Identifiability study of a pressurizer in a pressurized water nuclear power plant

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***Abstract*— In this paper, the identifiability of a pressurizer model is investigated. The modeled physical system is located in the primary circuit of a pressurized water nuclear power plant. A simple first principle model for the pressurizer is used for the calculations and it is shown that both the appropriately transformed and the original physical model parameters are structurally identifiable.**

I. Introduction

Recently, there has been an increasing need for reliable process models in different branches of industry that are capable of reproducing important dynamic phenomena and/or are suitable for control oriented model analysis and controller design. Once the model structure is fixed, the next key step is parameter estimation the quality of which is crucial in the later usability of the obtained model [1]. It is often important to build process models from first principles in original physical coordinates since the model analysis results have to be expressed directly in physical terms or the control goals and constraints are defined using real physical variables. However, the physical parametrization is often not the best one for system identification from a computational point of view and alternative parametrizations have to be found e.g. to obtain a convex objective function in the transformed parameters [2], [3].

This paper presents an identifiability study of a pressurizer located in the primary circuit of the Paks Nuclear Power Plant in Hungary. The Paks Nuclear Power Plant was founded in 1976 and started its operation in 1981. The plant operates four VVER-440/213 type reactor units with a total nominal (electrical) power of 1860 MWs. About 40 percent of the electrical energy generated in Hungary is produced here. The primary aim is to establish whether the original physical system parameters are identifiable using the available measurement setup, data and prior knowledge about the process. The system model has been constructed according to the basic principles described in [4] and it is the same as in [5] where the detailed modeling steps, the model structure validation and a numerical procedure for parameter estimation is described. However, no systematic identifiability analysis has been performed for the model yet. We note that the modeling and parameter estimation of the whole primary circuit dynamics (a subsystem of which is the pressurizer) can be found in [6], [7], [8].

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Basic early references for studying identifiability of dynamical systems are the books [9], [10]. The study and development of differential algebra methods contributed to the better understanding of important control-related problems [11], [12] and boosted the development of identifiability tests. The most important definitions and conditions of structural identifiability for general nonlinear systems were presented in [2] in a very clear way. Further developments in the field include the identifiability conditions of rational function state-space models [13] and the possible effect of special initial conditions on identifiability [14].

The structure of the paper is the following. After the introduction, the basic notions on structural identifiability are summarized in section II. Section III describes the model of the pressurizer while the identifiability calculations can be found in section IV. Section IV contains the application of the identifiability results and the conclusions can be read in section VI.

II. Basic notions on identifiability

The notations, definitions and conditions in this section are mostly taken form [2]. Let us denote a differential polynomial $F(u, \dot{u}, \dots, y, \dot{y}, \dots)$ by $F(u, y; p)$ where $p = \frac{d}{dt}$ The model class considered is of the following form

$$\dot{x} = f(x, u, \theta), \quad x(0) = x_0 \qquad (1)$$
$$y = h(x, u, \theta)$$

where $x \in \mathbb{R}^n$ is the state vector, $y \in \mathbb{R}^m$ is the output, $u \in \mathbb{R}^k$ is the input, and $\theta \in \mathbb{R}^d$ denotes the parameter vector. We assume that the functions f and h are polynomial in the variables x, u and θ.

Shortly speaking, global structural identifiability means that

$$\hat{y}(t|\theta') \equiv \hat{y}(t|\theta'') \Rightarrow \theta' = \theta'' \qquad (2)$$

where

$$\hat{y}(t|\theta) = h(x(t, \theta), u(t), \theta) \qquad (3)$$

and $x(t, \theta)$ denotes the solution of (1) with parameter vector θ.

The structure (1) is globally identifiable if and only if by differentiating, adding, scaling and multipying the equations the model can be rearranged to the parameter-by-parameter linear regression form:

$$P_i(u, y; p)\theta_i - Q_i(u, y; p) = 0 \quad i = 1, \dots, d \qquad (4)$$

It is visible from (4) that θ_i can be expressed as

$$\theta_i = \frac{Q_i(u,y;p)}{P_i(u,y;p)} \quad i = 1,\dots,p \tag{5}$$

if P_is are non-degenerate. Instead of (5), an estimate for θ_i can be given by using more information from the measurements in the following form:

$$\hat{\theta}_i = \frac{\int_0^T P_i(u(t),y(t))Q_i(u(t),y(t))dt}{\int_0^T P_i^2(u(t),y(t))dt} \tag{6}$$

requiring that the denominator in (6) is nonzero. It is important to remark that another important issue is to ensure that the inputs excite the system dynamics sufficiently so that the parameter vector can be determined in good quality numerically.

III. SYSTEM DESCRIPTION

A. Basic operating environment of the pressurizer

The VVER-440 type units belong to the group of pressurized water reactors (PWRs). The most important structural components of PWRs are the *active zone (reactor)*, the *primary circuit* and the *secondary circuit*. The controlled nuclear chain reaction is taking place in the active zone, where the fuel rods made of uranium dioxide and the absorbent control rods are located. The function of the primary circuit is to transfer the heat generated in the active zone towards the secondary circuit. Therefore the water in the primary circuit is circulated at a high speed by powerful circulation pumps. In PWRs the water in the primary circuit is not boiling which is achieved by maintaining high pressure (approximately 123 bars) using an electrically heated pressurizer unit. The steam generator is essentially a huge heat exchanger, where a significant part of the primary circuit heat is transferred to the secondary circuit. This heat is converted to mechanical and finally to electrical energy in the secondary circuit. The water of the secondary circuit in the steam generator is boiling and the vapor going out of the steam generator rotates the turbines that produce electrical energy.

B. Operation of the pressurizer

The pressurizer is a vertical tank and inside this tank there is hot water at a temperature of about 325°C and steam above. If the primary circuit pressure decreases, electric heaters switch on automatically in the pressurizer. Due to the heating more steam will evaporate and this leads to a pressure increase. If the increasing pressure in the pressurizer reaches a certain limit, firstly the heaters are turned off and then cold water is injected into the tank (if needed) to reduce the pressure down to the predefined range [15].

In the original configuration from which the measurement data were obtained, the electric heater consisted of four heating elements of discrete operation (on/off) mode, that is, the system input was an integer from the set $\{0,1,2,3,4\}$ describing the number of heating elements that are turned on. (We note that now the instantaneous heating power can be set continuously because the actuators have been reconstructed recently.) The controlled and measured output is the pressure in the tank (see Fig. 1). The accuracy of pressure measurements was $\pm 0.15\%$.

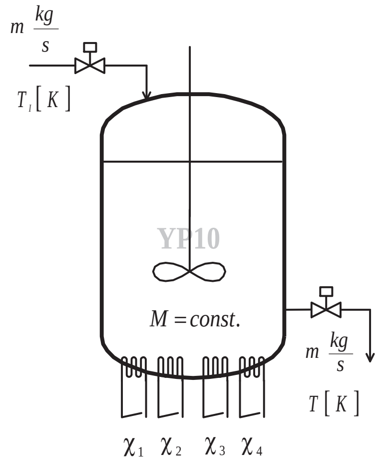

Fig. 1. Simplified flowsheet of the pressurizer

C. Physical model

The following modeling assumptions were used (see [5] for the details):

1) There are two perfectly stirred balance volumes, one for the water and another for the wall, and no balance volume for the vapor.
2) There is a single component in each of the balance volumes (water and iron, respectively).
3) Constant overall mass in both balance volumes.
4) Constant physico-chemical properties.
5) Vapour-liquid equilibrium in the tank.

This means the simplified model consists of one energy balance for the water and another one for the wall of the tank.

Water energy balance

$$\frac{dU}{dt} = c_p m T_I - c_p m T + K_W(T_W - T) + \sum_{i=1}^{4} W_{HE} \cdot \chi_i \tag{7}$$

Wall energy balance

$$\frac{dU_W}{dt} = K_W(T - T_W) - W_{loss} \tag{8}$$

The following constitutive equations describe the relationship between the internal energies and the corresponding temperatures:

$$U = c_p M T, \tag{9}$$
$$U_W = C_{pW} T_W, \tag{10}$$

The variables and parameters of the above model and their units of measure can be found in Table I. The manipulable input to the system is the external heating, all the other input variables are regarded as disturbances. These disturbances are the following:

- *Cold water infiltration*
  This effect is taken into account with the in-convection

T	water temperature	$^\circ$C
T_W	tank wall temperature	$^\circ$C
c_p	specific heat of water	$\frac{\mathrm{J}}{\mathrm{kg}^\circ\mathrm{C}}$
U	internal energy of water	J
U_W	internal energy of the wall	J
m	mass flow rate of water	$\frac{\mathrm{kg}}{\mathrm{s}}$
T_I	inlet water temperature	$^\circ$C
M	mass of water	kg
C_{pW}	heat capacity of the wall	$\frac{\mathrm{J}}{^\circ\mathrm{C}}$
W_{HE}	power of one electric heater	W
K_W	wall heat transfer coefficient	$\frac{\mathrm{W}}{^\circ\mathrm{C}}$
χ_i	on/off (1/0) state of the i$^{\text{th}}$ heater	–
W_{loss}	heat loss of the system	W

TABLE I

MODEL VARIABLES AND PARAMETERS

term $c_p m T_I$ in the water energy conservation balance (7), where the in- and outlet mass flowrate m is controlled to be equal (but might change in time) and the inlet temperature T_I can also be time-varying.

- *Energy loss*
  This effect is modelled as a loss term W_{loss} in the wall energy balance (8).

The pressure of saturated vapor in the gas phase of the tank depends nonlinearly on the water temperature. The experimental measured data found in the literature [16] have been used to create an approximate analytic function to describe the dependence. The function has the form

$$p = h(T) = \frac{e^{\varphi(T)}}{100}, \qquad \varphi(T) = c_0 + c_1 T + c_2 T^2 + c_3 T^3 \tag{11}$$

For the parameters of φ, the following values were obtained

$$c_0 = 6.5358 \cdot 10^{-1},\ c_1 = 4.8902 \cdot 10^{-2} \qquad c_2 = -9.2658 \cdot 10^{-5},\ c_3 = 7.6835 \cdot 10^{-8} \tag{12}$$

The graph of h can be seen in Fig. 2. The validity range of the

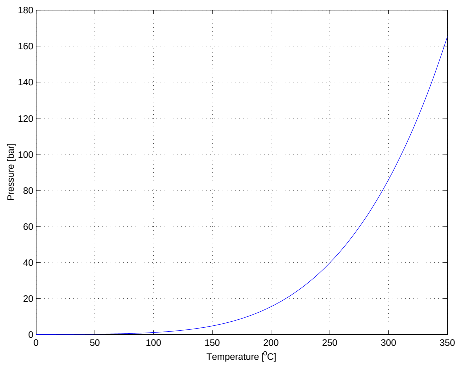

Fig. 2. Temperature dependence of the pressure of saturated vapor

model is the usual operating domain of the pressurizer, i.e. 315°C $\leq p \leq$ 350°C. In pressure terms, this means 105.65 bar$\leq p \leq$137.09 bar.

This means that although the pressure is the physically measured output, the relation between the temperature and pressure is assumed to be completely known and invertible. Therefore from now on, the water temperature T will be treated as the measured output. Unfortunately, the wall temperature T_W is not measured.

D. *State-space model*

Let us use the following standard notations for the model variables:

$$x_1 = T, \quad x_2 = T_W \tag{13}$$

$$u = \sum_{i=1}^{4} W_{HE} \cdot \chi_i \tag{14}$$

$$d_1 = T_I, \quad d_2 = W_{loss} \tag{15}$$

Then the equations (7)-(10) can be rewritten as

$$\dot{x}_1 = -\frac{m}{M}x_1 - \frac{K_W}{c_p M}x_1 + \frac{K_W}{c_p M}x_2 + \frac{m}{M}d_1 + \frac{1}{c_p M}u \tag{16}$$

$$\dot{x}_2 = \frac{K_W}{C_{pW}}x_1 - \frac{K_W}{C_{pW}}x_2 - \frac{1}{C_{pW}}d_2 \tag{17}$$

or in matrix form

$$\dot{x} = Ax + Bu + Ed \tag{18}$$

where

$$A = \begin{bmatrix} -\frac{m}{M} - \frac{K_W}{c_p M} & \frac{K_W}{c_p M} \\ \frac{K_W}{C_{pW}} & -\frac{K_W}{C_{pW}} \end{bmatrix}, \ B = \begin{bmatrix} \frac{1}{c_p M} \\ 0 \end{bmatrix}$$

$$E = \begin{bmatrix} \frac{m}{M} & 0 \\ 0 & -\frac{1}{C_{pW}} \end{bmatrix} \tag{19}$$

IV. IDENTIFIABILITY ANALYSIS

A. *Elimination of the state variables*

The environmental energy loss W_{loss} is a non-measurable disturbance and it will be treated as constant, although it is known that actually it varies depending mainly on the environmental temperature but this change is rather slow compared to the system dynamics. Let us introduce the following transformed parameters for Eqs. (16)-(17)

$$p_1 = \frac{m}{M},\ p_2 = \frac{K_W}{c_p M},\ p_3 = \frac{1}{c_p M}, \tag{20}$$

$$p_4 = \frac{K_W}{C_{pW}},\ p_5 = -\frac{1}{C_{pW}}W_{loss} \tag{21}$$

Then the system model can be written as

$$\dot{x}_1 = (-p_1 - p_2)x_1 + p_2 x_2 + p_1 d_1 + p_3 u \tag{22}$$

$$\dot{x}_2 = p_4 x_1 - p_4 x_2 + p_5 \tag{23}$$

$$y = x_1 \tag{24}$$

x_1 can be simply eliminated from (22)-(23) since it is the measured output:

$$\dot{y} = (-p_1 - p_2)y + p_2 x_2 + p_1 d_1 + p_3 u \tag{25}$$

$$\dot{x}_2 = p_4 y - p_4 x_2 + p_5 \tag{26}$$

Then, x_2 can be expressed from (25) as

$$x_2 = \frac{1}{p_2}\dot{y} + \frac{p_1+p_2}{p_2}y - \frac{p_1}{p_2}d_1 - \frac{p_3}{p_2}u \tag{27}$$

The second derivative of y is given by

$$\ddot{y} = (-p_1 - p_2)\dot{y} + p_2\dot{x}_2 + p_1\dot{d}_1 + p_3\dot{u} \tag{28}$$

Substituting (26) into (28) gives

$$\begin{aligned}\ddot{y} = (-p_1 - p_2)\dot{y} + p_2(p_4 y - p_4 x_2 + p_5) \\ + p_1\dot{d}_1 + p_3\dot{u}\end{aligned} \tag{29}$$

Finally, by substituting (27) into (29) we get the following differential relation between the input, disturbances and output:

$$\begin{aligned}\ddot{y} = (-p_1 - p_2 - p_4)\dot{y} + p_1p_4(d_1 - y) + p_3p_4u + p_2p_5 \\ + p_1\dot{d}_1 + p_3\dot{u}\end{aligned} \tag{30}$$

B. *Identifiability of the physical parameters*

Using the fact that T_I was known and constant during the observed operation, (30) can be simplified to

$$\begin{aligned}\ddot{y} = (-p_1 - p_2 - p_4)\dot{y} + p_1p_4(d_1 - y) + p_3p_4u \\ + p_2p_5 + p_3\dot{u}\end{aligned} \tag{31}$$

It is easy to see that (31) is in a standard regression form where the further transformed parameter vector θ is given by

$$\theta = \begin{bmatrix} (-p_1 - p_2 - p_4) \\ p_1p_4 \\ p_3p_4 \\ p_2p_5 \\ p_3 \end{bmatrix} \tag{32}$$

It is also visible that by taking the further time derivatives of (31) and expressing and substituting θ_is, the parameter-by-parameter regression form (4) can be obtained in the following way.

$$\begin{aligned} y^{(3)} &= \theta_1\ddot{y} - \theta_2\dot{y} + \theta_3\dot{u} + \theta_5\ddot{u} \\ y^{(4)} &= \theta_1 y^{(3)} - \theta_2\ddot{y} + \theta_3\ddot{u} + \theta_5 u^{(3)} \\ y^{(5)} &= \theta_1 y^{(4)} - \theta_2 y^{(3)} + \theta_3 u^{(3)} + \theta_5 u^{(4)} \\ y^{(6)} &= \theta_1 y^{(5)} - \theta_2 y^{(4)} + \theta_3 u^{(4)} + \theta_5 u^{(5)} \end{aligned} \tag{33}$$

From (31), (32) and (33) we get the lengthy expressions for the differential polynomials P_i and Q_i that are visible in Table II.

If we have an estimation for θ, then $p_1, \ldots, p_5$ can be computed in the following order:

$$p_3 = \theta_5,\ p_4 = \theta_3/p_3,\ p_1 = \theta_2/p_4, \tag{34}$$

$$p_2 = -\theta_1 - p_1 - p_4,\ p_5 = \theta_4/p_2 \tag{35}$$

The above computations show that the model (22)-(24) is *structurally identifiable* with parameters $p_1, \ldots, p_5$ if the disturbance T_I is constant.

There are altogether six physical parameters in the equations (20)-(21), namely: m, M, c_p, K_W, C_{pW}, and W_{loss}. Naturally, all these six parameters cannot be separately identified from $p_1, \ldots, p_5$ and we have to rely on some prior knowledge to be able to determine them.

The most realistic approach is that the liquid mass M is assumed to be known since its nominal value can be found in the technical documentation and it can also be computed from the available liquid level measurements. In this case, the physical parameters can be determined as follows

$$m = p_1M,\ c_p = \frac{1}{Mp_3},\ K_W = p_2c_pM \tag{36}$$

$$C_{pW} = \frac{K_W}{p_4},\ W_{loss} = -p_5C_{pW} \tag{37}$$

From the above results we can conclude that the model is structurally identifiable also in the physical coordinates if M is known a-priori.

V. Parameter estimation results

For the model structure validation a pressure measurement record of about 10 hours were used with a sampling time of 10s. The input of the system consisted of 5 switchings between two discrete values of the manipulable input, where the switching times were exactly known. It is important to note that the constraints of the industrial environment seriously limited the type of applicable input signals. During the measurements (in agreement with the previous assumptions) the disturbance variable T_I and the cold water inlet flow rate m were measured and constant.

The temperature-pressure curve was inverted by evaluating (11) at 200 equidistant points between 315 °C and 350 °C and by approximating the inverse using 3rd order splines.

The measured input and output of the system is shown in Fig. 3.

The objective function to be minimized was the standard squared two-norm of the difference between the measured and simulated output, i.e.

$$V_T = \int_0^T \epsilon^2(t,\theta)dt \tag{38}$$

where $\epsilon(t,\theta) = y(t) - \hat{y}(t|\theta)$ and y denotes the measured temperature data. The obtained physical parameter values were the following (their units of measure can be found in Table I):

$$m = 0.15,\ M = 30138,\ K_W = 63204, c_p = 4183 \tag{39}$$

$$C_{pW} = 4.8477 \cdot 10^7,\ W_{loss} = 1.3588 \cdot 10^5 \tag{40}$$

The objective function value with the above parameters was $V_T = 26.31$. The orders of magnitude and values of the estimated parameters are fully acceptable from a physical point of view. The fit between the measured and simulated temperatures is fairly good as it is visible in Fig. 4. It can also be seen on the small variations of the measured temperature that some unmodeled phenomena took place in the system or certain parameters were actually not constant during the operation (but still, this part of the measurements was one of the most usable for parameter estimation).

TABLE II

DIFFERENTIAL POLYNOMIALS IN THE PARAMETER-BY-PARAMETER REGRESSION FORM, $y^{(i)} := y_i$, $u^{(j)} := u_j$

$$
\begin{aligned}
P_i = \;& y_2(u_1(u_4y_5 - u_5y_4) + u_2(2u_4y_4 - u_3y_5) - u_3^2y_4 + (u_3u_4 - u_2u_5)y_3) + y_1(u_2(u_5y_4 - u_4y_5) + u_3^2y_5 - u_3u_4y_4 + (u_4^2 - u_3u_5)y_3) \\
& + u_1(y_3(-u_3y_5 - u_4y_4) + u_3y_4^2 + u_5y_3^2) + y_3(u_2^2y_5 + u_2u_3y_4) - u_2^2y_4^2 - u_2u_4y_3^2 + (u_3u_5 - u_4^2)y_2^2, \quad i = 1, \ldots, 5 \\
Q_1 = \;& -y_1(u_2(u_4y_6 - u_5y_5) - u_3^2y_6 + u_3u_4y_5 + (u_3u_5 - u_4^2)y_4) - y_2(u_1(u_5y_5 - u_4y_6) + u_2(u_3y_6 - u_4y_5) + (u_4^2 - u_3u_5)y_3) - u_1(y_3(u_3y_6 - u_5y_4) \\
& - u_3y_4y_5 + u_4y_4^2) - y_3(u_3^2y_4 - u_2^2y_6) - u_2^2y_4y_5 + u_2u_3y_4^2 - (u_2u_5 - u_3u_4)y_3^2 \\
Q_2 = \;& u_1(y_3(u_4y_6 - u_5y_5) + y_4(-u_3y_6 - u_4y_5) + u_3y_5^2 + u_5y_4^2) + y_2(u_2(u_5y_5 - u_4y_6) + u_3^2y_6 - u_3u_4y_5 + (u_4^2 - u_3u_5)y_4) + y_3(u_2(-u_3y_6 \\
& + 2u_4y_5 - u_5y_4) - u_3^2y_5 + u_3u_4y_4) + u_2^2(y_4y_6 - y_5^2) + u_2(u_3y_4y_5 - u_4y_4^2) + (u_3u_5 - u_4^2)y_3^2 \\
Q_3 = \;& (y_2(u_2(y_4y_6 - y_5^2) + y_3(u_3y_6 + u_4y_5 - 2u_5y_4) - u_3y_4y_5 + u_4y_4^2) + y_1(y_3(u_4y_6 - u_5y_5) + y_4(-u_3y_6 - u_4y_5) + u_3y_5^2 + u_5y_4^2) \\
& + y_2^2(u_5y_5 - u_4y_6) + y_3^2(-u_2y_6 - u_3y_5 - u_4y_4) + y_3(2u_2y_4y_5 + u_3y_4^2) - u_2y_4^3 + u_5y_3^3) \\
Q_4 = \;& (y_1(u_1(u_2(y_5^2 - y_4y_6) + y_3(2u_3y_6 - u_4y_5 - u_5y_4) - 2u_3y_4y_5 + 2u_4y_4^2) + u(y_3(u_5y_5 - u_4y_6) + y_4(u_3y_6 + u_4y_5) - u_3y_5^2 - u_5y_4^2) + y_3(u_3^2y_4 - u_2^2y_6) \\
& + u_2^2y_4y_5 - u_2u_3y_4^2 + (u_2u_5 - u_3u_4)y_3^2) + y_2(u(u_2(y_5^2 - y_4y_6) + y_3(-u_3y_6 - u_4y_5 + 2u_5y_4) + u_3y_4y_5 - u_4y_4^2) + d_1(u_2(u_4y_6 - u_5y_5) - u_3^2y_6 \\
& + u_3u_4y_5 + (u_3u_5 - u_4^2)y_4) + y(u_2(u_5y_5 - u_4y_6) + u_3^2y_6 - u_3u_4y_5 + (u_4^2 - u_3u_5)y_4) + y_1(u_1(u_5y_5 - u_4y_6) + u_2(u_3y_6 - 2u_4y_5 + u_5y_4) + u_3^2y_5 \\
& - u_3u_4y_4 + (2u_4^2 - 2u_3u_5)y_3) + u_1(y_3(u_2y_6 - 3u_4y_4) - u_2y_4y_5 + 2u_3y_4^2 + u_5y_3^2) + u_1^2(y_4y_6 - y_5^2) + y_3(u_2^2y_5 + u_2u_3y_4) - u_2^2y_4^2 - u_2u_4y_3^2) \\
& + y(u_1(y_3(u_4y_6 - u_5y_5) + y_4(-u_3y_6 - u_4y_5) + u_3y_5^2 + u_5y_4^2) + y_3(u_2(-u_3y_6 + 2u_4y_5 - u_5y_4) - u_3^2y_5 + u_3u_4y_4) + u_2^2(y_4y_6 - y_5^2) \\
& + u_2(u_3y_4y_5 - u_4y_4^2) + (u_3u_5 - u_4^2)y_3^2) + u_1(d_1(y_3(u_5y_5 - u_4y_6) + y_4(u_3y_6 + u_4y_5) - u_3y_5^2 - u_5y_4^2) + y_3^2(-u_2y_5 - u_3y_4) + u_2y_3y_4^2 + u_4y_3^3) \\
& + d_1(y_3(u_2(u_3y_6 - 2u_4y_5 + u_5y_4) + u_3^2y_5 - u_3u_4y_4) + u_2^2(y_5^2 - y_4y_6) + u_2(u_4y_4^2 - u_3y_4y_5) + (u_4^2 - u_3u_5)y_3^2) + y_1^2(u_2(u_4y_6 - u_5y_5) - u_3^2y_6 \\
& + u_3u_4y_5 + (u_3u_5 - u_4^2)y_4) + y_2^2(u(u_4y_6 - u_5y_5) + u_1(-u_3y_6 + 2u_4y_5 - u_5y_4) + u_2(2u_4y_4 - u_3y_5) - u_3^2y_4 + (u_3u_4 - u_2u_5)y_3) \\
& + u(y_3^2(u_2y_6 + u_3y_5 + u_4y_4) + y_3(-2u_2y_4y_5 - u_3y_4^2) + u_2y_4^3 - u_5y_3^3) + u_1^2(-y_3^2y_6 + 2y_3y_4y_5 - y_4^3) + (u_3u_5 - u_4^2)y_2^3) \\
Q_5 = \;& y_1(u_2(y_4y_6 - y_5^2) + y_3(u_4y_5 - u_3y_6) + u_3y_4y_5 - u_4y_4^2) + y_2(u_1(y_5^2 - y_4y_6) + y_3(-u_2y_6 - u_3y_5 + 2u_4y_4) + u_2y_4y_5 - u_3y_4^2) \\
& + u_1(y_3^2y_6 - 2y_3y_4y_5 + y_4^3) + y_2^2(u_3y_6 - u_4y_5) + y_3^2(u_2y_5 + u_3y_4) - u_2y_3y_4^2 - u_4y_3^3
\end{aligned}
$$

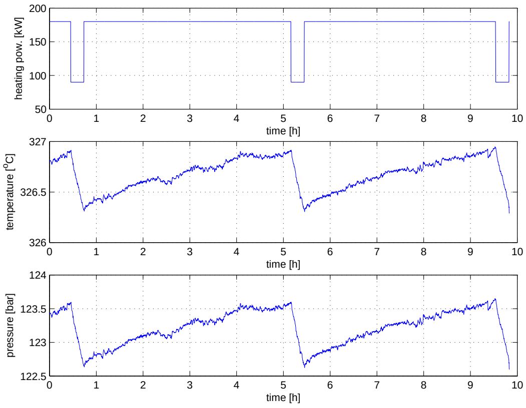

Fig. 3. Measured input and output of the system

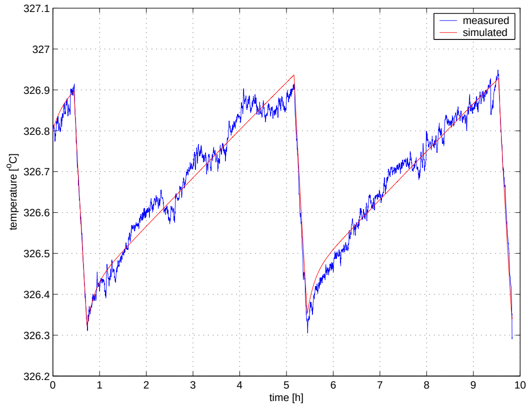

Fig. 4. Fit between measured and simulated temperatures

VI. CONCLUSIONS

The structural identifiability of a simple power plant pressurizer model was investigated in this paper. It was shown that out of the six physical parameters, five are identifiable. The parameter estimation gave physically meaningful results and the fit between the measured and simulated output was fairly good. The results can hopefully be extended to the case when some terms in the model (e.g. the heat transfer between the water, tank wall and environment) are modeled with expressions that are nonlinear in parameters.

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