MODELLING OF AN INTEGRATED SUPERHEATER BASED ON A WIENER APPROACH

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Abstract: This paper considers identification of a multiple-input single-output Wiener model of a new type of superheater integrated to a CFB boiler. The static part is based on energy- and mass balances. Simultaneous estimation of model parameters in both static and dynamic parts was based on the industrial data from an 80 MW CFB boiler. The results indicate that the approach can be satisfactorily used to capture and describe the steam temperature in a wide range of variation in the input variables.

Keywords**:** Identification, nonlinear gain, linear dynamics, heat flows, heat exchangers

1 INTRODUCTION

Combustion technology has undergone a number of different stages of development in terms of process and its configuration in order to fulfil environmental regulations and economical requirements. Especially the development of fluidisation technology in power plants (CFB and BFB boilers) has made it possible to burn – with good efficiency – a wide range of different fuels such as coal, peat, woodchips and recycled fuels. However, the potential benefit that could be achieved with new technologies and fuels can't be fully utilised unless the importance of the development of proper control structures is taken account. Many of the modern control design methods rely on the availability of a suitable model of the plant.

Linear time-invariant models are often used successfully in applications, although real plants are typically, at least mildly, nonlinear. Simple linear dynamic models can typically approximate the behaviour of nonlinear processes well only in a narrow operating area. Model based control schemes for nonlinear systems are becoming increasingly available and simple nonlinear models can provide much better approximations to the process dynamics than linear models (Pearson and Pottman, 2000). In practise, simple methods are needed to fit these nonlinear models to measured process data.

The process under investigation is a new type of integrated heat exchanger (INTREX^{TM}), which utilises the heat capacity of hot solids returned from the separator in a CFB boiler, thus the heat surfaces are actually located inside of a bubbling bed. The design of the integrated heat exchanger provides means for heat transfer control, which allows controlling of furnace temperatures to optimise emissions and combustion over a wide load range. This paper considers modelling and identification of an INTREX^{TM} superheater using Wiener-type of model structures.

2 NONLINEAR MODELLING

There are two main approaches to modelling:

1. In the first-principle approach the whole model, *i.e.*, the structure and parameters, is based on laws about the physical, chemical, mechanical, *etc.*, phenomena.
2. 'Black-box' identification is based on experimental data. The model structure is *a priori* selected and the involved parameters are estimated using techniques based on input/output data. (Ikonen and Najim, 2002; Visala,1997)

If sufficient theoretical knowledge is available, it seems obvious that 'white-box' models should be used. However, the development of 'white-box' models can be challenging and time consuming, and often the resulting models are unnecessarily detailed for control purposes (Visala, 1997; Ikonen *et al.*, 2000). In semi-physical 'grey-box' models, *a priori* knowledge is embedded in the model structure and certain parameters are estimated from the process data. If the model structure is correct and there is enough data for identification, a 'grey-box' model can be valid even outside of the operation area determined by the data used in identification.

2.1 Wiener systems

The dynamic behaviour of a nonlinear process can be – in many cases – approximated with a linear transfer function, using, *e.g.*, Wiener or Hammerstein structures. Both model-structures consist of a nonlinear static part and a linear dynamic part. In a Wiener structure the linear part precedes the non-linear static part (see Fig. 1).

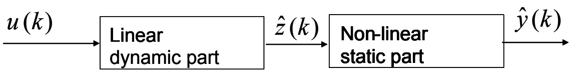

Fig. 1. Wiener structure.

The Wiener/Hammerstein approach has several advantages (Ikonen and Najim, 2001; 2002):

- The model structure reduces the degrees of freedom in the parameter estimation. Thus, the parameter estimation becomes feasible also in a non-linear and stochastic industrial environment.
- In a grey-box model, physical and experimental (input-output) information can be fused together. Note that *a priori* knowledge in industrial plants is typically expressed as steady-state relations.
- Linearity in the dynamic part simplifies not only the parameter estimation, but also the (closed loop) system analysis, modelling of disturbances, and controller design.

The static part, producing the output $\hat{y}(k)$ of the MISO Wiener model is given by a nonlinear function with parameters $\mathbf{w}$

$$\hat{y}(k) = f(\hat{\mathbf{z}}(k), \mathbf{w}) \ , \qquad (1)$$

where

$$\hat{\mathbf{z}}(k) = \left[\hat{z}_1(k), \hat{z}_2(k), ..., \hat{z}_i(k), ..., \hat{z}_I(k)\right]^{\mathrm{T}} . \qquad (2)$$

The dynamics can be described separately for each input u_i, $i = 1,2,\ldots,I$ using a linear transfer polynomial:

$$\hat{z}_i(k) = \frac{B_i(q^{-1})}{A_i(q^{-1})} u_i(k - d_i) \ , \qquad (3)$$

where

$$A_i(q^{-1}) = 1 + a_{i,1} q^{-1} + ... + a_{i,M_i} q^{-M_i} \ , \qquad (4)$$

$$B_i(q^{-1}) = b_{i,0} + b_{i,1} q^{-1} + ... + b_{i,N_i} q^{-N_i} \ . \qquad (5)$$

To ensure that the steady state gain is equal to one, (3) has to be modified. Let us modify the polynomials B_i as:

$$B_i^*(q^{-1}) = b_{i,0} + ... + b_{i,N_i-1} q^{-N_i-1} + b_{i,N_i}^* q^{-N_i} \ , \qquad (6)$$

$$b_{i,N_i}^* = 1 + \sum_{m=1}^{M_i} a_{i,m} - \sum_{n=0}^{N_i-1} b_{i,n} \ . \qquad (7)$$

N_i and M_i are the orders of the polynomials for the ith input, d_i is the delay of the ith input and q^{-1} is the backward shift operator.

The unknown parameters of the Wiener model need to be determined, *e.g.*, using input-output data observed from the process. If gradient-based techniques are used, the gradients with respect to the following parameters need to be computed (Ikonen and Najim, 2002):

- Parameters of the static part, $\mathbf{w}$.
- Parameters of the linear transfer function(s), *i.e.*, coefficients of the polynomials A_i and B_i as well as delays d_i.

Let us denote the derivatives of static part with respect to parameters $\partial\hat{y}(k)/\partial w_j(k)$ by $\psi_j(k)$, where $\mathbf{w} = [w_1, \ldots, w_j, \ldots, w_J]^{\mathrm{T}}$ and J is the number of parameters in the nonlinear static part, and the derivatives with respect to the inputs $\partial\hat{y}(k)/\partial\hat{z}_i(k)$ by $\phi_i(k)$.

The derivatives with the respect to the parameters of the linear dynamic part can be calculated using the chain rule:

$$\frac{\partial \hat{y}}{\partial a_{i,m}}(k) = \phi_i(k) \frac{\partial \hat{z}_i}{\partial a_{i,m}}(k) \ , \qquad (8)$$

$$\frac{\partial \hat{y}}{\partial b_{i,n}}(k) = \phi_i(k) \frac{\partial \hat{z}_i}{\partial b_{i,n}}(k) , \qquad (9)$$

where

$$\frac{\partial \hat{z}_i}{\partial b_{i,n}}(k) = u_i(k-n-d_i) - u_i(k-N_i-d_i) - \sum_{m=1}^{M_i} a_{i,m} \frac{\partial \hat{z}_i}{\partial b_{i,n}}(k-m) \tag{10}$$

$$\frac{\partial \hat{z}_i}{\partial a_{i,m}}(k) = u_i(k-N_i-d_i) - \sum_{j=1}^{M_i} a_{i,j} \frac{\partial \hat{z}_i}{\partial a_{i,m}}(k-j) - u_i(k-m) \tag{11}$$

Assuming that the parameters change slowly, the past derivatives can be stored, and (10) - (11) computed recursively to avoid excessive computations.

When instability is encountered, the parameters can be projected towards a stable region by multiplying polynomial A_i by a constant γ, $0 << \gamma < 1$, until all roots of the polynomial are inside of the unit circle:

$$A_i = 1 + \gamma a_{i,1} q^{-1} + \ldots + \gamma^{M_i} a_{i,M_i} q^{-M_i} . \tag{12}$$

3 MODEL DEVELOPMENT

The process under investigation is a new type of heat exchanger (INTREX™) integrated into the CFB boiler. The integrated heat exchanger is typically located in the lower part of furnace, being an integrated but separately fluidized chamber. Thus, the heat exchange-surface is actually located inside of a bubbling bed (see lower part of Fig. **2**).

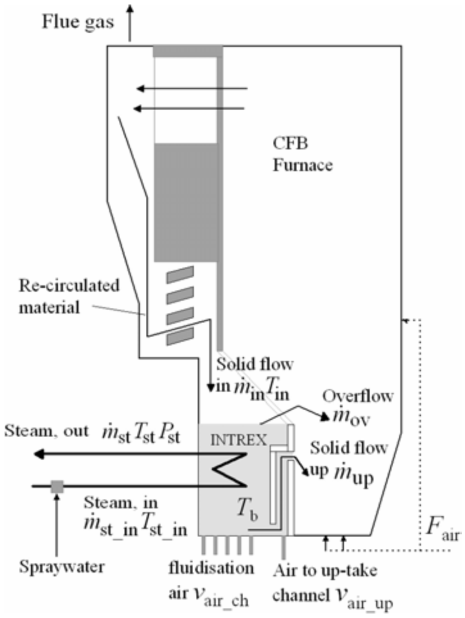

Fig. 2. Simplified structure of an integrated super-heater in a CFB boiler with external circulation. Modified from Lehtonen (1998).

The heat exchanger utilises the heat capacity of hot solids returned from the cyclones or solids taken straight from the furnace. Solid mass flow entering the heat exchanger chamber depends mainly on boiler load. The rate of heat transfer can be controlled by the fluidization velocity in the INTREX™ chamber and by controlling the mass flow of solids through the system. (Makkonen, 2000)

This paper presents a non-linear Wiener-type of model of the INTREX™, which is used as a final super-heater in an 80 MW CFB. The model structure is of a grey-box type, justified by knowledge on the physical and chemical phenomena, with components selected based on considerations from process control design requirements. Similar type of model structure for a conventional superheater is presented by Benyö, *et al.* (2005).

This highly non-linear process can be divided into several sub-systems. The main inputs and outputs between the sub-systems are presented in Fig.3. Also the dynamical parts of the Wiener-model are shown in Fig. 3.

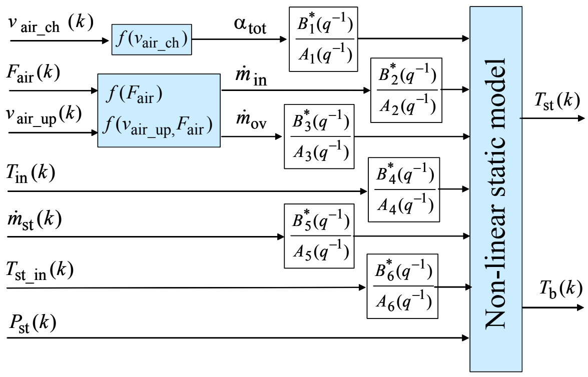

Fig. 3. Simplified structure of the INTREX™ super-heater model. See text for the notations.

Model inputs consist of the following:

- v_{air_ch} velocity of the air in chamber,
- v_{air_up} velocity of the air in up-take channel,
- F_{air} air flow to the CFB furnace,
- T_{in} temperature of the incoming solids,
- $\dot{m}_{st}$ steam mass flow,
- T_{st_in} temperature of incoming steam and
- P_{st} pressure of the steam.

Based on the input information the following variables can be calculated:

- $\dot{m}_{in}$ incoming solid flow,
- $\dot{m}_{ov}$ solid overflow and
- α_{tot} overall heat transfer coefficient.

System outputs are given by:

- T_{st} steam temperature and
- T_b bed temperature.

The main problem in modelling is due to the fact that the solid mass flows (inflows from separator and from furnace, outflow via up-take channel, and overflow) are unknown and not measurable. Thus they have to be estimated using some measurable values (air flows, load level, bed properties, *etc.*).

Furthermore, the disturbances at the combustion part have a dominant effect on the steam generation and on bed temperatures in the CFB furnace. Thus they affect the fresh steam properties and the incoming solid properties (temperatures, enthalpies), which can be considered as stochastic inputs to the INTREX™ model. The calculations of the heat transfer coefficient, the solid mass flows and the estimation of steam temperature are discussed next (see also Mononen, *et al.,* 2004)

3.1 Heat transfer coefficient

The heat transfer between horizontal tube bundles and fine sand fluidised with air has been studied theoretically as well as experimentally (see Beeby and Potter, 1984). According to Xavier, *et al.* (1980) the bed-tube heat transfer coefficient (α_{bt}) is a function of the fluidisation air velocity (v_{air_ch}). Also the density of the bed δ_b and average particle size (d_p) affect the shape of the bed - tube heat transfer coefficient:

$$\alpha_{bt} = f(v_{air\_ch}, \delta_b, d_p)\,. \tag{13}$$

The transferred amount of heat $\dot{Q}_{bs}$ between bed and steam can be presented as (Kunii and Levenspiel, 1991)

$$\dot{Q}_{bs} = A_w\, \alpha_{tot}\, \Delta T\,, \tag{14}$$

where A_w is the size of heat surface, α_{tot} is the overall heat transfer coefficient and ΔT is the average temperature difference between bed and steam. The overall heat transfer coefficient between bed and steam is calculated from

$$\frac{1}{\alpha_{tot}} = \frac{1}{\alpha_{bt}} + \frac{\Delta x}{\lambda} + \frac{1}{\alpha_{ts}}\,, \tag{15}$$

where α_{ts} is the tube-steam heat transfer coefficient, Δx is the wall thickness and λ is the thermal conductivity of material.

3.2 Solid flows

There are several solid mass flows affecting the behaviour of the system. However, these flows can not be measured, thus they have to be estimated using measurable values, *e.g.,* the airflows to the INTREX™, the airflows to CFB furnace, the boiler load, and the height (pressure difference) of the bed in the INTREX™ chamber.

Solid flow from cyclone to the INTREX™, $\dot{m}_{in}$, is assumed to depend linearly on the air flows to the CFB furnace:

$$\dot{m}_{in} = a_1 \cdot F_{air} - b_1\,, \tag{16}$$

where F_{air} is the sum of the air flows to the CFB, a_1 and b_1 are coefficients.

Solid flow through the up-take channel, $\dot{m}_{up}$ depends on the height of the bed and on the air velocity through the up-take channel:

$$\dot{m}_{up} = f(v_{air\_up}, h_b)\,, \tag{17}$$

where h_b is estimated or measured height of the bed (INTREX™ chamber), and v_{air_up} is the velocity of the air through the up-take channel.

Solids from cyclone returned directly to the CFB furnace (overflow) is assumed to be a function of the bed height:

$$\dot{m}_{ov} = f(h_b)\,. \tag{18}$$

The height of the bed (h_b) in steady state can be solved from (16) – (18) by taking into account that the mass-balance on the steady state is

$$\dot{m}_{in} = \dot{m}_{up} + \dot{m}_{ov}\,. \tag{19}$$

3.3 Steam temperature

The energy balance on the bed side is given as:

$$\frac{d(c_p m_b T_b)}{dt} = \dot{m}_{in} c_p T_{in} - \dot{m}_{up} c_p T_b - \dot{m}_{ov} c_p T_{ov} - \dot{Q}_{bs}\,, \tag{20}$$

where T_{in} is the temperature of incoming solids, T_{ov} is temperature of solids in overflow (function of T_{in}), c_p is the specific heat of solids and m_b is the mass of the bed. The heat flow from bed to steam can be expressed as (14) where $\Delta T = T_b - T_{st\_av}$ and T_{st_av} is the average steam temperature.

The energy balance on the steam side is given as

$$\dot{Q}_{st} = \dot{Q}_{st\_in} + \dot{Q}_{bs}\,, \tag{21}$$

where $\dot{Q}_{st\_in}$ is the heat flow of incoming steam.

The specific enthalpy of the steam after superheater is solved by

$$h_{st} = \dot{Q}_{st} / \dot{m}_{st} \tag{22}$$

and the final steam temperature is solved using a linear function based on the tables of water and steam properties (Schmidt, 1979):

$$T_{st} = f(h_{st}, P_{st})\,. \tag{23}$$

After a series of substitutions and arrangements the output steam temperature and bed temperature (in steady state) can be expressed as

$$\left[T_{\mathrm{st}}, T_{\mathrm{b}}\right] = f(\alpha_{\mathrm{tot}}, \dot{m}_{\mathrm{in}}, \dot{m}_{\mathrm{ov}}, T_{\mathrm{in}}, \dot{m}_{\mathrm{st}}, T_{\mathrm{st\_in}}, P_{\mathrm{st}}) \,. \quad (24)$$

4 IDENTIFICATION

Identification of the plant was based on measurement data from an 80 MW CFB with INTREX™ heat exchanger used as a final super-heater. The aim of parameter estimation was to determine parameters of the static part, **w,** and the parameters of the linear transfer functions. The Levenberg-Marquadt algorithm was applied to minimise the cost function

$$J(\boldsymbol{\theta}) = \frac{1}{2}\mathbf{R}(\boldsymbol{\theta})^T \mathbf{R}(\boldsymbol{\theta}) \,, \quad (25)$$

where $\boldsymbol{\theta}$ is the parameter vector consists of the parameters **w** and the coefficients $a_{i,m}$ and $b_{i,n}$. The components of vector **R** vector were given by the deviation in steam temperature

$$r_k = T_{\mathrm{st}}(k) - T_{\mathrm{st\_meas}}(k) \,, \quad k = 1,2,..,K, \quad (26)$$

where K is the length of the data.

The solid mass flows (solid in and solid overflow) and overall heat transfer coefficients can not be directly measured, thus they have to be calculated using measurable variables. For this reason, the following parameters (w_i) of the static part were chosen to be identified:

$$\alpha_{\mathrm{tot}} \leftarrow w_1 \alpha_{\mathrm{tot}} ; \; \dot{m}_{\mathrm{in}} \leftarrow w_2 \dot{m}_{\mathrm{in}} ; \; \dot{m}_{\mathrm{ov}} \leftarrow w_3 \dot{m}_{\mathrm{ov}} \,.$$

Since a gradient based method is to be used for the parameter estimation, the gradients of static part with respect to parameters $\psi_j(k) = \partial \hat{T}_{\mathrm{st}}(k) / \partial w_j(k)$ and $\phi_i(k) = \partial \hat{T}_{\mathrm{st}}(k) / \partial \hat{z}_i(k)$ need to be calculated. For this reason, the T_{st} (23) was approximated with linear function of h_{st} and P_{st}. The approximation is valid in the used temperature and pressure ranges.

The dynamics for each input i were chosen to be second order transfer polynomials with a unit gain:

$$\hat{z}_i(k) = \frac{B_i^*(q^{-1})}{A_i(q^{-1})} u_i(k-1) \,, \quad (27)$$

where

$$A_i(q^{-1}) = 1 + a_{i,1} q^{-1} + a_{i,2} q^{-2} \,, \quad (28)$$

$$B_i^*(q^{-1}) = b_{i,0} + b_{i,1}^* q^{-1} \quad (29)$$

and

$$b_{i,1}^* = 1 + (a_{i,1} + a_{i,2}) - b_{i,0} \,. \quad (30)$$

Notice that the steady state gains of the dynamic parts are always one, so that there is no redundancy in the parameters and no need for optimisation under constraints. The parameters of both static and dynamic parts can be estimated simultaneously.

Parameter estimation was based on real industrial data. The quality of data was not optimal for identification: The sample time and the data length were limited; also the changes on the input variables were limited. Several of the input variables were changed on the same time, thus the effect of one variable on the final output (steam temperature) was not always clear. Also, the control of steam temperature was on (spray water control). Fig. 4 shows the input data and the estimated and measured steam temperatures are presented in Fig. 5.

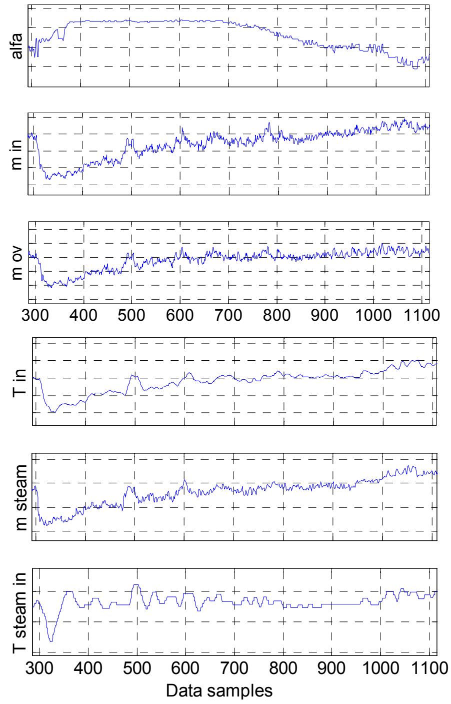

Fig. 4. The inputs to the model.

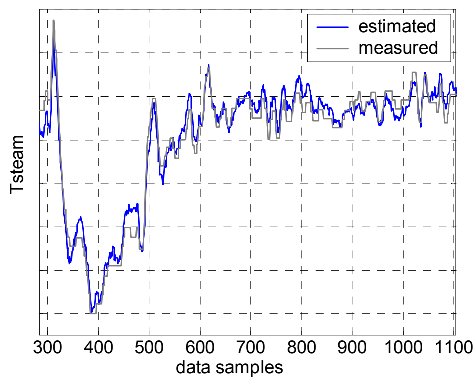

Fig. 5. The estimated and measured steam temperature.

The identified parameters of the static part are presented in Table 1. The calculation of heat transfer coefficient α_{tot} and solid mass flows (m_{in} and m_{ov}) gave slightly too small values, which had to be corrected by multiplying with parameters w_i when the model was fitted to the data.

Table 1. Identified parameters of static part

w_1	w_2	w_3
1.2666	1.399	1.1443

The results show that the model can satisfactorily describe the process during changes in the input variables (see Fig. 4) in a large range. There was not enough industrial data for a statistically proper validation of the model. However, the validation with changes of some input variables (fluidisation air velocity and velocity of the air to up-take channel) gave reasonable results.

A major advantage of the Wiener approach is the possibility to validate the model by examining the linear transfer polynomials. The time constants of the identified dynamics appear realistic (see Table 2). The dynamics B_2^* / A_2 - B_4^* / A_4 describing the solid properties (mass flow, solid temperature and solid overflow) show non-minimum phase behaviour. For continuous time system this kind of behaviour could be interpreted as a first order Padé approximation of the dead time. However, the behaviour of the zeros of a sampled continuous time system may be more complex; a stable second order (or higher) continuous time system can give a sampled system with unstable zeros (Åström *et al.*, 1984), which leads to non-minimum phase behaviour.

Table2. Transfer functions (see Fig. 3) Describing the dynamics after identification.

$$\frac{A_1}{B_1^*}(q^{-1}) = \frac{0.2693 + 0.2861q^{-1}}{1 - 0.1616q^{-1} - 0.283q^{-2}} \qquad \frac{A_2}{B_2^*}(q^{-1}) = \frac{-0.1181 + 0.1321q^{-1}}{1 - 1.703q^{-1} + 0.717q^{-2}}$$

$$\frac{A_3}{B_3^*}(q^{-1}) = \frac{-0.0404 + 0.1207q^{-1}}{1 - 0.5286q^{-1} - 0.3911q^{-2}} \qquad \frac{A_4}{B_4^*}(q^{-1}) = \frac{-0.0947 + 0.10296q^{-1}}{1 - 1.749q^{-1} + 0.7573q^{-2}}$$

$$\frac{A_5}{B_5^*}(q^{-1}) = \frac{0.385 + 0.044q^{-1}}{1 - 0.0904q^{-1} - 0.4806q^{-2}} \qquad \frac{A_6}{B_6^*}(q^{-1}) = \frac{0.3373 + 0.0784q^{-1}}{1 - 0.1171q^{-1} - 0.4672q^{-2}}$$

5 CONCLUSIONS

The process under investigation is a new type of integrated heat exchanger (INTREX^{TM}), which utilises the heat capacity of hot solids returned from the separator in a CFB boiler. In this paper a short description of the modelling and identification of INTREX^{TM} superheater using Wiener-type model structure was given. The proposed model is simple and transparent. The results show that the model can describe the steam temperature satisfactorily in a wide range of changes on the input variables. However, unknown and unmeasurable solid mass flows have an important role in the model. Thus, the estimation of mass flows still needs to be studied. Furthermore, the inputs of the model are overly sensitive for the disturbances in the combustion part.

Integrated heat exchanger extends the possibilities for the control design over conventional super-heaters. The design of advanced control strategies necessities a plant model, and thus final aim of the developed model is to use it in the design of control strategies for the integrated heat exchanger.

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REFERENCES

Beeby, C and O. Potter (1984). Heat transfer between a horizontal tube bundle and fine particles with air or steam, *AIChE Journal*, **30**, 6, 977-980

Benyó, I., J. Kovács. J. Mononen and U. Kortela (2005). Modelling of steam temperature dynamics of a superheater, *International Journal of Simulation*, accepted as invited paper.

Ikonen, E., K. Najim and U. Kortela (2000). Neuro-fuzzy modelling of power plant flue-gas emissions. *Engineering applications of artificial intelligence,* **13**, 705-717.

Ikonen, E., K. Najim (2001). Non-linear process modelling based on a Wiener approach. (*Proc Instn Mech Engrs,* **215**, 15 – 27.

Ikonen, E. and K. Najim (2002). *Advanced process identification and control.* Marcel Dekker Inc., New York, 310 p.

Kunii, D. and O. Levenspiel (1991). *Fluidization engineering.* Butterworth-Heinemann, 491 p.

Lehtonen, P. (1998): Memo 4.12.1998, Foster Wheeler Energia Oy, Finland.

Makkonen, P. (2000). Foster Wheeler CFB with the new INTREX^{TM} superheater, *VGB Power Tec,* **2**, 30-34.

Mononen, J., E. Ikonen and M. Paloranta (2004). Identification of an integrated superheater using Wiener models. *Proceedings of IASTED International Conference Power and Energy Systems*, 28. Clearwater Beach, Fl, U.S.A, Nov 28 -1. Dec 2004, 430-435.

Pearson, R.K. and M. Pottman (2000). Gray-box identification of block oriented nonlinear models, *Journal of Process Control,* **10**, 301-315.

Schmidt E. (1979). *Properties of water and steam in SI-units*, Springer-Verlag Berlin, Heidelberg New York, R. Oldenbourg Munchen, 1979, 190 p.

Visala, A. (1997). *Modeling of nonlinear processes using Wiener-NN representation and multiple models*, Helsinki University of Technology, Doctoral thesis.

Xavier A.M., D.F. King, J.F. Davidson and D. Harrison (1980). Surface-bed heat transfer in a fluidised bed at high pressure, *Proceedings of the International Fluidization Conference*, Henniker, New Hampshire, August 3-8, 1980, 209-216.

Åström, K.J., P. Hagander and S. Sternby (1984). Zeros of Sampled Systems, *Automatica*, **20**, 31-38.