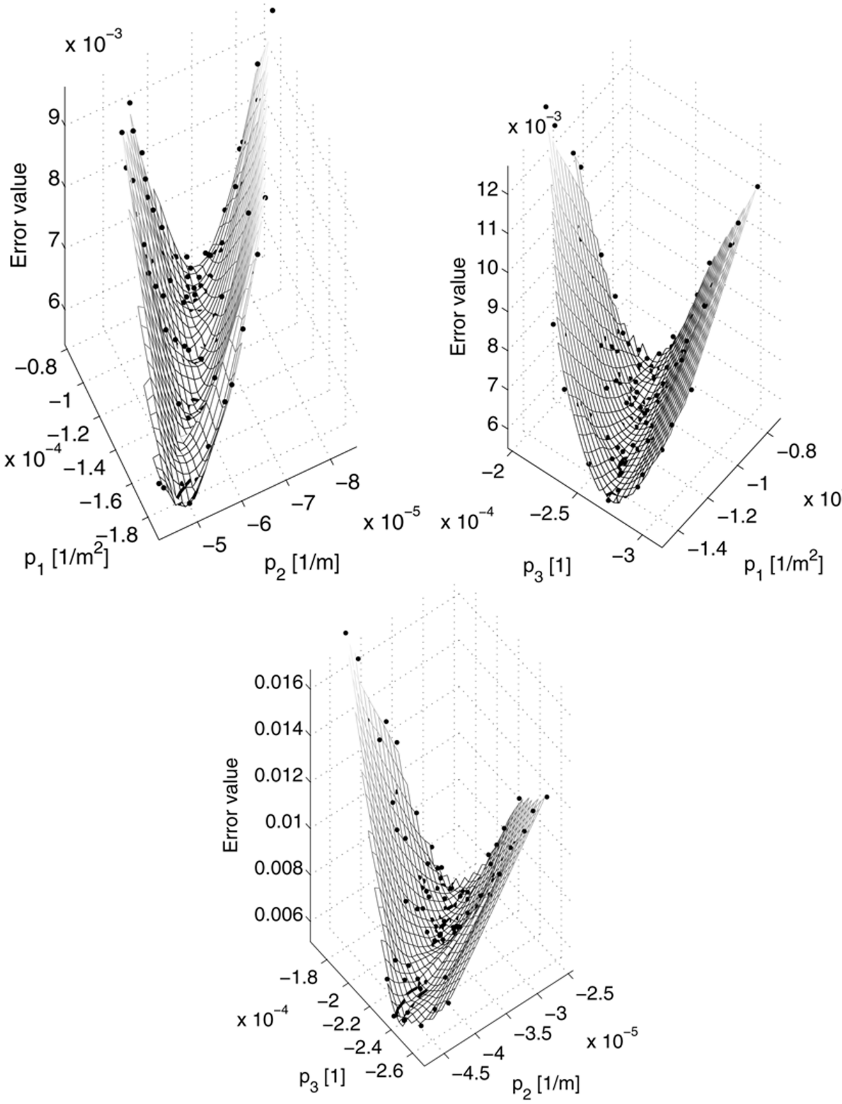

Fig. 3. Projections of the error function of the estimates in case of the reactor of unit 1.

terms of the 2-norm between the measured and model-computed output signals, i.e.

$$f_{\mathrm{obj}}(\theta) = \sqrt{\frac{\int_0^T (\hat{y}(t,\theta) - y(t))^2 dt}{\int_0^T y^2(t) dt}} \tag{14}$$

where θ is the model parameter vector, y is the measured output, $\hat{y}$ is the model-computed (simulated) output signal, and T denotes the time-span of the measurement/simulation.

Thus, the parameter estimation problem is basically an optimization problem which is bound constrained to keep the estimated parameter values in a physically meaningful range. Since the right-hand sides of (1)–(7) are nonlinear functions of certain parameters [e.g., a and b in (6)], the classical least squares (LS) method cannot be applied for identification. Note that it is possible to decompose the system into a linear-in-parameters part, where the LS method is applicable, and into a nonlinear-in-parameters one, and develop an iterative estimation method based thereon [10]. However, the problem of keeping the estimated parameter values in their physically meaningful domain is not solvable in a straightforward way by using this method.

For the evaluation of f_{obj}, the simulation of the system dynamics with some parameter vector θ is required which is a computationally expensive operation. This means that the numerical approximation and evaluation of the gradient of f_{obj} requires much computational effort and moreover, it can often be unreliable because of the noise of some measurements. These facts motivated us to choose a simple yet effective numerical optimization method that does not need the computation of the gradient of the objective function. The *Nelder-Mead simplex search method* [14] is a well-known direct search algorithm [15] for multidimensional optimization without derivatives, with numerous extensions and parameter estimation applications [8], [16]. Since the ranges of the model parameters were relatively well known from plant documentation, the proper selection of initial parameter values was possible and the original Nelder-Mead algorithm could be used without modification.

The brief operational principle of the Nelder-Mead algorithm is the following (for details, see, e.g., [17]). A simplex is the

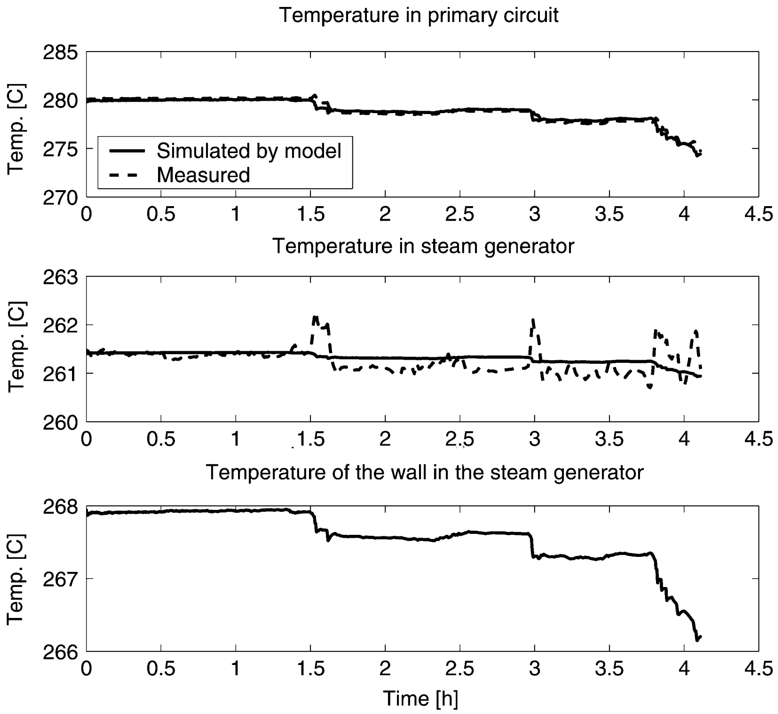

Fig. 4. Temperatures fitting in case of the PC-SG-W subsystem and unit 1.

convex hull of $n+1$ vertices in an n-dimensional space. The method starts from an initial working simplex which is created using the given initial parameter value. The algorithm then performs a sequence of transformations (that can be reflection, expansion, contraction or shrink) of the working simplex, to decrease the objective function values at the vertices. The algorithm is terminated when the size of the simplex is sufficiently small, or when the function values at the vertices are close to each other in some norm. In each iteration step, the algorithm typically needs only one or two objective function evaluations which is quite low compared to most other methods. It is important to note that the simplex search algorithm (similarly to many nonlinear optimization techniques) does not guarantee that the obtained point is a global minimum on the whole parameter domain. Therefore, it is very important to use as much prior information about the modeled process as possible to choose proper initial parameter values for the method.

The quality of the estimates is investigated by the analysis of the error function. It has been achieved by plotting every two-dimensional projection of the error function and its contour plot as a function of each pair of estimated parameters. If the contours of the error function are circular, then the corresponding estimated values are not correlated. However, if the contours become elongated ellipses (i.e., the shape of the two-dimensional projection of the error function looks like a "valley" in the vicinity of its minimum), then it suggests a deterministic relationship (linear, if the minimum points of the objective function are located along a line) between the two investigated parameters.

It is important to note, that the above-inferred deterministic relationship between parameters can be caused by either the overparametrization of the model or by the not sufficiently exciting nature of the system input or disturbance signals applied to the identification. Since we could only use passive measured data from the nuclear power plant under closed-loop control where the excitation was provided by the load changes, such deterministic relationships were envisaged.

TABLE IV
ESTIMATED REACTOR PARAMETERS. TS MEANS TIME SPAN

		unit 1	unit 3	unit 4
Parameter	**Unit**	TS: 4h	TS: 2.5h	TS: 2.5h
p_1	m^{-2}	$-1.36 \cdot 10^{-4}$	$-1.23 \cdot 10^{-4}$	$-1.32 \cdot 10^{-4}$
p_2	m^{-1}	$-6.05 \cdot 10^{-5}$	$-5.46 \cdot 10^{-5}$	$-6.68 \cdot 10^{-5}$
p_3	1	$-2.88 \cdot 10^{-4}$	$-1.97 \cdot 10^{-4}$	$-2.88 \cdot 10^{-4}$
S	$\%/s$	2884.4	1954.3	2901
Error	-	$5.58 \cdot 10^{-3}$	$7.903 \cdot 10^{-3}$	$3.552 \cdot 10^{-3}$

IV. RESULTS AND DISCUSSION

A. Reactor

The parameter estimation was based on (1). The input variable was v, the output variable was N. Parameter β was known, while p_1, p_2, p_3, and S were estimated.

It can be seen from (1) that N is a state variable, but here it also plays the role of an output variable from the point of view of the input-output identification of the reactor submodel, in spite of the fact that N is a measured state variable in the full model of the primary circuit. Measured data were obtained from the Verona system [18].

During parameter estimation the values of p_1, p_2 and p_3 were estimated while the value of S was computed from the estimated values of p_1, p_2 and p_3 to maintain the initial steady state.

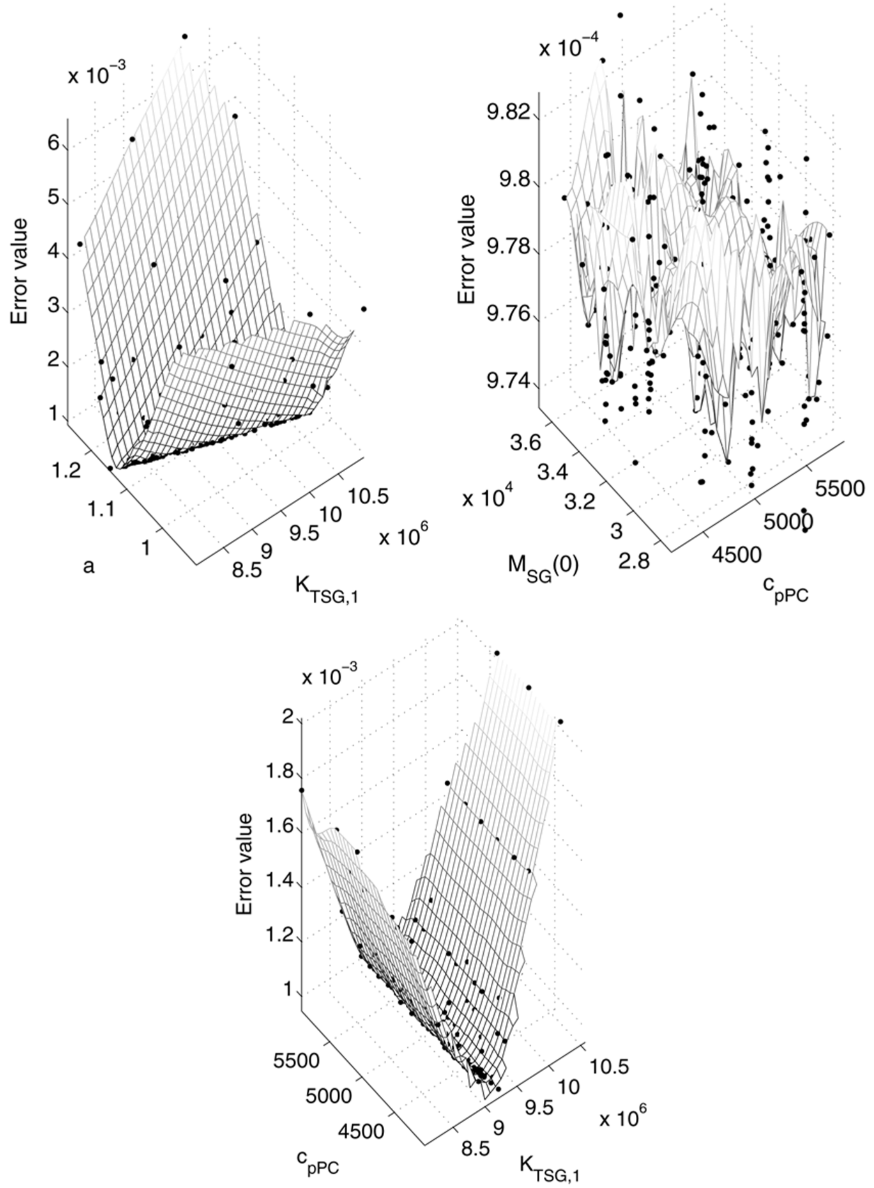

Fig. 5. Examples for the projections of the error function in case of the PC-SG-W subsystem and unit 1.

The estimated parameters and the measure of fit are given in Table IV. The neutron flux fitting in case of unit 1 can be seen in Fig. 2. The reason for the difference between the simulated and measured neutron flux is the oversimplified dynamic model without reactivity feedback. The two-dimensional projections of the error function of the estimates (without contour plots) are given in Fig. 3 in case of unit 1. The valley type shapes on the subfigure show that there are linear relationships among the parameters of the reactor that are probably caused by the operation of the reactor power controller.

B. Liquid in the Primary Circuit, Steam Generator and Wall (PC-SG-W Subsystem)

The applied equations were (2)–(6). The input variables were W_R, m_{in} and $m_{SG,\mathrm{in}}$, and the disturbances were $T_{\mathrm{PC},I}, m_{\mathrm{out}}, T_{SG,\mathrm{SW}}, m_{\mathrm{SG,out}}$. The outputs were T_{PC} and T_{SG}. The estimated parameters were $c_{p,\mathrm{PC}}, K_{T,\mathrm{SG},1}$, $K_{\mathrm{loss,PC}}, K_{T,\mathrm{SG},2}, K_{\mathrm{loss,SG}}, c^L_{p,\mathrm{SG}}, c_{p,W} \cdot M_W$, a and b.

TABLE V
ESTIMATED PRIMARY CIRCUIT, STEAM GENERATOR, AND TUBE-WALL PARAMETERS. TS MEANS TIME SPAN

Parameter	**Unit**	unit 1 TS: 4h	unit 3 TS: 2.5h	unit 4 TS: 2.5h
$c_{p,PC}$	$J/kg/K$	4902.6	5096.7	5035.9
$K_{T,SG,1}$	W/K	$9.15 \cdot 10^6$	$8.88 \cdot 10^6$	$9.80 \cdot 10^6$
$K_{loss,PC}$	W/K	$3.03 \cdot 10^6$	$2.40 \cdot 10^6$	$3.33 \cdot 10^6$
a	–	1.0963	1.0729	1.112
$M_{SG}(0)$	kg	31810	31688	30788
$c^L_{p,SG}$	$J/kg/K$	4696.9	4707.6	4618.3
$K_{loss,SG}$	W	$1.54 \cdot 10^8$	$1.91 \cdot 10^8$	$1.13 \cdot 10^8$
$K_{T,SG,2}$	W/K	$3.30 \cdot 10^6$	$2.31 \cdot 10^6$	$2.48 \cdot 10^6$
b	–	2.00	2.68	1.81
$c_{p,W} \cdot M_W$	J/K	$1.927 \cdot 10^7$	$1.632 \cdot 10^7$	$1.92 \cdot 10^7$
$T_W(0)$	^oC	267.9	266.09	269.76
Error	-	0.09691	0.099413	0.10423

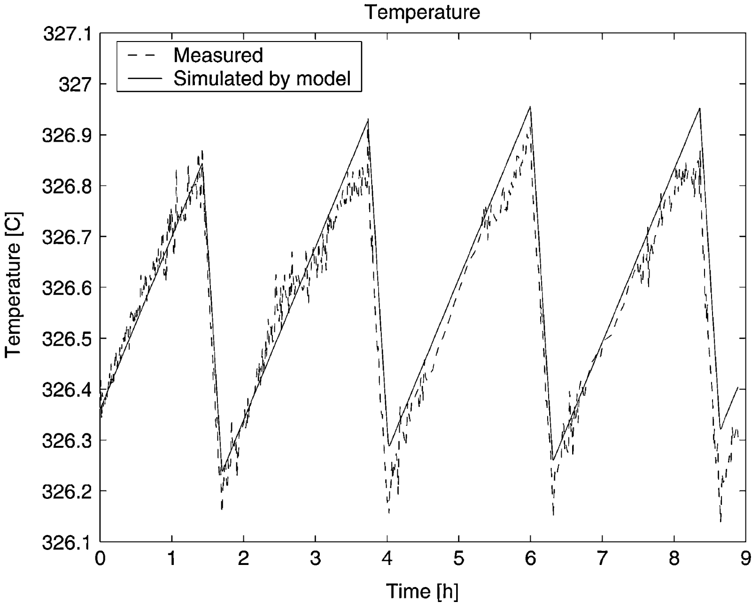

Fig. 6. The temperature fitting in pressurizer based on the Old data.

TABLE VI
ESTIMATED PRESSURIZER PARAMETERS

Parameter	Unit	Old data Time span: 8.88 h
$c_{p,PR}$	$J/kg/K$	5886.3
$W_{loss,PR}$	W	$1.68 \cdot 10^5$
Error	-	$5.9828 \cdot 10^{-4}$

Because there were two output variables, the error function defined in (14) was modified. The net error function was the average of the error functions computed from each output variable.

Measured data were obtained from the Verona system [18]. Since the mass of the water in the secondary side of the steam generator was not measured, only the inlet water and the outlet vapor flow rates were known. It means that the initial water mass $M_{\mathrm{SG}}(0)$ should also have been estimated. The initial value of its estimation was its normal value $M_{\mathrm{SG}}(0) = 32000$ kg known from technical (geometrical) parameters of the steam generator [19].

Because of the nearly perfect operation of the level controller, the overall mass of the primary circuit was assumed to be constant, and has not been estimated but a constant $M_{\mathrm{PC}} = 200t$ value has been used that is computed from the main technical data of the VVER 440/213 type plants [20].

Note that there was no direct information about the temperature of the tube-wall of the steam generator. Therefore, we had to estimate its initial value, too. The average of the initial values of the temperature of the liquid in the primary circuit and the temperature of the liquid in the secondary circuit was applied as the initial temperature of the tube-wall.

During parameter estimation the values of $K_{\mathrm{loss,PC}}$ and $K_{\mathrm{loss,SG}}$ were not estimated directly, but their values were computed from the estimated values of other parameters to maintain the initial steady state.

The estimated parameters and the measure of fit are given in Table V. The temperature fitting in case of unit 1 can be seen in Fig. 4. The apparent differences between the measured and simulated steam generator temperature are caused by the unmodeled operating mode changes of the generators and turbines that act as fast disturbances to the system.

For the sake of brevity, only some of the two-dimensional projections of the error function of the estimates that show typical relations between parameters are given in Fig. 5 in case of unit 1. Based on the shape of the error function indicating parameter relationships, the parameters of the PC-SG-W subsystem can be divided into two groups:

- There is a linear relationship among the parameters $K_{T,\mathrm{SG},1}, K_{T,\mathrm{SG},2}, a, b, c_{p,\mathrm{PC}}$ and $T_W(0)$ as indicated by the valley type shapes of their two-dimensional projections of the error function. This group of parameters, however, is independent of the other parameters. (See the left and bottom subfigures in Fig. 5.)
- There is a large uncertainty in the estimation of the parameters $c_{p,\mathrm{SG}}^L, M_{\mathrm{SG}}(0)$ and $c_{p,W} \cdot M_W$ as the shape of the function in the right subfigure of Fig. 5 indicates. Here a relatively flat area is observed near the minimum, but the measurement noise affected the error function much more than the change in the parameters. It indicates that the error function is not sensitive enough to these parameters, therefore their estimated value is highly unreliable. However, these parameters were found to be independent of the other ones.

C. Pressurizer

Equation (7) was applied for the parameter estimation. The input variables in this case were m_{in} and $W_{\mathrm{heat,PR}}$, while T_{PC} and m_{out} were disturbances. The output was T_{PR}, and the set of estimated parameters was $c_{p,\mathrm{PR}}, W_{\mathrm{loss,PR}}$.

Since a good quality and long measured data sequence from the unit computer exists describing the dynamics of pressurizer using the old "on-off type" pressure controller, this data sequence (named 'Old data') was used for parameter estimation.

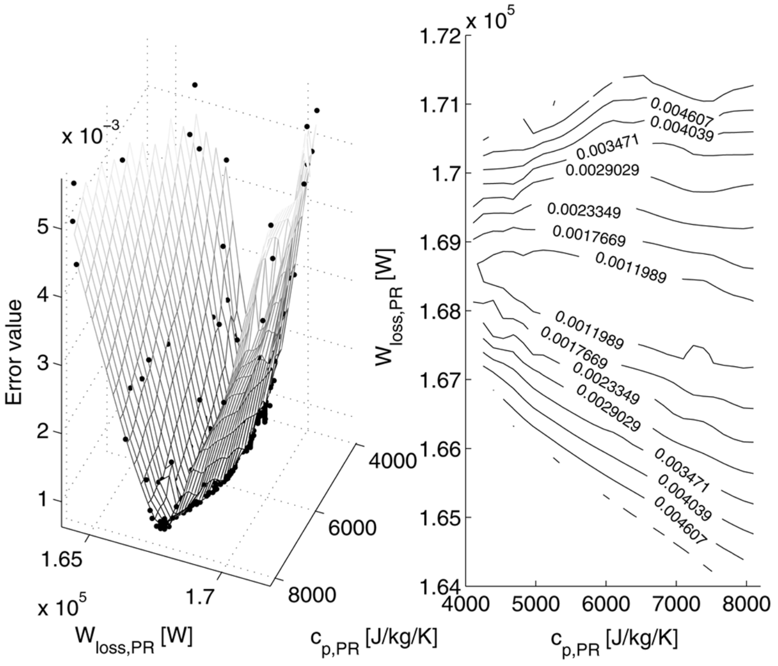

Fig. 7. Error function of the estimates in the pressurizer based on the Old data.

The estimated parameters are given in Table VI. An example of the fit in the output signal is shown in Fig. 6. The error function of the estimates (there are only two parameters) and its contour plot are given in Fig. 7. The figure shows that there is a linear relationship between the parameters of the pressurizer.

D. Model Integration, Fine Tuning, and Validation

In this final step, the previously separately identified subsystems were integrated into one model described by (1)–(7). The states and output variables (see Table III) were computed from the model and compared to the corresponding measured variables. During this simulation the measured input and disturbance variables (see Table III) were the inputs of the model and the initial values of the state variables of the model were also given from the measurements. This integrated model was used to fine-tune the "most influential" above identified parameters to achieve a better overall fit.

The initial values of estimated parameters in this fine-tuning step were the estimated values of the decomposed system. The estimated "most influential" parameters were determined by sensitivity analysis of the integrated system. The estimated parameters were $c_{p,\text{PC}}, K_{T,\text{SG},1}, a, c^L_{p,SG}, K_{T,\text{SG},2}, b, c_{p,W} \cdot M_W, c_{p,\text{PR}}$ $W_{\text{loss},\text{PR}}$. The heat loss of the liquid in the primary circuit and that of the steam generator were determined such that they maintained their initial steady state. During this identification, the error function was the average of the error functions for the temperature of the liquid in the primary circuit, the temperature in the steam generator, the temperature in the pressurizer, and that of the power of the reactor. The result of the curve fitting of this parameter estimation can be seen in Fig. 8, while the values of the fine-tuned estimated parameters are collected in Table VII. The unmodeled spikes in the pressurizer and steam generator temperatures are caused by the parallel operating mode changes of the reactor controller and the turbine/generator control system that are not incorporated into our simple model.

V. CONCLUSION

The parameter estimation procedure of the primary circuit dynamics in a pressurized water nuclear power plant has been described in this paper. The result of the reported work is a low dimensional nonlinear dynamic model with physically meaningful structure that is suitable for controller design, and describes the most important dynamic phenomena in the primary loop of VVER-type nuclear power plants, such as load changes between day and night periods and responses to the limited change of the modeled external disturbances. To achieve the parameter estimation, the primary circuit has been decomposed to subsystems based on a system and control theoretical point of view taking into consideration the present controller configuration, too. The model variables have been classified appropriately, and the unknown model parameters have been estimated using a quadratic error function and a nonlinear optimization algorithm, namely, the Nelder-Mead simplex search method. The necessary measurement data were collected from three units of the Paks Nuclear Power Plant, located in Hungary. The identified model shows good fit to the measured data and it will probably serve as a basis for the integrated redesign of the primary loop controllers in the near future. The model is not suitable for describing dynamics under nonstandard operating conditions, such as faults.

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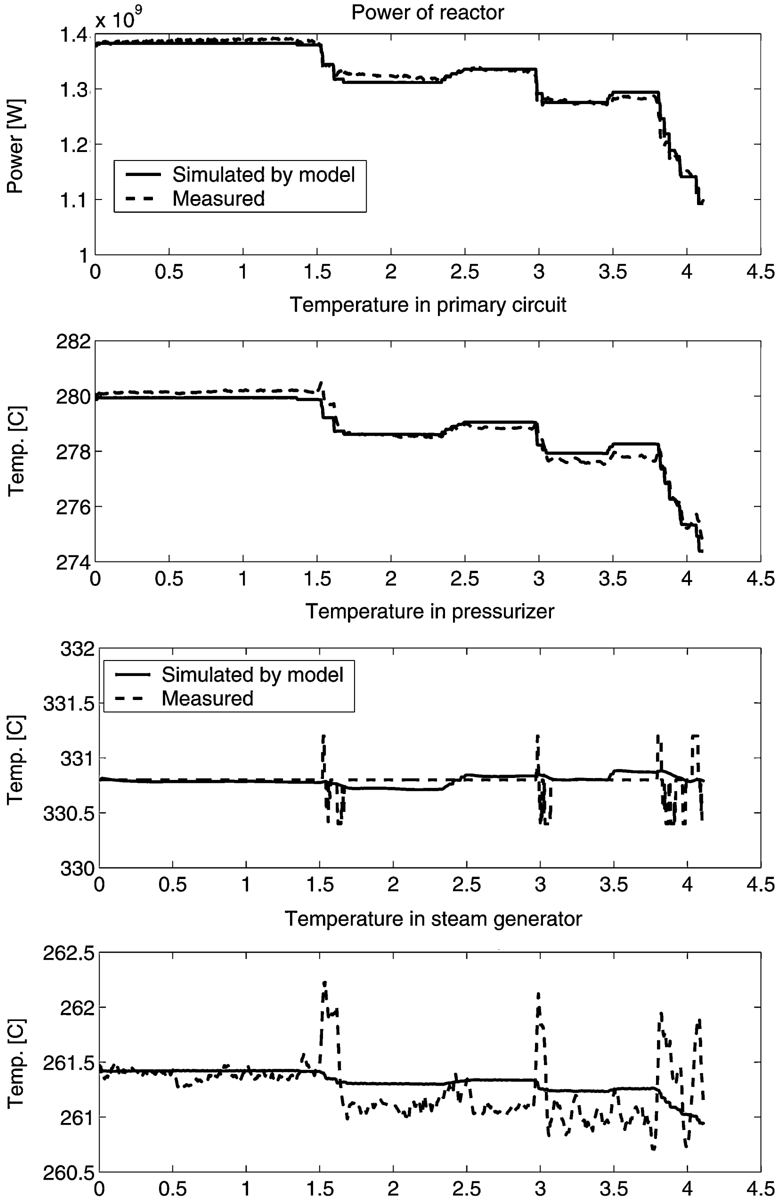

Fig. 8. Temperatures fitting of the primer circuit integrated system in case of unit 1.

TABLE VII
ESTIMATED PARAMETERS OF THE INTEGRATED SYSTEM. TS MEANS TIME SPAN

		unit 1	unit 3	unit 4
Parameter	**Unit**	TS: 4h	TS: 2.5h	TS: 2.5h
$c_{p,PC}$	$J/kg/K$	5281	5093.8	5043.1
$K_{T,SG,1}$	W/K	$9.19 \cdot 10^6$	$8.86 \cdot 10^6$	$9.80 \cdot 10^6$
$K_{loss,PC}$	W/K	$3.00 \cdot 10^6$	$2.40 \cdot 10^6$	$3.33 \cdot 10^6$
a	–	1.097	1.073	1.112
$c_{p,SG}^L$	$J/kg/K$	4651.1	4669.7	4681.9
$K_{loss,SG}$	W	$1.52 \cdot 10^8$	$1.92 \cdot 10^8$	$1.15 \cdot 10^8$
$K_{T,SG,2}$	W/K	$3.30 \cdot 10^6$	$2.33 \cdot 10^6$	$2.48 \cdot 10^6$
b	–	2.004	2.688	1.806
$c_{p,W} \cdot M_W$	J/K	$2.031 \cdot 10^7$	$1.666 \cdot 10^7$	$1.93 \cdot 10^7$
$c_{p,PR}$	$J/kg/K$	5895.4	5903.3	5896.4
$W_{loss,PR}$	W	$1.48 \cdot 10^5$	$1.72 \cdot 10^5$	$1.73 \cdot 10^5$
Error	-	0.20336	0.26365	0.15048

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