DEMONSTRATION OF FIRST-PRINCIPLE MODEL ADJUSTMENT APPROACH WITH THE USE OF A SIMPLIFIED HEATER MODEL

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Summary

The paper discusses a process of formulation and identification of a first-principle data-driven heater model. The model is formulated using a system of continuous ordinary differential equations capturing usually nonlinear relations among variables of the model. The considering model applies three categories of parameters: geometrical, physical and phenomenological. Geometrical and physical parameters are deduced from construction or operational documentation. The phenomenological parameters are the adjustable ones. First-principle models are frequently adjusted by trial-and-error, which can lead to non-optimal results. In order to avoid deficiencies of the trial-and-error approach, a formalized mathematical method using optimization techniques to minimize the error criterion, and find optimal values of adjustable model parameters, was proposed and demonstrated in this work.

Keywords: first principle model, data driven model, grey-box methods.

DEMONSTRACJA PODEJŚCIA DO STROJENIA MODELU OPARTEGO NA PRAWACH FIZYKI NA PODSTAWIE UPROSZCZONEGO MODELU PODGRZEWACZA

Streszczenie

Artykuł omawia proces modelowania podgrzewacza regeneracyjnego pracującego w systemie bloku energetycznego z wykorzystaniem strojonych równań fizycznych. Model jest formułowany z użyciem układu zwyczajnych równań różniczkowych obejmujących wzajemne nieliniowe relacje pomiędzy zmiennymi modelu. Rozważany model stosuje trzy kategorie parametrów: geometryczne, fizyczne, oraz fenomenologiczne. Parametry geometryczne oraz fizyczne są ustalane na podstawie dokumentacji konstrukcyjnej oraz operacyjnej. Parametrami strojonym są parametry fenomenologiczne. Modele wyprowadzane na podstawie praw fizycznych są często strojone metodą prób i błędów, co może prowadzić do nieoptymalnych wyników. Dla ominięcia wad metody została zastosowana metoda najmniejszych kwadratów do strojenia parametrów fenomenologicznych modelu podgrzewacza tj. współczynników wymiany ciepła.

Słowa kluczowe: model oparty na prawach fizyki, model danych, metody grey-box.

NOMENCLATURE

$\dot{m}$ - mass flux [kg/s]
$\dot{Q}$ - energy flux [J/s]
h - enthalpy [J/kg]
H - internal energy [J]
ρ - density [kg/m^3]
p - pressure [Pa]
T - temperature [K]
V - chamber volume [m^3]
k - heat transfer coefficient [W·m^{-2}·K^{-1}]
F - heat exchange area [m^2]
c_p - specific isobaric heat [J·kg^{-1}·K^{-1}]
x - state variable
A, B, C, D - linear state-space model representation

1. INTRODUCTION

The initial phase in modelling of a technical system is collecting and systematic treatment of available knowledge. The a priori knowledge about a given phenomenon comes from the analysis, comprising of finding all possible connections to other phenomena and physical laws, preceding the modelling. The a priori knowledge is of key importance in modelling although its availability is always limited by the complexity of the physical system.. Even if the governing physical principia are known, it is usually difficult to formulate the specific relationships and obtain particular values of the parameters. Availability of the a priori knowledge and the modelling purpose determine the following: (i) the final type of the model, (ii) the accuracy requirements, (iii) the type of specific modeling procedure, (iv) the complexity of the model and lastly, (v) the method and the cost of its realization. According to the degree to which the a priori knowledge is available, then either a first-principle or a data-driven model, or a combination of both, can be applied (cf. Fig 1). First-principle (FP) models use understanding of the system underlying physics to derive its mathematical representation. FP models are expensive in development since expertise in the area of knowledge at the advanced level is required to derive equations from physical laws, while data-driven (DD) models use system test data to derive its mathematical representation. The advantage of the former approach is the depth of the insight into the behavior of the system and thus ability to predict the performance, while the advantage of the latter is the speed in which an accurate model can be constructed and confidence gained thanks to the use of the data obtained from the actual system. The difficulty of the former approach lies in the determination of the phenomenological parameters like the friction or the heat transfer coefficient. First-principle models are frequently adjusted by trial-and-error, which can lead to non-optimal results. On the other hand, the disadvantage of DD models is the need to handle multiple data sets in order to cover the range of system operation.

2. HIGH PRESSURE FEEDWATER HEATER INSTALLATION

A feasibility study presented in this paper is focused on numerical studies on fault detection in application to thermal systems. Heaters installations are typically affected by fouling and corrosion phenomena which may have effect on heat transfer and fluid transportation process [4, 5]. Feedwater heaters are typically designed as three-zone heat exchangers with a condensing section, desuperheater and integrated subcooler (Fig. 1).

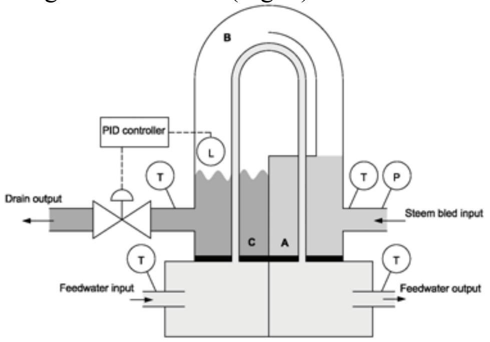

Fig. 1. Schem of a feedwater heater [5] (A: desuperheating area; B: condensing area; C: subcooling area; T: temperature sensor; L: level sensor; P: Pressure sensor)

The drainage system of the feedwater heater consists of a drain removal path from each heater. The normal drain flow path is cascaded to the next lower stage heater, and the alternate path is diverted to the condenser. When the turbine is loaded at a given rate, steam is allowed to enter the bank of heaters through extraction outlets [4, 5].

Reliability of feedwater heaters is strongly influenced by their design, applied materials and operating conditions [5]. Most common faults of heaters concern piping systems. Fouling is an accumulation of undesirable material (deposits) on heat exchanger surfaces resulting in deterioration in thermal performance and increase of pressure drop. Evaluation of heater performance can be approached by continuous monitoring of parameters responsible for intensity of heat transfer process. Under normal operating conditions the heat transfer coefficient is constant or slowly decreasing due to a layer of settled material building up on the heat transfer surface. It may happen that large pieces of the settled material can break away from the surface. When the settled material breaks off, the heat transfer coefficient may change the value. Tube bursting makes the feedwater flow into the external jacket of the heater, and consequently feedwater gets mixed with condensate. The leakages have several causes: (i) electrochemical corrosion, (ii) erosion caused by water or steam, and (iii) fatigue – due to mechanical vibrations. Details of each cause of fault, common places of occurrence and discussion on materials for heater's construction are provided in [5]. Moreover, operation of the heater may be influenced by faults of auxiliary devices, such as three-way servovalves regulating flow of fluids through the heater. There occur also malfunctions of control system elements, e.g. sensors measuring operational parameters of the heater and giving information to the controller. Consequences of consecutive malfunctions for the whole power unit are described in [3, 4].

3. THE NONLINEAR AND LINEARIZED FEEWATER HEATER MODELS

A continuous-time heat exchanger model was formulated using ordinary differential equations (ODEs). The model was implemented in Matlab as the 'idnlgrey' model structure with the use of first-order differential equations (1) and as the 'idgrey' model structure with the use of linearized state-space equations (2). The third implementation was a block-diagram model in Simulink. System Identification Toolbox commands were used to perform linear and nonlinear grey-box modeling using heater model implemented in m-file, while Simulink Parameter Estimation tool was used to identify the heater model implemented in Simulink. System Identification Toolbox grey-box models require to specify the structure of the ODE model in an m-file. A linear model system is modeled with use both, i.e. the 'idgrey' and the 'idnlgrey 'objects. However, only nonlinear dynamics can be handled using the 'idnlgrey' model object. The 'idgrey' object requires that an m-file to describe the linear dynamics in the state-space form, such that this m-file returns the state-space matrices as a function of the parameters. The 'idnlgrey' object requires to write an m-file or MEX-file to describe the dynamics as a set of first-order differential equations, such that this file returns the output and state derivatives as a function of time, input, state, and parameter values. Simulink models require defining inputs-outputs of a model, specifying the free parameters, and choosing the optimization method. A nonlinear simplified heater model is described with the following equations:

$$\begin{aligned}\frac{dT_{12}}{dt} &= f_{12}(T_{12},T_{34},\dot{m}_1,\dot{m}_2,T_1,T_2) = \\ &= \frac{\dot{m}_1}{\rho_{12}V_{12}}(T_1-T_2)+\frac{k_{12-34}F(T_{12}-T_{34})}{V_{12}\rho_{12}c_{p12}} \\ \frac{dT_{34}}{dt} &= f_{34}(T_{12},T_{34},\dot{m}_3,\dot{m}_4,T_3,T_4) = \\ &= \frac{\dot{m}_3}{\rho_{34}V_{34}}(T_3-T_4)+\frac{k_{12-34}F(T_{12}-T_{34})}{V_{34}\rho_{34}c_{p34}}\end{aligned} \tag{1}$$

where ρ, V, c_p are function of pressure, temperature, and enthalpy. The model is schematically presented in figure 2.

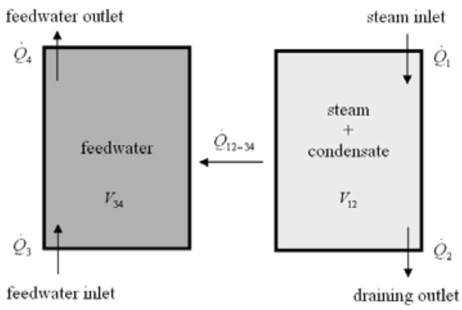

Fig. 2. Scheme of the simplified heater model

A linearized model has the form as follows:

$$\begin{aligned}Ax &= Bu + C \\ y &= Cx\end{aligned} \tag{2}$$

where the state, input, and output vectors are, in deviation form as folows:

$$x = \begin{bmatrix} T_{12}-T_{012} \\ T_{34}-T_{034} \end{bmatrix} \tag{3}$$

$$u = \begin{bmatrix} \dot{m}_1-\dot{m}_{01} \\ \dot{m}_3-\dot{m}_{03} \\ T_3-T_{03} \\ T_1-T_{01} \end{bmatrix} \tag{4}$$

$$y = \begin{bmatrix} T_{12}-T_{012} \\ T_{34}-T_{034} \end{bmatrix} \tag{5}$$

The elements of the state-space A matrix are found by:

$$\begin{aligned}A_{11} &= \frac{\partial f_{34}}{\partial(T_{12}-T_{012})} = \frac{\partial f_{12}}{\partial T_{12}} = \\ &= -\frac{\dot{m}_1}{\rho_{12}V_{12}} - \frac{k_{12-34}F}{V_{12}\rho_{12}c_{p12}}\end{aligned} \tag{6}$$

$$\begin{aligned}A_{12} &= \frac{\partial f_{12}}{\partial(T_{34}-T_{034})} = \frac{\partial f_{12}}{\partial T_{34}} = \\ &= \frac{k_{12-34}F}{V_{12}\rho_{12}c_{p12}}\end{aligned} \tag{7}$$

$$\begin{aligned}A_{21} &= \frac{\partial f_{34}}{\partial(T_{12}-T_{012})} = \frac{\partial f_{34}}{\partial T_{12}} = \\ &= \frac{k_{12-34}F}{V_{34}\rho_{34}c_{p34}}\end{aligned} \tag{8}$$

$$\begin{aligned}A_{22} &= \frac{\partial f_{34}}{\partial(T_{34}-T_{034})} = \frac{\partial f_{34}}{\partial T_{34}} = \\ &= \frac{\dot{m}_3}{\rho_{34}V_{34}} - \frac{k_{12-34}F}{V_{34}\rho_{34}c_{p34}}\end{aligned} \tag{9}$$

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \tag{10}$$

The elements of the state-space B matrix are found by:

$$B_{11} = \frac{\partial f_{12}}{\partial(\dot{m}_3-\dot{m}_{03})} = \frac{\partial f_{12}}{\partial \dot{m}_3} = 0 \tag{11}$$

$$B_{12} = \frac{\partial f_{12}}{\partial(\dot{m}_1 - \dot{m}_{01})} = \frac{\partial f_{12}}{\partial \dot{m}_1} = \frac{T_1 - T_2}{\rho_{12} V_{12}} \quad (12)$$

$$B_{13} = \frac{\partial f_{12}}{\partial(T_1 - T_{01})} = \frac{\partial f_{12}}{\partial T_1} = \frac{\dot{m}_1}{\rho_{12} V_{12}} \quad (13)$$

$$B_{14} = \frac{\partial f_{12}}{\partial(T_3 - T_{03})} = \frac{\partial f_{12}}{\partial T_3} = 0 \quad (14)$$

$$B_{21} = \frac{\partial f_{34}}{\partial(\dot{m}_3 - \dot{m}_{03})} = \frac{\partial f_{34}}{\partial \dot{m}_3} = \frac{T_3 - T_4}{\rho_{34} V_{34}} \quad (15)$$

$$B_{22} = \frac{\partial f_{34}}{\partial(\dot{m}_1 - \dot{m}_{01})} = \frac{\partial f_{34}}{\partial \dot{m}_1} = 0 \quad (16)$$

$$B_{23} = \frac{\partial f_{34}}{\partial(T_1 - T_{01})} = \frac{\partial f_{34}}{\partial T_1} = 0 \quad (17)$$

$$B_{24} = \frac{\partial f_{34}}{\partial(T_3 - T_{03})} = \frac{\partial f_{34}}{\partial T_3} = \frac{\dot{m}_3}{\rho_{34} V_{34}} \quad (18)$$

$$B = \begin{bmatrix} 0 & B_{12} & B_{22} & 0 \\ B_{21} & 0 & 0 & B_{24} \end{bmatrix} \quad (19)$$

The C matrix is the identity matrix given as:

$$C = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (20)$$

The parameters considered in a simulation are given in table 1.

Table 1. Heaters' parameters

Nominal parameters	**Symbol**	**Unit**	**Value**
Heat exchange area	F	m^2	500
Inlet steam mass flow	$\dot{m}_1$	kg/s	23 ±1σ
Outlet steam mass flow	$\dot{m}_2$	kg/s	NA
Inlet feedwater mass flow	$\dot{m}_3$	kg/s	596 ±1σ
Outlet feedwater mass flow	$\dot{m}_4$	kg/s	NA
Steam+condensate density	ρ_{12}	$[kg/m^3]$	1.2
Feedwater density	ρ_{34}	$[kg/m^3]$	952
specific isobaric heat (steam + condensate)	c_{p12}	$[J \cdot kg^{-1} \cdot K^{-1}]$	2e+003
specific isobaric heat (feedwater)	c_{p34}	$[J \cdot kg^{-1} \cdot K^{-1}]$	4.2e+003
Steam+condensate temperature	$T_{12} = T_2$	[deg]	NA
Feedwater temperature	$T_{34} = T_4$	[deg]	NA
Inlet steam temperature	T_1	[deg]	269
Inlet feedwater temperature	T_3	[deg]	108
Steam+condensate volume	V_{12}	$[m^3]$	2.9
Feedwater volume	V_{34}	$[m^3]$	4
Heat transfer coefficient	$k_{12=34}$	$[W \cdot m^{-2} \cdot K^{-1}]$	1150

The aim of the numerical benchmarking exercise is to estimate values of free parameters using three different methods, i.e. the 'idgrey', 'idnlgrey' from System identification Toolbox, and Simulink Parameter Estimation. The system identification was performed as two cases, i.e. A and B. Case A assumes a heat transfer coefficient as a free parameter (Table 2) while the Case B assumes two free parameters (Table 3), i.e. heat transfer coefficient and steam volume. The input data was disturbed by noise of zero mean and variance 1. On the other hand, the output data was additionally disturbed by zero-mean white noise of variance equal 5.

The "True value" parameter defines the target value of the parameter assumed in the simulation, while "Initial guess" means the initial value assumed in the optimization process. The "Error" field evaluates the percentage difference between the "True value" and the "Estimated value" of the parameter. Example of model parameters' trajectories during estimation process in Case B is presented in figure 3.

Table 2. Estimated free parameters (Case A)

	Linear Grey-Box Model	**Nonlinear Grey-Box Model**	**Simulink Estimation**
	k	k	k
Model	Linear (linearized)	Nonlinear	Nonlinear
'True' value	1150	1150	1150
Initial guess	45	45	45
Estimated value	1150	1150	1150
Error [%]	0.1%	0.05%	0.1%
Computation time [s]	15s	120s	70s

Table 3. Estimated free parameters (Case B)

	Linear Grey-Box Model		**Nonlinear Grey-Box Model**		**Simulink Estimation**	
	k	V12	k	V12	k	V12
Model	Linear (linearized)		Nonlinear		Nonlinear	
'True' value	1150	4	1150	4	1150	4
Initial guess	45	1	45	1	45	1
Estimated value	1150	4	1150	4	1150	4
Error	0.15%	0.13%	0.1%	0.09%	0.08%	0.13%
Computation time [s]	25s		210s		160s	

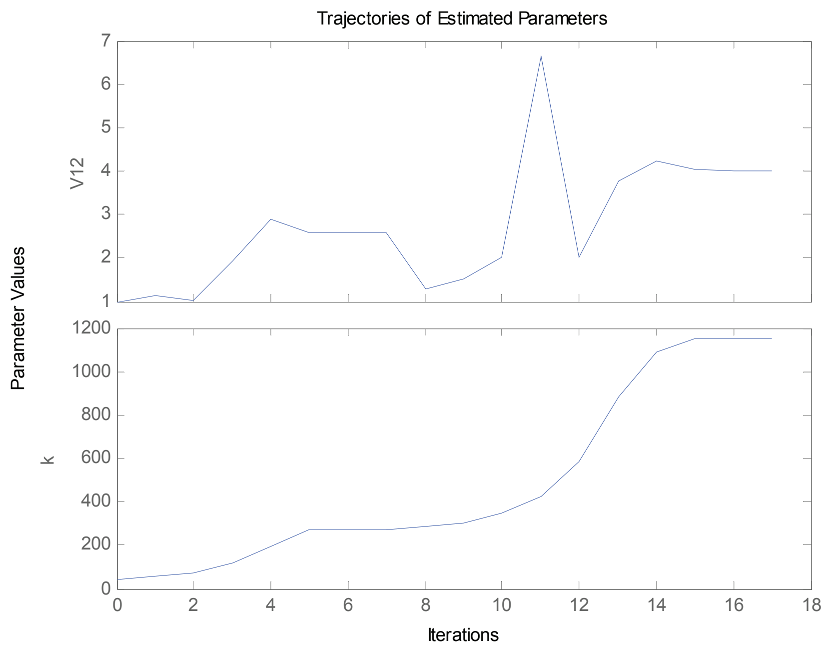

Fig. 3. Trajectories of adjusted model parameters (Case B)

4. SUMMARY AND CONCLUSIONS

The paper demonstrates a first-principle data-driven approach towards modeling of a feewater heater. The model offers physical insight and sufficient numerical performance to be applicable in understanding underlying physical phenomena, designing control systems, and optimizing processes after supplemented with additional physical equations [1, 3]. FPDD models can be used in many areas where physical understanding is critical, e.g. design of new products or early warning diagnostics of large industrial installations. The model is represented by nonlinear state-space equations having geometrical and physical parameters deduced from available documentation, and adjustable phenomenological parameters (i.e. heat exchange or leakage coefficients) that are estimated from measurement data.

The paper compares three implementation approaches (idgrey, idnlgrey, and Simulink), or based on the simplified heat exchange model, i.e. linear and nonlinear. The preferable environment for modeling of complex power plant installations is Simulink providing the causal block diagram GUI. Block diagram model representation is more suitable since it allows to incrementally expand the model of new components, e.g. equations, look-up-tables with experimental characteristics. Hence, the advantage of Simulink Estimation Tool is flexibility that any Simulink model including soft and hard nonlinearities can be identified and calibrated from experimental data. In case of System Identification toolbox from the Matlab package the model has to be formulated as a set of first order differential equations into m-file using 'idgrey' or 'idnlgrey' model structures. This operation increases lead-time of the model development. On the other hand, the benchmarking study shows (Table 1-2) lower performance of the System Identification toolbox compared to Simulink.

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REFERENCES

[1] T. Barszcz, P. Czop, *Estimation of feedwater heater parameters based on a grey–box approach*, Int. J. Appl. Math. Comput. Sci., 2011, Vol. 21, No. 4.
[2] T. Barszcz, P. Czop, *A Feedwater Heater Model Intended for Model-Based Diagnostics of Power Plant Installations*, Applied Thermal Engineering, Vol. 31, No. 8-9, June 2011, Pages 1357-1367.
[3] T. Barszcz, P. Czop. *Methodologies and Applications of Virtual Power Plant*: New Environment for Power Plant Elements Modeling, Institute of Sustainable Technologies, Radom 2007
[4] [D. Flynn (eds.), *Thermal Power Plants - Simulation and Control*, The Institution of Electrical Engineers, London 2000.
[5] E. Zbroińska-Szczechura, J. Dobosiewicz. *Uszkodzenia i diagnostyka wymienników ciepła w elektrociepłowniach*, Energetyka, grudzień 2004.

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