Paksi Atomerőmű primerkörének modellezése és paramétereinek becslése

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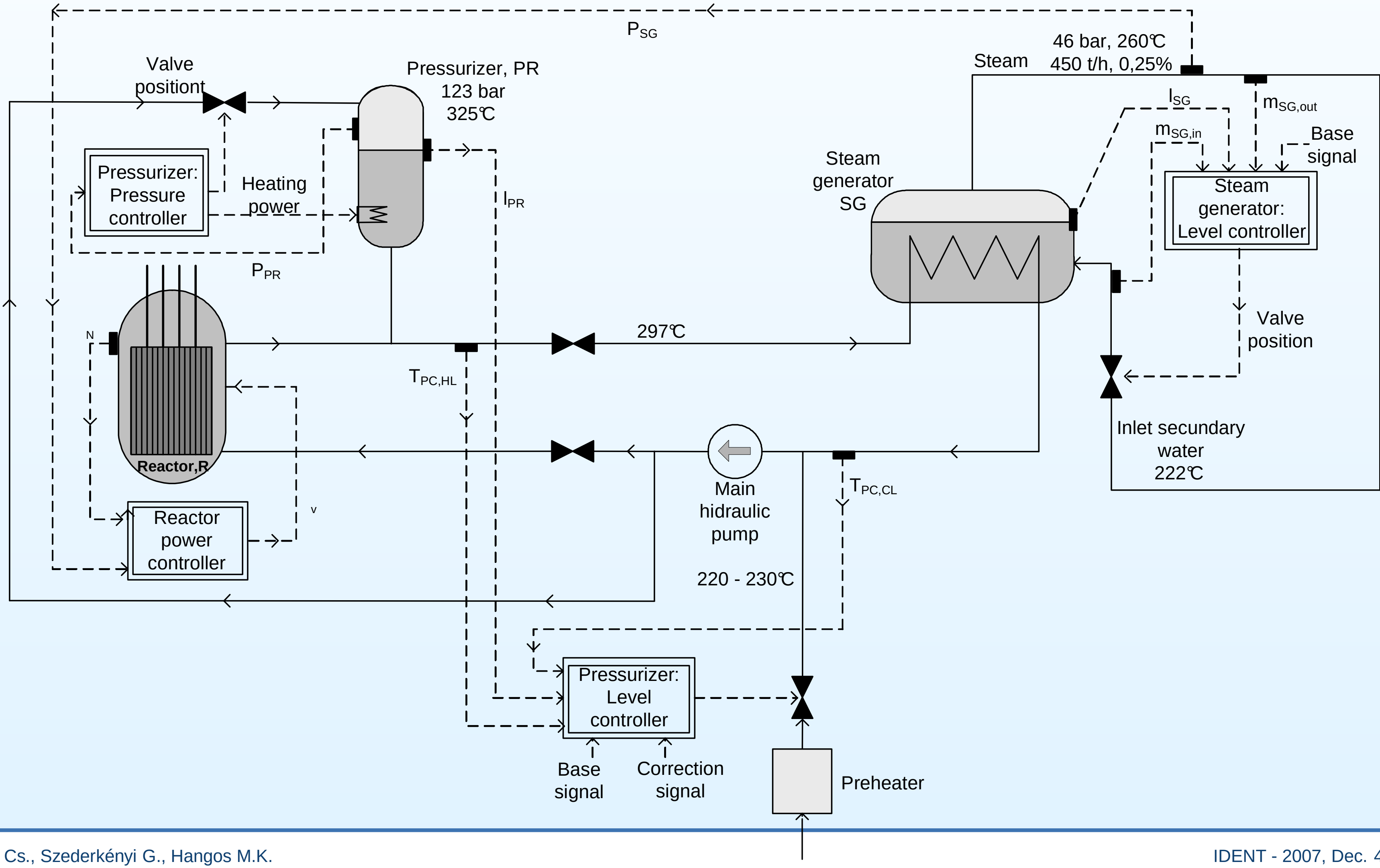
Aim and the physical system

Aim: developing a dynamic model of the primary circuit of VVER plants for controller design purposes. Model has to be minimal and its parameters have to be physical meaning.



Global assumptions

G1 *The set of operating units* considered in the simple dynamic model includes the reactor, the water in the primary circuit, the pressurizer, the steam generator and **the tube-wall in the steam generator**.

G2 *The dynamic model of the operating units* is derived from simplified mass, energy and neutron balances constructed for a single balance volume that corresponds to the individual unit.

G3 *The considered controllers* in the simplified 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. All the other controllers are assumed to be ideal.

G4 *The domain of the model* includes the dynamic behavior in normal operating mode together with the load changes between the day and night periods. In other words, failures and faulty mode transitions cannot be described by this simplified model.

Operating units and their dynamics

- Reactor: neutron balance.
- Liquid in the primary circuit: mass and energy balance.
- Steam generator: mass and energy balance.
- Pressurizer: energy balance.
- **Tubes of the steam generator**: energy balance.

Model: Liquid in the primary circuit

Assumptions:

PC1 There is only a single concentrated parameter balance volume for the total liquid amount in the primary circuit that is assumed to be in liquid phase and assumed to be pure water (the amount of boron is regarded to be negligible).

PC2 The density of the liquid (water) (φ) is assumed to depend on the temperature following a second order polynomial, and its dependence on the pressure is neglected.

PC3 The specific heat of the liquid (water) ($c_{p,PC}$) is assumed to be a constant value (its dependence on the temperature and pressure is neglected).

PC4 The effect of the heating in the pressurizer that is applied to regulate the pressure is neglected in the energy balance for the liquid in the primary circuit.

PC5 The temperature increase of the liquid in the reactor is approximately $30^o C$.

PC6 **Heat transferred from the primary circuit to the steam generator depends polynomially on the temperature difference between the average temperature of primary liquid and the temperature of the wall of the steam generator.**

PC7 The energy loss of the liquid in the primary circuit is supposed to be a linear function of its temperature.

Model: Liquid in the primary circuit

The overall mass balance (PC1)

$$\frac{dM_{PC}}{dt} = m_{in} - m_{out} \tag{1}$$

The energy balance (PC1 and PC4):

$$\frac{dU_{PC}}{dt} = c_{p,PC} m_{in} T_{PC,I} - c_{p,PC} m_{out} T_{PC,CL} + W_R - 6 \cdot W_{SG} - W_{loss,PC} \tag{2}$$

Water density: (PC2)

$$\varphi(\widetilde{T}) = c_{\varphi,0} + c_{\varphi,1}\widetilde{T} + c_{\varphi,2}(\widetilde{T})^2 \tag{3}$$

Temperature in the cold and hot leg: (PC5) $T_{PC,HL} = T_{PC} + 15$ and $T_{PC,CL} = T_{PC} - 15$.
Transferred heat to the steam generator: (PC6):

$$W_{SG} = K_{T,SG,1}(T_{PC} - T_W)^a \tag{4}$$

The energy loss of the liquid in the primary circuit (PC7):

$$W_{loss,PC} = K_{loss,PC}\left(T_{PC} - T_{out,PC}\right) \tag{5}$$

Model: Intensive form

Deriving the intensive form of the energy balance equations to obtain differential equations for the measurable temperature $T_{\bullet}$. The energy-temperature relationship is $U_{\bullet} = c_{p,\bullet} M_{\bullet} T_{\bullet}$ Differentiate it with respect to time and assumes constant specific heat, then

$$\frac{dU_{\bullet}}{dt} = c_{p,\bullet} M_{\bullet} \frac{dT_{\bullet}}{dt} + c_{p,\bullet} T_{\bullet} \frac{dM_{\bullet}}{dt}$$

The intensive forms of the energy balance equation for the balance volumes PC, SG and W are:

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

$$\begin{aligned} \frac{dT_{SG}}{dt} &= \frac{1}{c^L_{p,SG} M_{SG}} \left[c^L_{p,SG} m_{SG,in} \left(T_{SGSW} - T_{SG} \right) + c^L_{p,SG} m_{SG,out} T_{SG} - \right. \\ & \left. -m_{SG,out} E_{evap,SG} + K_{T,SG,2} \left(T_W - T_{SG} \right)^b - K_{loss,SG} \left(T_{SG} - T_{out,SG} \right) \right] \end{aligned} \quad (7)$$

$$\frac{dT_W}{dt} = \frac{1}{c_{p,W} M_W} \left(K_{T,SG,1} \left(T_{PC} - T_W \right)^a - K_{T,SG,2} \left(T_W - T_{SG} \right)^b \right) \quad (8)$$

Model: State space model

$$\frac{dN}{dt} = \frac{p_1 v^2 + p_2 v + p_3}{\Lambda} N + S \quad (9)$$

$$\frac{dM_{PC}}{dt} = m_{in} - m_{out} \quad (10)$$

$$\frac{dT_{PC}}{dt} = \frac{1}{c_{p,PC} M_{PC}} [c_{p,PC} m_{in} \left(T_{PC,I} - T_{PC}\right) + c_{p,PC} m_{out} 15 + W_R -$$

$$-6 \cdot K_{T,SG,1} \left(T_{PC} - T_W\right)^a - K_{loss,PC} \left(T_{PC} - T_{out,PC}\right)] \quad (11)$$

$$\frac{dM_{SG}}{dt} = m_{SG,in} - m_{SG,out} \quad (12)$$

$$\frac{dT_{SG}}{dt} = \frac{1}{c^L_{p,SG} M_{SG}} [c^L_{p,SG} m_{SG,in} \left(T_{SGSW} - T_{SG}\right) + c^L_{p,SG} m_{SG,out} T_{SG} -$$

$$-m_{SG,out} E_{evap,SG} + K_{T,SG,2} \left(T_W - T_{SG}\right)^b - K_{loss,SG} \left(T_{SG} - T_{out,SG}\right)] \quad (13)$$

$$\frac{dT_W}{dt} = \frac{1}{c_{p,W} M_W} \left(K_{T,SG,1} \left(T_{PC} - T_W\right)^a - K_{T,SG,2} \left(T_W - T_{SG}\right)^b\right) \quad (14)$$

$$\frac{dT_{PR}}{dt} = \frac{1}{c_{p,PR} M_{PR}} [\chi_{m_{PR}>0} c_{p,PC} m_{PR} T_{PC,HL} + \chi_{m_{PR}<0} c_{p,PR} m_{PR} T_{PR} -$$

$$-W_{loss,PR} + W_{heat,PR} - c_{p,PR} m_{PR} T_{PR}] \quad (15)$$

$$W_R = c_\Psi N \quad (16)$$

$$p_{SG} = p^T_*(T_{SG}) \quad (17)$$

$$\ell_{PR} = \frac{1}{A_{PR}} \left(\frac{M_{PC}}{\varphi(T_{PC})} - V^0_{PC}\right) \quad (18)$$

$$p_{PR} = p^T_*(T_{PR}) \quad (19)$$

Model: Variables and parameters

Variables

- *State variables*: N, M_{PC}, T_{PC}, T_{PR}, M_{SG}, T_{SG}, T_W
- *Input variables*: v, m_{in}, $m_{SG,in}$, $W_{heat,PR}$
- *Disturbances*: m_{out}, $m_{SG,out}$, $T_{SG,SW}$, $T_{PC,I}$
- *Output variables*: N (W_R), ℓ_{PR} (M_{PC}), p_{PR}, p_{SG}

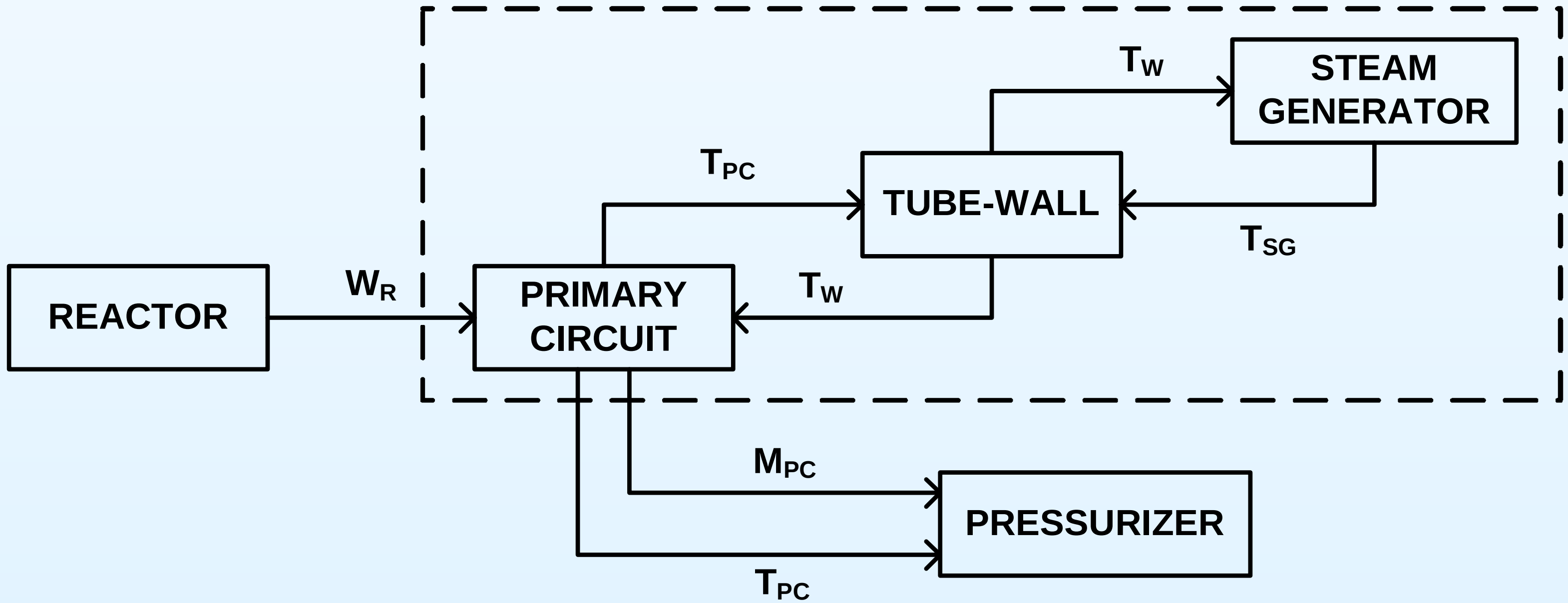
Constants

- Reactor: parameters of nuclear physics: $\frac{1}{\Lambda}$, S; parameters of the control rod: p_1, p_2, p_3; other: c_Ψ.
- Liquid in the primary circuit: $c_{p,PC}$, $K_{T,SG,1}$, $K_{loss,PC}$, a.
- Steam generator: $c^L_{p,SG}$, $K_{T,SG,2}$, $K_{loss,SG}$, b.
- Wall of the steam generator: $c_{p,W} \cdot M_W$.
- Pressurizer: $c_{p,PR}$, $W_{loss,PR}$, V^0_{PC}.

Known constants are $T_{out,PC} = 100\ ^oC$, $T_{out,SG} = 260\ ^oC$ (in case of the unit 1 and 3) and $T_{out,SG} = 259\ ^oC$ (in case of the unit 4)

PE: Decomposition

It is seen from the state equations (9)-(15) that the parameters in the neutron flux balance equation (9) can be estimated independently of the parameters of the other operating units.
Then the coupled equations (10)-(14) describing the dynamics of the liquid in the primary circuit, in the steam generator and the dynamics of the tube-wall of the steam generator form another component.
The third component is the pressurizer that depends on the dynamics of the liquid in the primary circuit.



PE: Measurements 1

Table 1: *Measured variables*

Identifier	Variable	Type:(**s**tate, **i**nput, **o**utput, **d**isturbance)
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
$T_{PC,I}$	PC inlet temperature	d
$T_{PC,CL}$	PC cold leg temperature	(s)
$T_{PC,HL}$	PC hot leg temperature	(s)
p_{PR}	PR pressure	o,(s)
T_{PR}	PR temperature	s
ℓ_{PR}	PR water level	o,(s)
$W_{heat,PR}$	PR heating power	i
$m_{SG,in}$	SG water mass flow rate	i
$m_{SG,out}$	SG steam mass flow rate	d
$T_{SG,SW}$	SG inlet water temperature	d
p_{SG}	SG steam pressure	o

PE: Measurements 2

In order to span a relatively wide operating domain, transient data have been collected. These transient data show the increasing and decreasing the power of the units when shifting from day to night load conditions and back.

There are two independent measurement and data storing systems:

- Unit computer: stores all kinds of data connected with the unit. Stored data are non-uniformly sampled: new value is stored if the difference between the previously stored value and the new value has reached an adjustable limit.
- Verona system: is a reactor safety system storing data connected with only the reactor. Stored values are uniformly sampled, the sampling time is $10\ s$.

Each quantity is measured by more sensors at the same time and the value of the measurement is composed from them. It means that the measured values are highly reliable, however, they contain random measurement errors.

From the collected data the following time intervals are chosen for the parameter estimation:

- Unit 1.: $436000\ s\ -\ 450000\ s$, time span: $3.88\ h$.
- Unit 3.: $15000\ s\ -\ 24000\ s$, time span: $2.5\ h$.
- Unit 4.: $9000\ s\ -\ 18000\ s$, time span: $2.5\ h$.

PE: A priori knowledge

Table 2: *Estimated parameters of the primary circuit model*

Notation	**Definition**	**Operating 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 the heat transfer	PC, SG, W	$\approx 1 - 2$
$c^L_{p,SG}$	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	$230 - 250\ m^3$

PE: Estimation method

- It has been carried out sequentially and component-wise following the dependencies outlined above.
- First, the reactor unit (Eq. (9)) that is nonlinear in its parameters has been identified.
- The second dynamic sub-system is the liquid in the primary circuit, the liquid in the steam generator and the tube-wall of the steam generator (Eqs. (10)-(14)) that is nonlinear in its physical parameters but linear in its variables.
- The third dynamic sub-system is the pressurizer (Eq. (15)) that is again nonlinear (hybrid) in its parameters.
- An optimization-based parameter estimation method, the Nelder-Mead simplex method was used.
- For error value we measure the fit in terms of the 2-norm between the measured and the model-predicted output signals, i.e.

$$e = \sqrt{\frac{\int_0^T (\hat{y}(t) - y(t))^2 dt}{\int_0^T y^2(t) dt}} \tag{20}$$

  where y is the measured output, $\hat{y}$ is the model-predicted (simulated) output signal and T denotes the time-span of the measurement/simulation.
- Suitable initial values are needed.

PE: Quality of the estimates

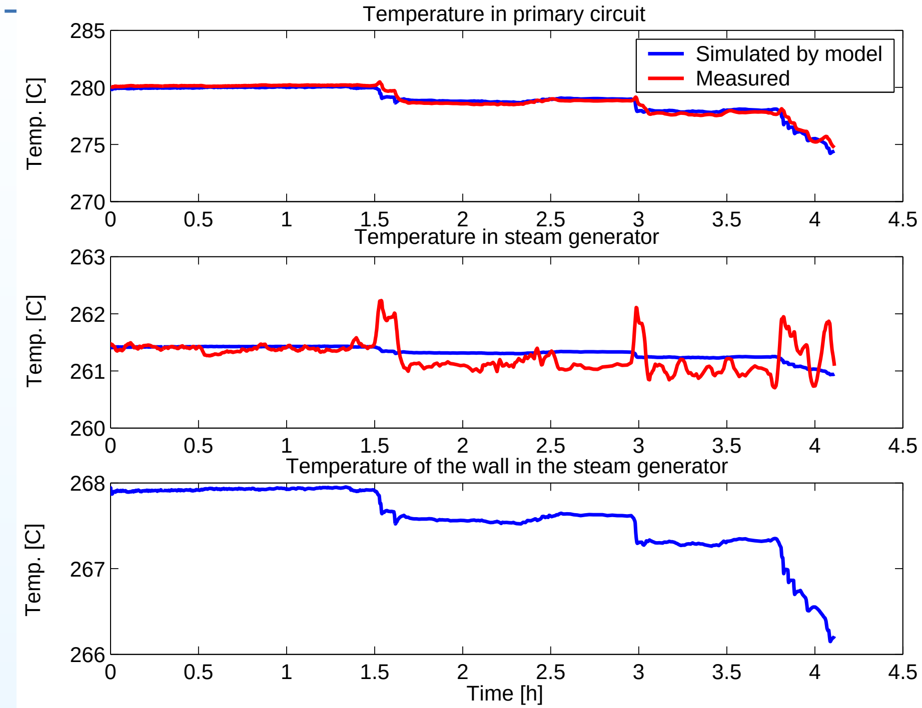
- The quality of estimates is investigated by the analysis of the error function.
- It has been achieved by plotting any two dimensional projection of the error function and its contour plot as a function of each pair of estimated parameters.
- If the shape of the contours of the error function is circle then it means that these two investigated parameters have unique values. If the shape of the contours becomes ellipse then it means there is a connection between the two investigated parameters.

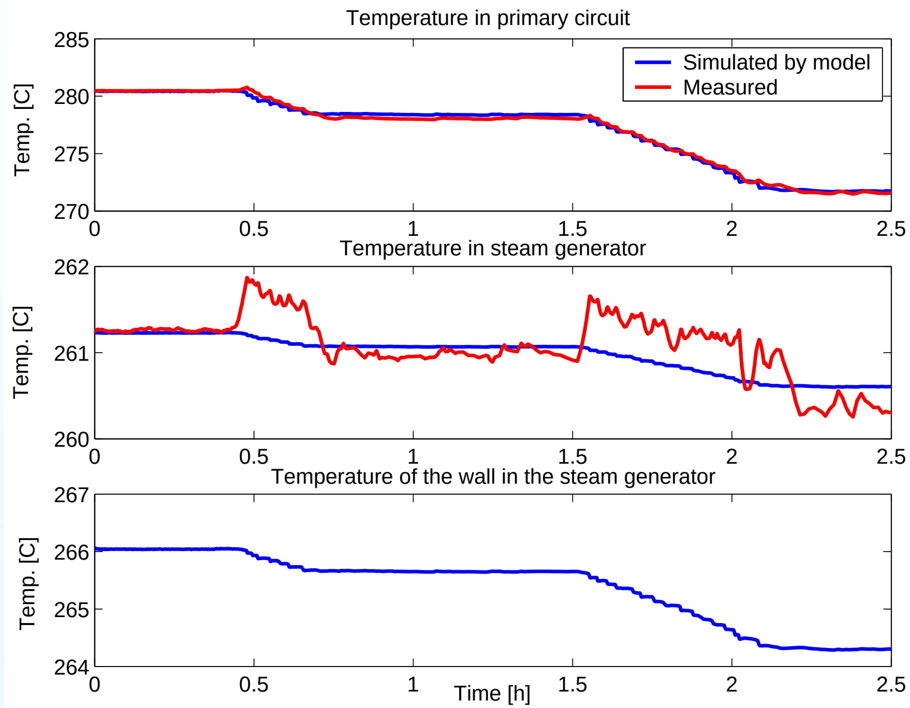
Results: PC+SG+W 1

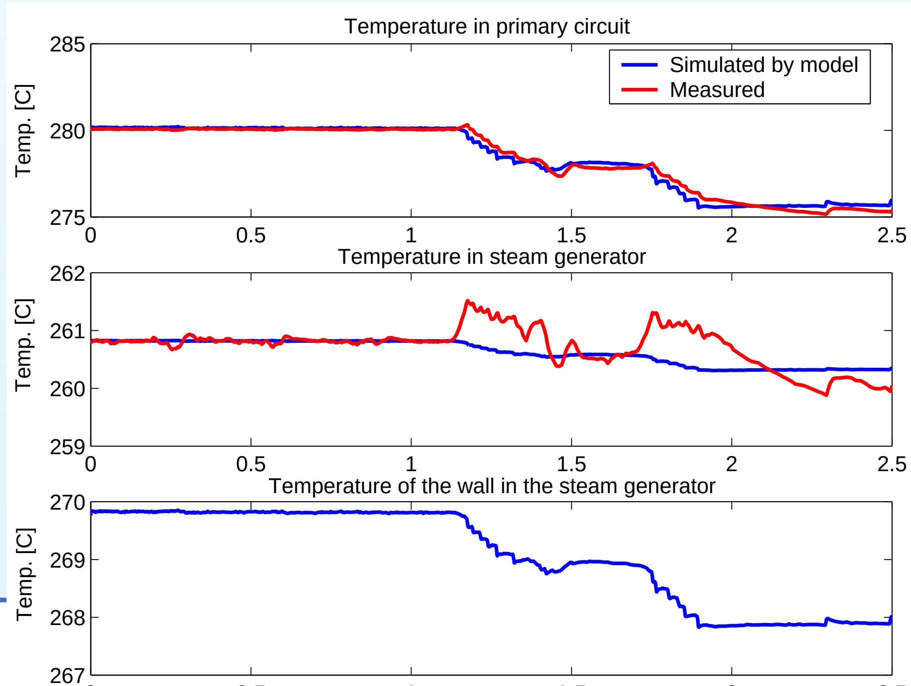
Measured data are obtained from the Verona system. The initial water mass $M_{SG}(0)$ and the initial temperature of the tube-wall $T_W(0)$ must also be estimated. The values of $K_{loss,PC}$ and $K_{loss,SG}$ are not estimated directly but their values are computed from the estimated values of other parameters to maintain the initial steady state.

Parameter	**Unit**	unit 1 Time span: 4h	unit 3 Time span: 2.5h	unit 4 Time span: 2.5h
$c_{p,PC}$	$J/kg/K$	4902.6	5096.7	5035.9
$K_{T,SG,1}$	W/K	$9.1526 \cdot 10^6$	$8.8755 \cdot 10^6$	$9.7964 \cdot 10^6$
$K_{loss,PC}$	W/K	$3.0272 \cdot 10^6$	$2.4097 \cdot 10^6$	$3.3293 \cdot 10^6$
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	$1.5431 \cdot 10^8$	$1.9093 \cdot 10^8$	$1.1284 \cdot 10^8$
$K_{T,SG,2}$	W/K	$3.3034 \cdot 10^6$	$2.3060 \cdot 10^6$	$2.4801 \cdot 10^6$
b	$-$	2.0033	2.6788	1.8062
$c_{p,W} \cdot M_W$	J/K	$1.9267 \cdot 10^7$	$1.6319 \cdot 10^7$	$1.9225 \cdot 10^7$
$T_W(0)$	^oC	267.896	266.09	269.759
Error	-	0.09691	0.099413	0.10423

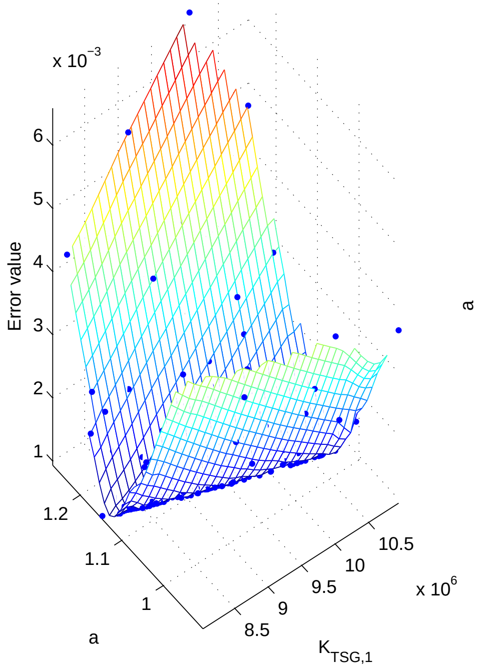
Results: PC+SG+W 2

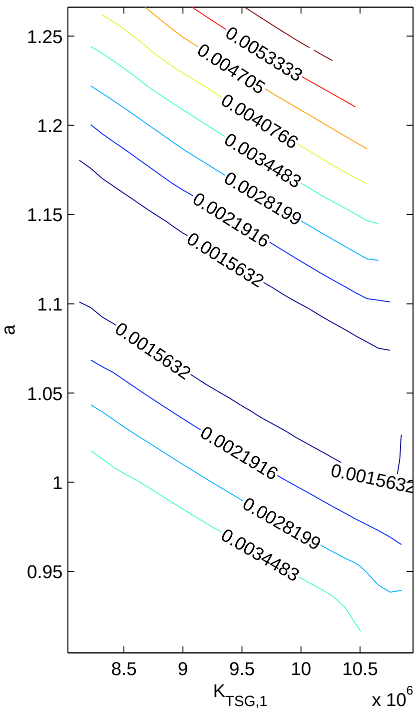


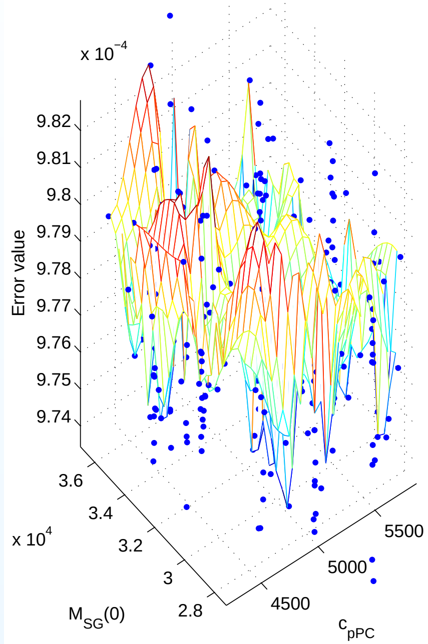


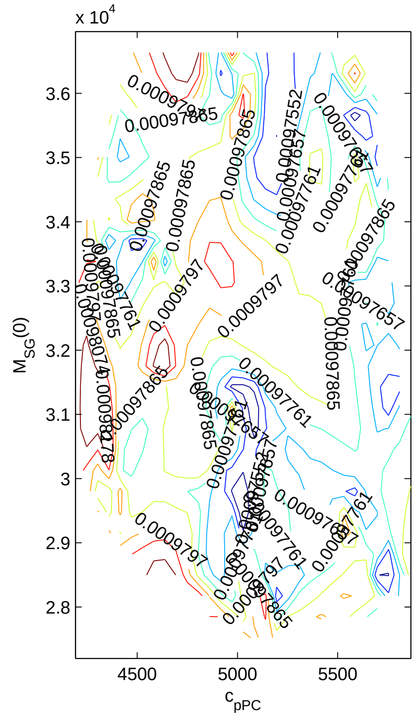


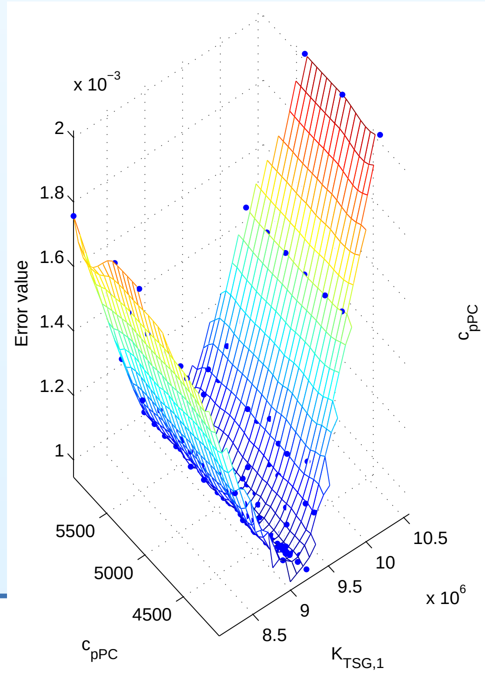
Results: Quality of estimates 2

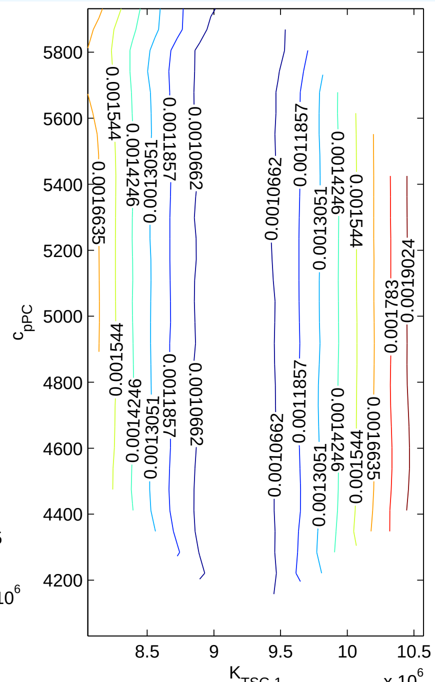




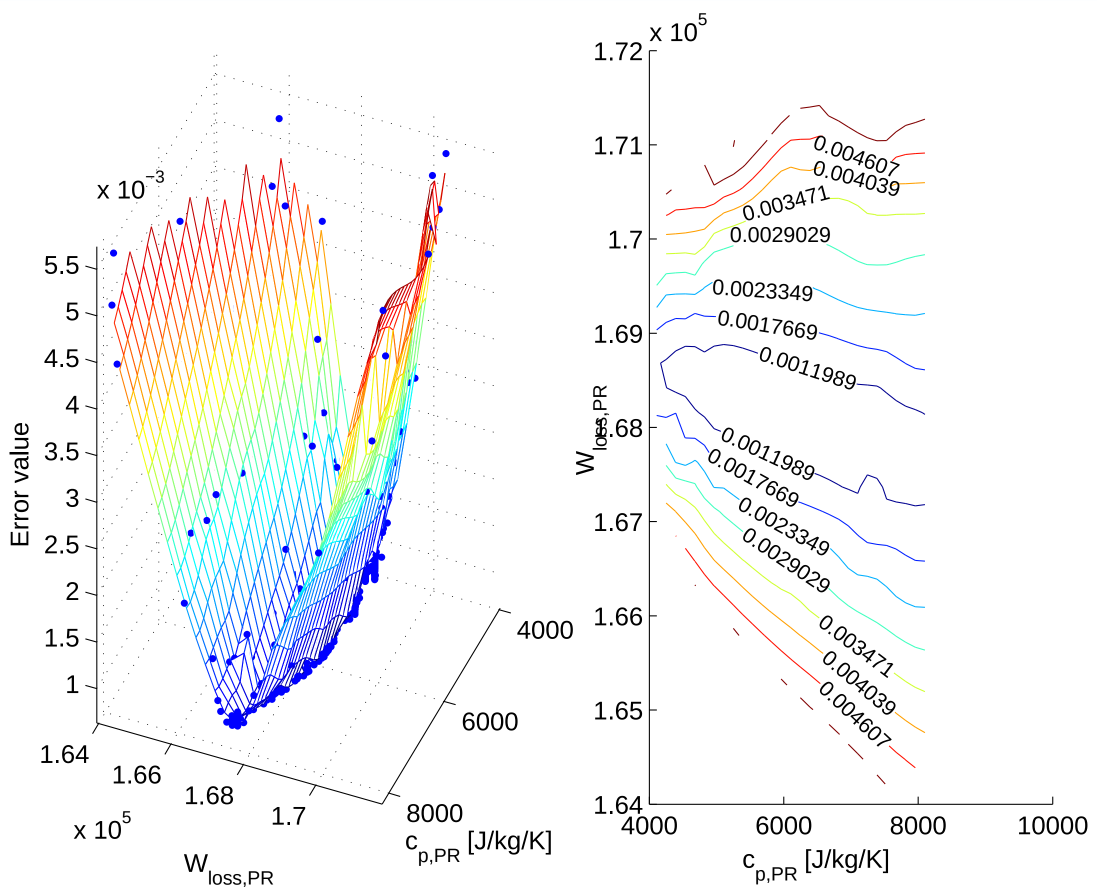








Results: Quality of estimates 3



Results: Quality of estimates 4

- There is a linear relationship between any of pairs of the estimated parameters of the reactor.
- The parameters of PC+SG+W can be grouped into two groups:
  - There is a linear connection among the parameters $K_{T,SG,1}$, $K_{T,SG,2}$, a, b and $T_W(0)$. They are independent from the other parameters.
  - There is an unpredictable connection among the parameters $c^L_{p,SG}$, $c_{p,PC}$, $M_{SG}(0)$ and $c_{p,W} \cdot M_W$. They are independent from the other parameters.
- There is a weak linear relationship between the two estimated parameters of the pressurizer.

Discussion and Conclusion

- A minimal model of the primary circuit has been developed based on the first engineering principles.
- Operating units are: the reactor, liquid in the primary circuit, the steam generator, the tube-wall and the pressurizer.
- Parameter estimation of this model has been achieved using decomposition and simplex method.
- The values of parameters having physical meaning are fit well with their a priori domains.
- Quality of estimates has been investigated by the analysis of the error functions.
- Relationships among the parameters have been determined.