MODELLING OF STEAM TEMPERATURE DYNAMICS OF A SUPERHEATER

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Keywords

steam superheater, non-linear models, Wiener system, Hammerstein system

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 medias 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 applying the Levenberg-Marquadt method for identification. The identification and the validation of the model is 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 demanding. According to the validation result, the model is suitable to test superheater control structures on it.

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,
m	
fg_rad	representative temperature of the combustion chamber,
m	metal of the pipe,
in	inlet,
out	outlet,
conv	convective,
rad	radiative.

Introduction

During modelling the steam superheating process can be understood as a combination of two subprocesses: the hydrodynamic and the thermal. Dynamic time constants of these two processes are significantly different, the hydrodynamic changes happen in tenth of seconds meanwhile the magnitude of the time constants of the thermal process are the tens of second. Therefore these processes are usually modelled separately. The model presented in this paper concerns only the thermal process.

Different approaches for modelling the superheater are already available in the literature. The aim of these models is to describe the dynamic behaviour of the temperature of the steam leaving the superheater. The models could 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, that solution may be complex.

Zima (2001) presented a model applying the 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 known and constant.

The distributed parameter problem was also addressed by the Profos model (Profos 1962). The model based on the one-pipe approximation of the process. This linearized model is derived by performing Laplace transformation once by the time and again 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.

Proceedings 16th European Simulation Symposium
György Lipovszki, István Molnár © SCS Press, 2004
ISBN 1-56555-286-5(book) / ISBN 1-84233-106-x(CD)

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 was 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 the heat flow assumed to be known.

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 feature to be identified easily. The heat transfer coefficients are not known, thus the model identification must include the approximation of this parameter. For the identification the gradient based Levenberg-Marquadt algorithm was applied.

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 non-linearity. Wiener and Hammerstein structures are typical examples of such structures.

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

- the function can be derivated 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 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 1.

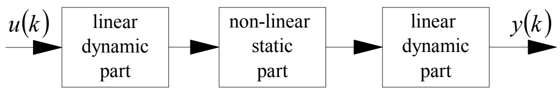

Figure 1. The Wiener-Hammerstein cascade model

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 1 contains several linear dynamics. The more detailed model for the superheater is given in Figure 2

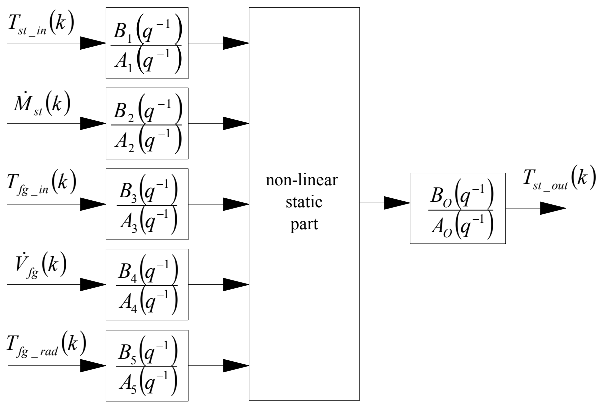

Figure 2. The Wiener-Hammerstein cascade model for the superheater

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 output temperature is expressed from the energy balance equations of the steam (3), flue gas (4) and wall (1), and from the convective (5,6), and radiative heat transfer (7) 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

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

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

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

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

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

The average steam and flue gas temperature.

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

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

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

- the radiative heat transfer is approximated to be linear to the temperature difference (7);
- the representative temperatures for the convective heat transfer calculations are the linear average of the inlet and outlet steam and flue gas temperatures (8,9), and not the logarithmic means, as it is suggested in the literature.

In this function 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 in 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 (7-9) approximations were needed.)

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

The estimated and the measured steam outlet temperature on the identification data range are shown in Figure 3. The inputs (steam inlet temperature, mass flow, etc) are illustrated in Figure 4.

The validation of the identified model was performed on another measurement series from the same boiler. The model performance is presented in Figure 5; the inputs of the model are given in Figure 6.

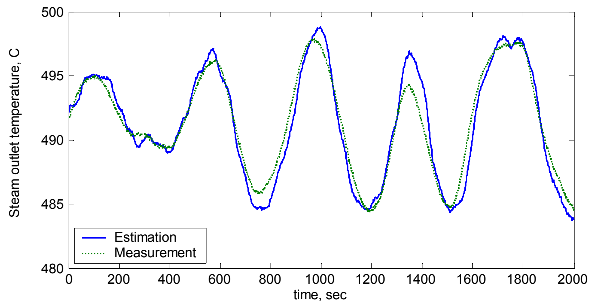

Figure 3. The measured and estimated outlet steam temperature in the identification

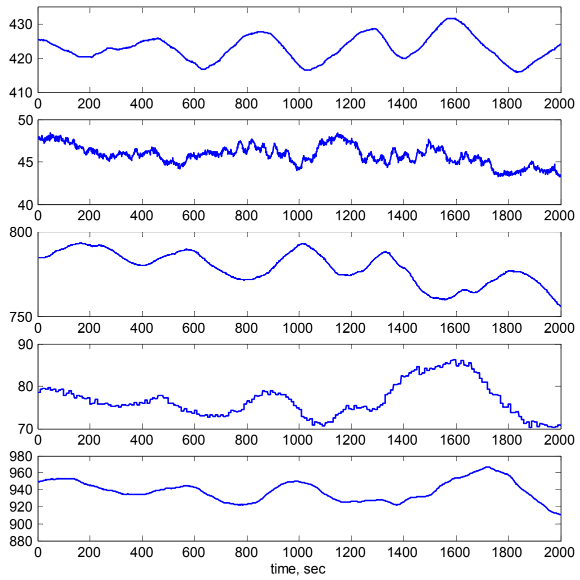

Figure 4. The model input variables (steam inlet temperature, steam mass flow, flue gas inlet temperature, flue gas volume flow, flue-gas representative temperature in the combustion chamber respectively) on the time range applied in the identification

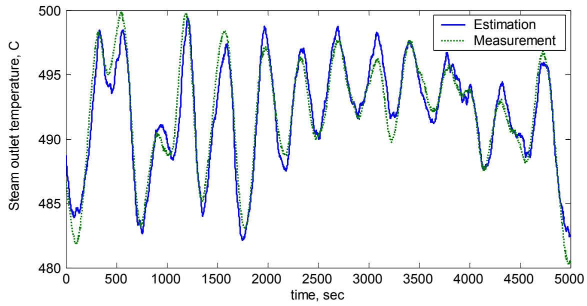

Figure 5. The measured and estimated outlet steam temperature in the validation

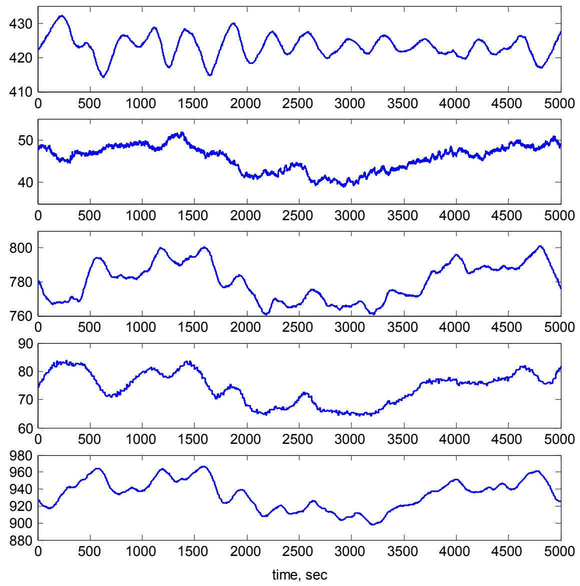

Figure 6. The model input variables in the validation (same as in Figure 4)

Conclusions

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

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

Acknowledgement

This research was supported by the Academy of Finland, project no. 73281 and 48545. The research work was also supported by the Graduate School of Electronics, Telecommunication and Automation.

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