MODELLING OF STEAM TEMPERATURE DYNAMICS OF A SUPERHEATER

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Abstract: The paper presents a MISO Wiener-Hammerstein cascade model describing the thermal process of a single steam superheater stage. The non-linear static part is based on the energy balance of the media involved in the process. The linear part involves the time dependence of the process. The derivative of the model can be easily obtained, which allows to apply the Levenberg-Marquadt method for identification. The identification and the validation of the model are presented on the measurement of the second superheater stage of a 180 MW fluidized bed boiler. The proposed model is simple and transparent, its identification is not too complicated. According to the validation result, the model is suitable for testing superheater control structures on it.

Keywords: Steam superheater, non-linear models, Wiener system, Hammerstein system

NOMENCLATURE

T	temperature,	K
A	surface area,	m^2
V	volume,	m^3
m	mass,	kg
ρ	density,	kg/ m^3
c	specific heat,	kJ/(kg·K)
h	enthalpy,	kJ/kg
Q	heat flow,	kJ/s
α	heat transfer coefficient,	kJ/(s·K)

indices

st	steam,
fg	flue gas,
fg_rad	representative temperature of the combustion chamber,
met	metal of the pipe,
in	inlet,
out	outlet,
conv	convective,
rad	radiative.

INTRODUCTION

From the modelling point of view the steam superheating process can be understood as a combination of two sub processes: the hydrodynamic and the thermodynamic process. The dynamic time constants of these are significantly different; the hydrodynamic changes happen in tenth of seconds meanwhile the magnitude of the time constants of the thermal process are in the range of tens of seconds. Therefore these processes are usually modelled separately. The model presented in this paper concerns only the thermal process.

Numerous approaches are available in the literature for modelling the superheater. The main output of these models is the dynamic behaviour of the steam temperature at the superheater outlet. The models can be sorted according to the extension of the derived process. Namely whether it covers only the steam side process assuming the transferred heat flow being known; or it also contains the heat transfer phenomena (approximating the heat transfer coefficients) as well, or even the combustion process (heat release).

The models are generally considering the first-principle equations (mass, momentum and energy balances) and the phenomenological correlations (*e.g.* heat transfer correlations). According to the time and spatial distribution of the temperature in the superheater, the process is described by partial differential equations, of which solution may be complex.

Zima (2001) presented a model applying a powerful method of the finite difference method for the solution of the partial differential equations. In his model, the heat transfer coefficients were assumed to be *a priori* known and constant.

The distributed parameter problem was also addressed by the Profos model (Profos 1962). The model is based on the one-pipe approximation of the process. This linearized model was derived by performing Laplace transformation once by the time and once by the spatial variable on the partial difference equations. The extended Profos model presented by Czinder (1996) incorporates the dynamical behaviour of the outlet temperature of the flue gas flow.

Oda *et al.* (1995) introduced a simplified model for testing a model reference controller. The model implements the same phenomena as the previous ones; but the distributed parameter problem is solved by applying two of the same concentrated parameter model-block. The fuel flow also appears among the model inputs, and the temperature of the flue gas is estimated. In the model, only radiative heat transfer was assumed. The presented validation data shows good matching between the estimation and measurement of the steam temperature.

Maffezzoni (1997) presented a model to describe the boiler turbine dynamics. The proposed simple linearized model concerns only the steam side phenomena utilising *a priori* known heat flow.

For the simulation of the superheater process, black box models are also proposed in the literature. For example, Alippi and Piuri (1995) reported a computationally simple, distributed non-linear model; however their model covers not only the superheating process, but the whole power plant. The identification of their neural model was performed on a 320 MW one-through boiler. The inputs of their superheater model were the same as the inputs of the model proposed in this paper.

In this paper, the Wiener-Hammerstein cascade model is applied for the modelling of the superheated steam temperature behaviour. The Wiener and Hammerstein models are widely used for modelling of non-linear process, because of their transparency, the capability to capture well the behaviour of the process and because of the easy identification. This type of model is applied in different fields, *e.g.* for modelling biological systems (Hunter and Korenberg 1986); for stochastic systems (Averin 2003); for modelling of combustion process of fluidized bed boiler (Ikonen 2001).

Due to the lack of available technical data, the parameters of the steady state relationship (*e.g.* the heat transfer coefficients), must be also approximated during the identification. The gradient-based Levenberg-Marquadt algorithm was applied in the identification.

The superheating process

The superheating process is an important part of the steam generation and so a main part of the Rankin-cycle of the power plant. In drum type boilers the steam flow leaves the drum at saturated temperature and then it is superheated in heat exchangers called superheaters. The live steam enters the turbines after the main steam valve.

The superheater heat exchanger surfaces are usually divided into two or three stages. Between the stages water sprayers (attemperators) are mounted to control the steam flow. The steam temperature controller defines the amount of the sprayed water. The live steam temperature (T_1) determines the average temperature of the heat income $\left(\overline{\overline{T}}_1\right)$, which strongly influences the cycle efficiency, $\eta = 1 - \frac{T_2}{\overline{\overline{T}}_1}$, where T_2 is the average temperature of the heat abstraction (*i.e.* condensation). Therefore regulation of live steam temperature is always an important question in the power plants.

A typical fluidized boiler is presented in Figure 1. The three superheater stages are placed in a special order: the second stage is over the combustion chamber, followed by the third stage, and the final one is the first stage. This order has an important effect also on the modelling. The heat transfer at the second superheater stage is not only convective (from flue gas), but also radiative (from the combustion flame).

Figure 1. Typical boiler

Wiener Hammerstein Cascade process model

In many cases, the behaviour of non-linear process can be approximated by linear transfer functions for describing the system dynamics, and a non-linear static function describing the steady-state relations. Wiener and Hammerstein structures, in Figures 2a and 2b, are typical examples of such structures.

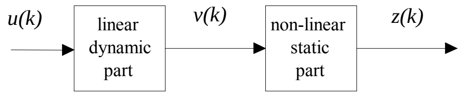

Figure 2a Wiener model structure.

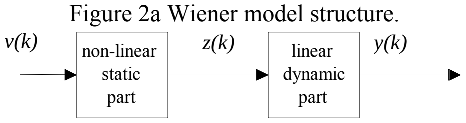

Figure 2a: Hammerstein model structure.

The Wiener and Hammerstein models have several advantages, the most important ones:

- The function can be derived by the parameters of the static part and by the parameters of the linear dynamic parts as well;
- the linearity of the dynamic part simplifies not only the parameter estimation, but also the (closed loop) system analysis, modelling of disturbance, and controller design;
- the *a priori* knowledge about industrial processes usually concerns the steady state relations. With this model structure it is easy to incorporate it into the model.

The applied simple Wiener-Hammerstein cascade model (Haber and Keviczky 2002) consists of linear dynamic parts and one non-linear static term connected in series, as shown in Figure 2b.

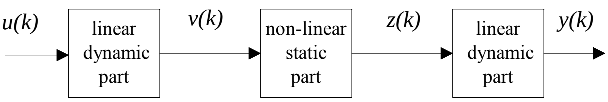

Figure 2b: The Wiener-Hammerstein cascade model

With this model structure the different dynamical behaviour of the inputs are simply incorporated. The linear dynamic part on the output involves the distributed behaviour of the process.

The superheater model

In the case of the superheater, the static part is a multi-input single-output function. Thus, the first linear dynamic part in Figure 2b contains several linear dynamics. The detailed model for the superheater is given in Figure 3.

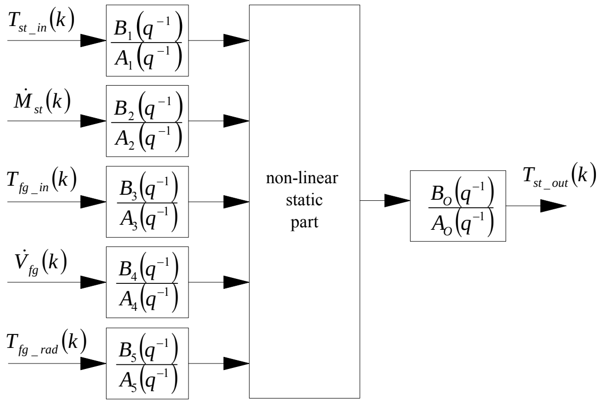

Figure 3: The Wiener-Hammerstein cascade model for the superheater

All the dynamic parts are chosen to be second order transfer function with unit gain. Thus one dynamic model has only three parameters:

$$A_i(q^{-1}) = 1 + a_{i,1}q^{-1} + a_{i,2}q^{-2} \quad (1)$$

$$B_i(q^{-1}) = b_{i,0}q^{-1} + (1 + a_{i,1} + a_{i,2} - b_{i,0})q^{-2} \quad (2)$$

The nonlinear static part is based on a concentrated parameter static model of the superheater process. The outlet temperature is expressed from the energy balance equations of the wall (3), steam (4), and flue gas (5) and from the convective (6,7), and radiative heat transfer (8) equations.

The energy balance of the wall:

$$\dot{Q}_{st} = \dot{Q}_{fg} + \dot{Q}_r \quad (3)$$

The energy balance of the steam flow:

$$\dot{Q}_{st} = c_{st} \cdot \dot{m}_{st}(T_{st\_out} - T_{st\_in}) \quad (4)$$

The energy balance of the flue gas flow:

$$\dot{Q}_{fg} = c_{fg} \cdot \dot{V}_{fg} \cdot \rho_{fg} \cdot (T_{fg\_in} - T_{fg\_out}) \quad (5)$$

The heat transfer from the wall into the steam

$$\dot{Q}_{st} = \alpha_{st}(T_{met} - T_{st}) \quad (6)$$

The convective heat transfer from the flue gas flow to the wall:

$$\dot{Q}_{fg} = \alpha_{fg}(T_{fg} - T_{met}) \quad (7)$$

The radiative heat transfer from the combustion chamber to the wall:

$$\dot{Q}_r = \alpha_{rad}(T_{fg\_rad} - T_{met}) \quad (8)$$

The temperature distribution among the wall is assumed to be linear and the average steam and flue gas temperatures are:

$$T_{st} = \frac{T_{st\_in} + T_{st\_out}}{2} \quad (9)$$

$$T_{fg} = \frac{T_{fg\_in} + T_{fg\_out}}{2} \quad (10)$$

To facilitate the expression of the outlet steam temperature the following approximations were applied:

- the radiative heat transfer is approximated to be linear to the temperature difference (8);
- the representative temperatures for the convective heat transfer calculations are the linear average of the inlet and outlet steam and flue gas temperatures (9,10), and not the logarithmic means, as it is suggested in the literature.

The convective heat coefficients are approximated as linear functions of the fluid flows around the surface, thus

$$\alpha_{st}(k) = a_{st} \cdot \dot{m}_{st}(k) + b_{st} \quad (11)$$

$$\alpha_{fg}(k) = a_{fg} \cdot \dot{V}_{fg}(k) + b_{fg} \quad (12)$$

After a series of substitutions and arrangements the output steam temperature can be expressed:

$$T_{st\_out} = f\left(T_{st\_in}, \dot{m}_{st}, T_{fg\_in}, \dot{V}_{fg}, T_{rad}\right) \quad (13)$$

IDENTIFICATION AND VALIDATION

The identification of the model was performed on the measurement data of a 185 MW Bubbling Fluidized Bed Boiler.

The aim of the identification is to determine the model parameters: the $b_{i,1}$ $a_{i,1}$ and $a_{i,2}$ coefficients of the dynamic parts and the a_{st}, b_{st}, a_{fg}, b_{fg} and α_{rad} parameters of the static part. The parameters to be identified are put into the θ vector.

Most of the input variables (steam mass flow, steam inlet temperature, flue gas inlet temperature and representative temperature of the combustion chamber) were taken directly from the measurement. The flue gas volume flow was calculated by an Adaptive Neuro-Fuzzy Interference System (ANFIS) that describes the combustion process. The applied ANFIS model is presented by Hímer (2003) in details.

The minimization was performed by a gradient-based second order method, the Levenberg-Marquadt algorithm as it is given by Ikonen (2001). The cost function is:

$$J(\theta) = \frac{1}{2} R(\theta)^T R(\theta) \quad (14)$$

where the components of the R vector are

$$r_k = T_{st\_out}(k) - T_{st\_out\_meas}(k) \quad (15)$$

where $k=1,2,\ldots,N$, and N is the number of data records.

The Levenberg-Marquadt iteration is given:

$$\theta(l+1) = \theta(l) - \left[G(\theta)^T G(\theta) + \mu(l) I\right]^{-1} G(\theta)^T R(\theta) \quad (16)$$

where the elements of the G matrix are:

$$g_{k,p} = \frac{\partial r_k}{\partial \theta_p} \quad (17)$$

and the $\mu(l)$ is increased whenever the step would result to an increased value of the cost function, otherwise reduced.

Since the optimization algorithm is a gradient-based method, the derivatives of the cost function according to the parameters to be optimized must be calculated. (This is the main reason why the steam outlet temperature must have been expressed explicitly, and CHECK (7-9) approximations were needed.)

The $g_{k,p}$ expressions are given in the followings. First, the derivatives according to the parameters of the output $\frac{B_o(q^{-1})}{A_o(q^{-1})}$ transfer function are presented:

$$\frac{\partial T_{st\_out}}{\partial b_{o,n}}(k) = z(k-n-d) - z(k-n_B-d) - \sum_{m=1}^{n_{A,o}} \left[a_{o,m} \frac{\partial T_{st\_out}}{\partial b_{o,n}}(k-m) \right]$$

$$\frac{\partial T_{st\_out}}{\partial a_{o,n}}(k) = z(k-n_B-d) - T_{st\_out}(k-n) - \sum_{m=1}^{n_{A,o}} \left[a_{o,m} \frac{\partial T_{st\_out}}{\partial a_{o,n}}(k-m) \right].$$

The derivatives according to the parameters of the non-linear steady state function:

$$\frac{\partial T_{st\_out}}{\partial w_j}(k) = b_{o,0} \Psi_j(k-d) + \left(1 + a_{o,1} + a_{o,2} - b_{o,0}\right) \Psi_j(k-1-d) - \sum_{m=1}^{n_{A,o}} \left[a_{o,m} \frac{\partial T_{st\_out}}{\partial w_j}(k-m) \right]$$

where

w_j are the parameters of the non-linear static part and

$$\Psi_j = \frac{\partial z}{\partial w_j}(k)$$

the derivatives of the static parts according to these parameters.

Finally, the derivatives according to the parameters of the input $\frac{B_i(q^{-1})}{A_i(q^{-1})}$ transfer functions are presented:

$$\frac{\partial T_{st\_out}}{\partial b_{i,n}}(k) = \Phi_i(k)\frac{\partial v_i}{\partial b_{i,n}}(k)$$

$$\frac{\partial T_{st\_out}}{\partial a_{i,n}}(k) = \Phi_i(k)\frac{\partial v_i}{\partial a_{i,n}}(k)$$

where:

$\Phi_i(k) = \frac{\partial T_{st\_out}}{\partial v_i}$, and

$$\frac{\partial v_i}{\partial b_{i,n}}(k) = u_i(k-n-d) - u_i(k-n_{B,i}-d) - \sum_{m=1}^{n_{A,i}}\left[a_{i,m}\frac{\partial v_i}{\partial b_{i,n}}(k-m)\right]$$

$$\frac{\partial v_i}{\partial a_{i,n}}(k) = u_i(k-n_{B,i}-d) - v_i(k-n) - \sum_{m=1}^{n_{A,i}}\left[a_{i,m}\frac{\partial v_i}{\partial a_{i,n}}(k-m)\right];$$

and v_i represents the i-th input of the non-linear steady state part.

During the iteration, the estimated A_i polynomials can happen to become unstable. To avoid the unlikely result of applying unstable transfer function, the new parameters were checked in every iteration rounds. If instability was encountered, the parameters were projected into the stable region.

The estimated and the measured steam outlet temperature on the identification data set are shown in Figure 4. The corresponding inputs (steam inlet temperature, mass flow, *etc*) are illustrated in Figure 5.

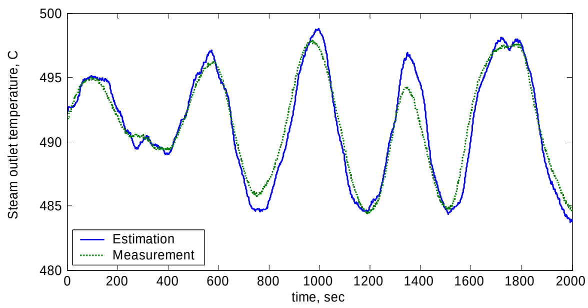

Figure 4: The measured and estimated outlet steam temperature in the identification

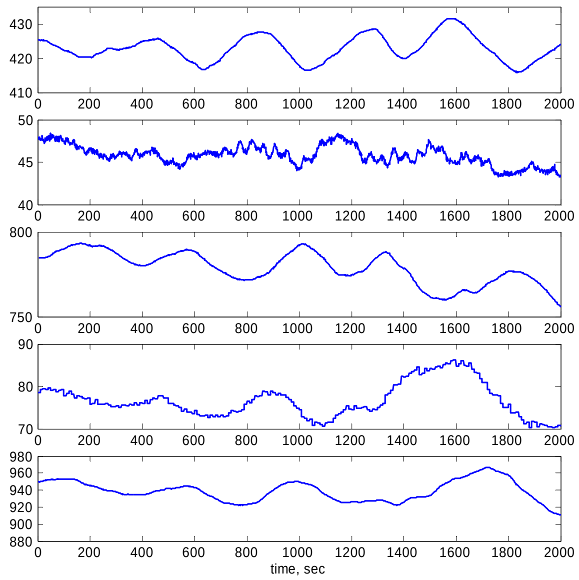

Figure 5: The model input variables (steam inlet temperature, steam mass flow, flue gas inlet temperature, flue gas volume flow, flue-gas representative temperature in the combustion chamber respectively) on the time range applied in the identification

The validation of the identified model was performed on another measurement series from the same boiler. The model performance is presented in Figure 6; the inputs of the model are given in Figure 7.

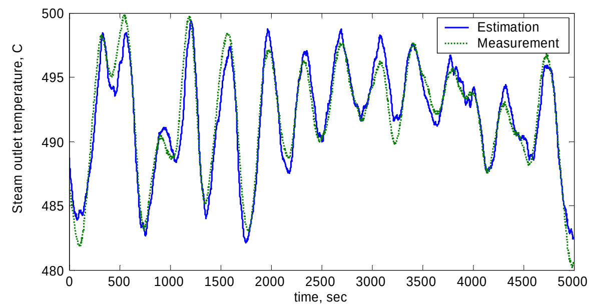

Figure 6: The measured and estimated outlet steam temperature in the validation

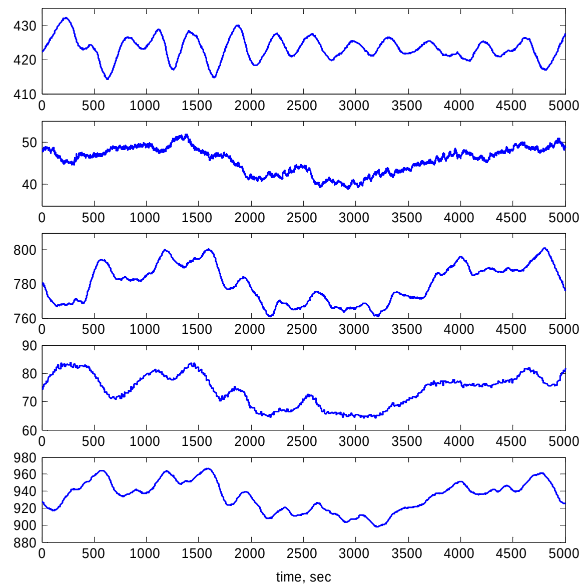

Figure 7: The model input variables in the validation (the axis are the same as in Figure 5)

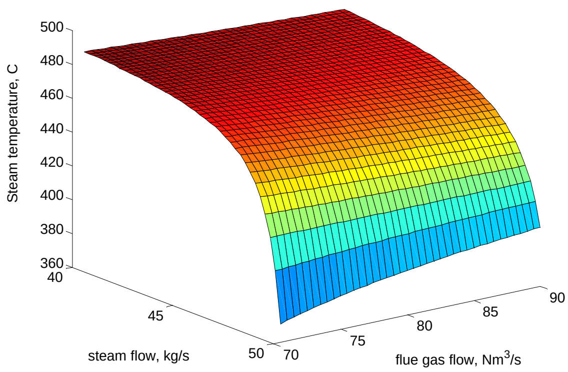

Figure 8: The steady state characteristic: the superheated steam temperature as a function of the steam and fuel flow.

The identified model works well also on the validation data series. The resulted dynamical behaviour were checked separately as well, and showed reasonable behaviour, no serious oscillation or non-minimum phase behaviour occurred. The steady state characteristic is also according to the expectations. The Figure 8 shows the steam outlet temperature as a function of the steam and fuel flow with constant other variables. The figure shows the non-linearity of the steam temperature.

CONCLUSIONS

This paper described a Wiener–Hammerstein cascade non-linear model for superheater steam temperature. The steady state characteristic of the model is based on the phenomenological equations; meanwhile the dynamic behaviour is merely identified.

The validation data shows good results. The applied structure seems to be satisfactory for this problem and undemanding from the computational burden point of view. The model is suitable to test the superheater control structures.

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BIOGRAPHY

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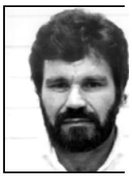

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