Modelling and simulating fire tube boiler performance

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Abstract

A model for a flue gas boiler covering the flue gas and the water-/steam side has been formulated. The model has been formulated as a number of sub models that are merged into an overall model for the complete boiler. Sub models have been defined for the furnace, the convection zone (split in 2: a zone submerged in water and a zone covered by steam), a model for the material in the boiler (the steel) and 2 models for resp. the water/steam zone (the boiling) and the steam. The dynamic model has been developed as a number of Differential-Algebraic-Equation system (DAE). Subsequently MatLab/Simulink has been applied for carrying out the simulations. To be able to verify the simulated results an experiments has been carried out on a full scale boiler plant.

Keywords: Control of boilers. Dynamic boiler modelling and simulation, internal circulation, experimental verification, DAE, MATLAB and SimuLink.

1 INTRODUCTION

The projects overall goal is to be able to control boilers more efficiently and hereby to be able to optimize the boiler design and operation.

Boilers are normally controlled by means of 2 control loops:

- a control loop for controlling the pressure on the boiler, i.e. *pressure controller* (i.e. controlling the heat input to the boiler - e.g. firing)
- a control loop for controlling the water level in the boiler, i.e. *feed water controller*

These controllers are independent i.e. input/output or internal variables are not exchanged between the control loops. Detailed description of *Control of Boilers* can be found in [6].

Several projects having the goal to model and simulate boilers' dynamically performance have been carried out over the years. Among several the following [2], [4] and [7] can be mentioned. So, with this background: Why is it still interesting to analyze boilers? First of all boilers are still being applied for new purposes, related to change of fuels, increased requirements with respect to emissions, new inventions within areas like water-chemistry, materials, etc. Secondly as the market competition increases, boilers are being designed closer and closer to the limit, i.e. better knowledge about dynamical behavior is required. As a result of the liberalization of the energy markets, where new opportunities for selling or buying energy arise, more focus is put on the dynamic performance of the boilers. Increased requirements, with respect to dynamic performance, have a built-in contradiction: Both natural circulating and once-through boilers need a reservoir for absorbing shrinking and swelling during the dynamic operation of the boiler (e.g. start-up), on the one hand, to be able to absorb the fluctuations within the boiler a large reservoir is required/desirable. On the other hand, the material thickness in a pressurized vessel (the reservoir) is approximately proportional to the diameter, i.e. the higher pressure, the larger material thickness. However the allowable temperature gradients for the pressurized vessel decrease as the wall-thickness increases (the stresses in the boiler material related to the temperature gradients are approximately proportional to the square of the material thickness).

In the actual project a dynamic model for the boiler performance has been developed. The model consist of sub models for:

- the furnace (combustion chamber) - see section 2.1
- the water/steam submerged part of the convection zone - see section 2.2
- the steam covered part of the convection zone - see section 2.3
- the boiler material (the steel) - see section 2.5
- the water/steam submerged part of the convection zone - see section 2.5
- the steam covered part of the convection zone - see section 2.5

These models have been merged into an overall model having the following controllable input parameters:

- the fuel flow $\dot{m}_{fuel}$
- the air flow $\dot{m}_{air}$
- the feed water flow $\dot{m}_{fw}$

the following non-controllable input parameters:

- the fuel temperature T_{fuel}
- the air temperature T_{air}
- the feed water temperature T_{fw}
- the steam flow $\dot{m}_s$

and the following output parameters:

- the boiler pressure p_s
- the water level in the boiler L_w

This approach has also been applied for water tube boilers - see e.g. [7].

To verify the developed model tests and measurements have been carried out on a full scale boiler plant.

A sketch of the boiler and the models can be seen in Figure 1.

Modelling and simulation are the main topics of the Ph.D. project being written by the author.

2 MODELLING

As mentioned the model consist of a number of sub models that are exchanging data according to Figure 1.

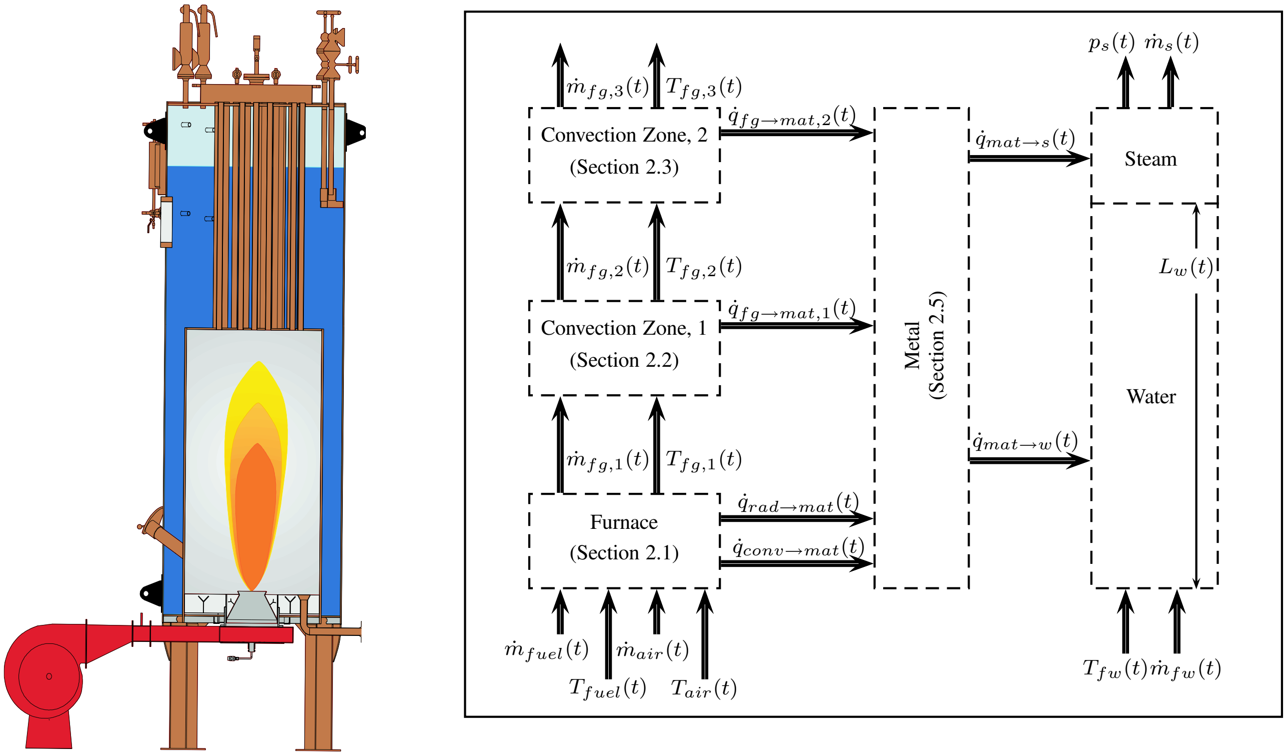

Figure 1: Sketch and model of MISSION$^{\text{TM}}$ OB.

2.1 FURNACE

The furnace is modelled by means of the following equations:

$$\dot{q}_{fuel} + \dot{q}_{air} - \dot{q}_{fg,1} - \dot{q}_{rad\rightarrow mat} - \dot{q}_{conv\rightarrow mat} - \frac{dU_{fur}}{dt} = 0 \tag{1}$$

where each component can be written as:

$$U_{fur} = M_{fur} \cdot h_{fur} = V_{fur} \cdot \rho_{fur} \cdot c_{p,fur} \cdot (\overline{T}_{fur} - T_{ref}) \tag{2}$$

$$\dot{q}_{fuel} = \dot{m}_{fuel} \cdot (H_{fuel} + h_{fuel}) = \dot{m}_{fuel} \cdot (H_{fuel} + c_{p,fuel} \cdot T_{fuel}) \tag{3}$$

$$\dot{q}_{air} = \dot{m}_{air} \cdot h_{air} = \dot{m}_{air} \cdot c_{p,air} \cdot (T_{air} - T_{ref}) \tag{4}$$

$$\dot{q}_{fg,1} = \dot{m}_{fg,1} \cdot h_{fg,1} = \dot{m}_{fg,1} \cdot c_{p,fg,1} \cdot (T_{fg,1} - T_{ref}) \tag{5}$$

$$\dot{q}_{rad\rightarrow mat} = \alpha_{rad} \cdot (T_{fur}^4 - T_{mat}^4) \tag{6}$$

$$\dot{m}_{fg,1} = \dot{m}_{fuel} + m_{air} \tag{7}$$

$$\dot{q}_{conv\rightarrow mat} = \alpha_{conv} \cdot (T_{fur} - T_{mat}) \tag{8}$$

$$\overline{T}_{fur} = \frac{T_{fg,1} + T_{ad}}{2} \tag{9}$$

$$T_{ad} = \frac{\dot{q}_{fuel} + \dot{q}_{air}}{\dot{m}_{fg,1} \cdot c_{p,fg,ad}} \tag{10}$$

2.2 CONVECTION ZONE 1

$$\dot{q}_{fg,1} - \dot{q}_{fg,2} - \dot{q}_{fg\rightarrow mat,1} - \frac{dU_{fg,1}}{dt} = 0 \tag{11}$$

where each component can be written as:

$$U_{fg,1} = M_{fg,1} \cdot h_{fg,1} = M_{fg,1} \cdot c_{p,fg,1} \cdot (\overline{T}_{fg,1} - T_{ref}) \tag{12}$$

$$\overline{T}_{fg,1} = \frac{T_{fg,1} + T_{fg,2}}{2} \tag{13}$$

$$\dot{q}_{fg,2} = \dot{m}_{fg,2} \cdot h_{fg,2} = \dot{m}_{fg,2} \cdot c_{p,fg,2} \cdot (T_{fg,2} - T_{ref}) \tag{14}$$

$$\dot{m}_{fg,1} = \dot{m}_{fg,2} = \dot{m}_{fg,3} \tag{15}$$

$$\dot{q}_{fg\rightarrow mat,1} = A(L_w)_{fg,1} \cdot \alpha_{fg,1} \cdot (\overline{T}_{fg,1} - T_{mat}) \tag{16}$$

$$M_{fg,1} = V_{fg,1}(L_w) \cdot \rho_{fg,1} \tag{17}$$

2.3 CONVECTION ZONE 2

$$\dot{q}_{fg,2} - \dot{q}_{fg,3} - \dot{q}_{fg\rightarrow mat,2} - \frac{dU_{fg,2}}{dt} = 0 \tag{18}$$

where each component can be written as:

$$U_{fg,2} = M_{fg,2} \cdot h_{fg,2} = M_{fg,2} \cdot c_{p,fg,2} \cdot (\overline{T}_{fg,2} - T_{ref}) \tag{19}$$

$$\overline{T}_{fg,2} = \frac{T_{fg,2} + T_{fg,3}}{2} \tag{20}$$

$$\dot{q}_{fg,3} = \dot{m}_{fg,3} \cdot h_{fg,3} = \dot{m}_{fg,3} \cdot c_{p,fg,3} \cdot (T_{fg,3} - T_{ref}) \tag{21}$$

$$\dot{q}_{fg\rightarrow mat,2} = A(L_{max} - L_w) \cdot \alpha_{fg,2} \cdot (\overline{T}_{fg,2} - T_{mat}) \tag{22}$$

$$M_{fg,2} = V_{fg,2}(L_{max} - L_w) \cdot \rho_{fg,2} \tag{23}$$

2.4 BOILER MATERIAL - STEEL

$$\dot{q}_{rad\rightarrow mat} + \dot{q}_{conv\rightarrow mat} + \dot{q}_{fg\rightarrow mat,1} + \dot{q}_{fg\rightarrow mat,2} - \dot{q}_{mat\rightarrow w} - \dot{q}_{mat\rightarrow s} - \frac{dU_{mat}}{dt} = 0 \tag{24}$$

where each component can be written as:

$$\dot{q}_{mat\rightarrow w} = A(L_w) \cdot \alpha_{mat,w} \cdot (T_{mat} - T_w) \tag{25}$$

$$\dot{q}_{mat\rightarrow s} = A(L_{max} - L_w) \cdot \alpha_{mat,s} \cdot (T_{mat} - T_s) \tag{26}$$

$$T_w = T_s = Saturation\ temperature\ at p_s \tag{27}$$

$$U_{mat} = M_{mat} \cdot c_{p,mat} \cdot (T_{mat} - T_{ref}) \tag{28}$$

$$M_{mat} = V_{mat} \cdot \rho_{mat} \tag{29}$$

2.5 WATER/STEAM SECTION

$$\dot{q}_{mat\to w} + \dot{q}_{fw} - \dot{q}_{w\to s} - \frac{dU_w}{dt} = 0 \tag{30}$$

$$\dot{q}_{mat\to s} + \dot{q}_{w\to s} - \dot{q}_s - \frac{dU_s}{dt} = 0 \tag{31}$$

where each component can be written as:

$$\dot{q}_{fw} = \dot{m}_{fw} \cdot h_{fw} = \dot{m}_{fw} \cdot c_{p,fw} \cdot (T_{fw} - T_{ref}) \tag{32}$$

$$\dot{q}_s = \dot{m}_s \cdot h_s = \dot{m}_s \cdot c_{p,s} \cdot (T_s - T_{ref}) \tag{33}$$

$$\dot{m}_{fw} - \dot{m}_s - \frac{dM_s}{dt} - \frac{dM_w}{dt} = 0 \tag{34}$$

at this stage it is presumed that $n_{circ} = f(p_s, \dot{q}_{mat\to w}, \dot{m}_{fw})$.
This hypothesis will be analyzed further during the analysis of the test data.

$$n_{circ} = c_1 \cdot \dot{q}_{mat\to w}^{c_2} + c_3 \cdot \dot{m}_{fw}^{c_4} + c_5 \cdot \dot{p}^{c_6} \tag{35}$$

$$\rho_{1,A} = \left[\frac{\overline{x}}{\rho_{1A,s}} + \frac{1-\overline{x}}{\rho_{1A,w}} \right]^{-1} \tag{36}$$

$$\overline{x} = \frac{0 + x_s}{2} = \frac{1}{2 \cdot n_{circ}} \tag{37}$$

$$(\dot{m}_s - \dot{m}_{s,1\to 2}) \cdot h_s - \frac{dU_2}{dt} = 0 \tag{38}$$

$$M_1 = M_{1,s} + M_{1,w} = M_{1A,s} + M_{1A,w} + M_{1B,w} = V_{1A,s} \cdot \rho_{1A,s} + V_{1A,w} \cdot \rho_{1A,w} + V_{1B,w} \cdot \rho_{1B,w} \tag{39}$$

$$\frac{dV_w}{dt} + \frac{dV_s}{dt} = 0 \tag{40}$$

In the model the flue gas properties have been calculated according to [10] and the water steam properties according to [9].

3 SIMULATION

The first step in the simulation is the calculation of the *Furnace* performance, where the input parameters are:

- mass flow of fuel, $\dot{m}_{fuel}(t)$
- temperature of fuel, $T_{fuel}(t)$
- mass flow of air, $\dot{m}_{air}(t)$
- temperature of air, $T_{air}(t)$

As a result of the *Furnace* simulation the following values are calculated:

- heat transferred from the flue gas to the boiler metal by convection, $\dot{q}_{conv \rightarrow mat}(t)$
- heat transferred from the flue gas to the boiler metal by radiation, $\dot{q}_{rad \rightarrow mat}(t)$
- mass flow of flue gas, $\dot{m}_{fg}(t)$
- furnace gas outlet temperature, $T_{fg,1}(t)$

these figures are used as input to the *Metal* and the *Convection zone, 1* simulation.

The second step in the boiler simulation is the *Convection zone, 1* simulation, where the performance of the water embedded zone of the convection section is simulated (with $\dot{m}_{fg,1}(t)$ and $T_{fg,1}$ from the *Furnace* simulation as input). To determine the *size* of the *Convection zone, 1* the length of the water embedded zone $L_w(t)$ has to be known, the value is calculated in *Water/Steam section* and given as input to the *Convection zone, 1* section. As a result of the *Convection zone, 1* simulation the following figures are calculated:

- mass flow of flue gas, $\dot{m}_{fg,2}(t) \equiv \dot{m}_{fg,1}(t)$
- gas outlet temperature, $T_{fg,2}(t)$
- heat transferred from the flue gas to the boiler metal in section 1, $\dot{q}_{fg \rightarrow mat,1}(t)$

The third step in the boiler simulation is the *Convection zone, 2* simulation, where the performance of the steam covered zone of the convection section is simulated (with $\dot{m}_{fg,2}(t)$ and $T_{fg,2}$ from the *Convection zone, 1* simulation as input). The length (i.e. *size*) of this zone is known as the total length of the convection section (L_{max}) minus the length of *Convection zone, 1* ($L_w(t)$). As a result of the *Convection zone, 2* simulation the following figures are calculated:

- mass flow of flue gas, $\dot{m}_{fg,3}(t) \equiv \dot{m}_{fg,2}(t)$
- gas outlet temperature, $T_{fg,3}(t)$
- heat transferred from the flue gas to the boiler metal in section 2, $\dot{q}_{fg \rightarrow mat,2}(t)$

where $\dot{m}_{fg,3}(t)$ and $T_{fg,3}(t)$ are output from the boiler plant model.

After having finalized the *flue gas side* of the simulation, the *Metal* (i.e. the boiler material - steel) can be calculated. In principle the *Metal* is just a capacity that absorbs or liberate energy depending on the boiler operation conditions. The *Metal* section takes the energy flows from the *flue gas side* simulations as input and calculates the following figures:

- energy flow to the water embedded zone of the *Water/Steam* section, $\dot{q}_{mat \rightarrow w}(t)$
- energy flow to the steam covered zone of the *Water/Steam* section, $\dot{q}_{mat \rightarrow s}(t)$

Finally the *Water/Steam* section is simulated. This section takes the energy flows from the material as *internal* input parameters. From the *external* feed water flow (i.e. $\dot{m}_{fw}(t)$) and feed water temperature (i.e. $T_{fw}(t)$) are given. As output from the *Water/Steam* simulation the following *external output* parameters are given:

- steam pressure, $p_s(t)$
- water level, $L_w(t)$

4 EXPERIMENTAL VERIFICATION

For verifying the model experiments have been carried out on a full scale boiler plant - see Figure 2 and Figure 1. The boiler applied for the experiments is an Aalborg Industries A/S (see: [1]) boiler type MISSION^{TM} OB. This is a newly developed bottom fired fire tube boiler for light and heavy fuel oil.

To verify the model (i.e. the dynamic performance model) step-input have been given to the plant - see Figure 3.

The verification of the model is carried out by means of the measurements from the boiler test plant, the constants [1] in the model (e.g. coefficients of heat transfer) are determined by means of a Gauss-Newton algorithm (see: **??**) to obtain the best possible accordance between the model and the measurements. Subsequently the estimated constants are evaluated against *expected* values.

5 CONCLUSION

In this paper a model for simulating a fire tube boiler has been given. The model consist of a number of sub models for the different components being present in the boiler. Each of the sub-models are build up as a set of Differential-Algebraic Equations (DAE's). Subsequently the models are *merged* into a *global* model for the system. MatLab/SimuLink has been applied for integrating the model.

The model is presently being verified on a full scale plant where measurements have been carried out.
The simulation model combined with the experimental verification will be analyzed further during the remaining part of the Ph.D. project (*optimization of boilers*).

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[1] Some of the constants are actually not constant as they may have a weak dependence of e.g. temperature.

Figure 2: Experimental verification on MISSION^{TM} OB test plant.

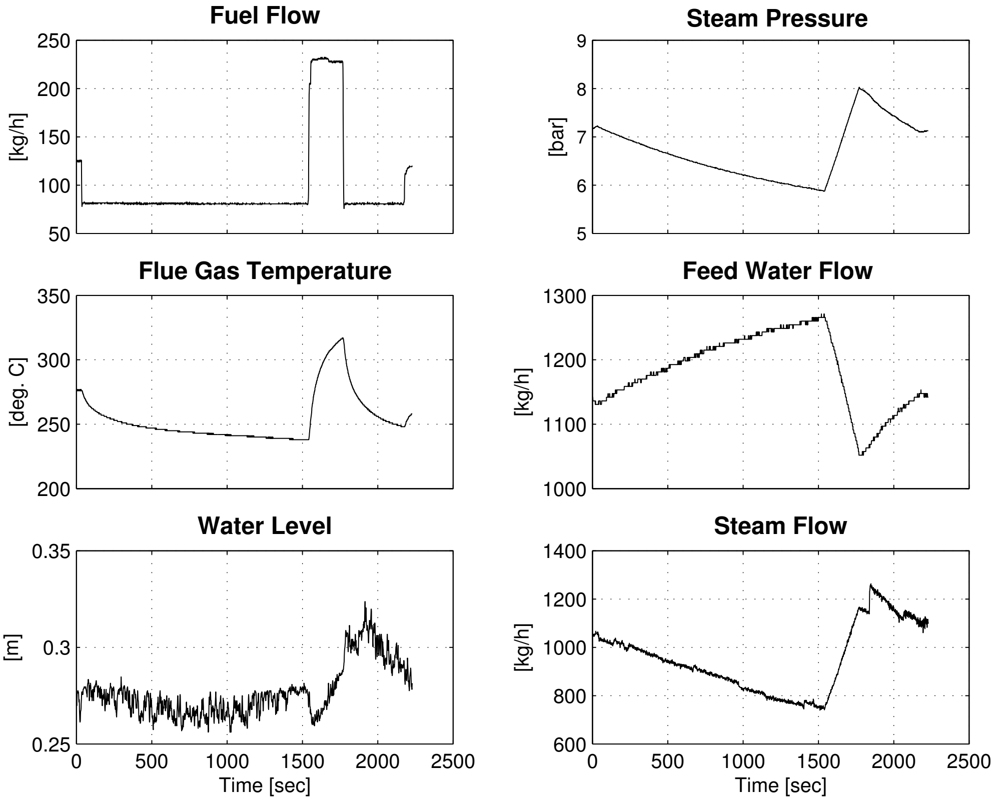

Figure 3: Step-input on fuel flow (i.e. firing) on MISSION^{TM} OB test plant.

6 PERSPECTIVES

The Ph.D project will be finalized in the middle of 2004 and the following work on the fire tube boiler model is foreseen:

- Further tests
- Refinement of model
  - Full integration of flue gas and water/steam side
  - Further development of two-phase models (pool boiling)
  - Modelling deviations from ideal (e.g. temperature distribution)
  - Improve models for internal circulation
- Optimization of design versus dynamic operation

APPENDIX A
Nomeclature

In this appendix the applied symbols are explained.

Symbol	Content	Unit	Subscript	Content
A	Area	[m^2]	ad	adiabatic
H	Heating Value	[kJ/kg]	air	Air
L	Length	[m]	s	Steam
M	Mass	[kg]	fuel	Fuel (LO/HFO)
T	Temperature	[$degC/K$]	rad	Radiation
U	Energy content	[kJ]	mat	Material
V	Volume	[m3]	conv	Convection
c_p	Specific heat capacity	[$kJ/kg/K$]	fur	Furnace
h	Enthalpy	[kJ/kg]	fg	Flue Gas
$\dot{m}$	Mass flow	[kg/s]	ref	Reference
p	Pressure	[$bara$]	1	Water embedded zone
$\dot{q}$	Energy flow	[kJ/s]	2	Steam covered zone
u	Specific energy content	[kJ/kg]		
x	Quality	[$-$]		
α	Coefficient of heat transfer	[$W/m^2/K$]		
ρ	Density	[kg/m^3]		

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