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Constrained control of a once-through boiler with recirculation ⋆

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Abstract: There is an increasing need to operate power plants at low load for longer periods of time. When a once-through boiler operates at a sufficiently low load, recirculation is introduced, significantly altering the control structure. This paper illustrates the possibilities for using constrained control to obtain optimal load gradients in the recirculation mode. A model predictive controller is designed for a simulation model with good results. It is also shown how the feed water flow can be used as an extra control signal.

1. INTRODUCTION

The increasing liberalisation of the energy markets have led to a greater need for operating power plants in ways for which they were not designed. For instance, plants designed to work at full load for most of the time are suddenly required to take part in load regulation and to operate at low load for extended periods of time. This leads to a need for reconsidering the control structure at low load.

This paper focuses on the achievable load gradients for once-through (Benson) boilers in the low load region, where recirculation is introduced. The main limitations on the achievable load gradients are due to various constraints on physical parameters rather than to the achievable bandwidth in the linear sense. Traditionally, the load gradients have simply been limited conservatively, so that no constraints are violated, but here we wish to examine the maximal achievable gradients satisfying the constraints. Thus, a constrained control strategy is ideal for this problem. In this paper we will use the *model predictive control* (MPC) method implemented in the *Multi-Parametric Toolbox* (MPT) (Kvasnica et al. (2004)).

Predictive and constrained schemes have of course been applied to power plant control before (Kim et al. (2005); Ferrari-Trecate et al. (2004); Peng et al. (2005); Poncia and Bittanti (2001); Gibbs (1992); Prasad et al. (2002, 1998)), but these references all deal with drum boilers, or in a few cases once-through boilers in medium to high load. As discussed in Section 2, the control problem changes significantly when the load is so low that recirculation is needed.

The main focus of this paper is on the application rather than on theoretical developments. After discussing the low load control problem, a linear MPC strategy will be presented in Section 5. Simulation results will then be presented in Section 6, showing the performance that can be achieved by constrained control and some of the potential benefits from using the feed water flow as an additional control signal.

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2. LOW LOAD OPERATION

Traditionally, low load operation has only been employed as a part of start-up procedures, but with recent changes in the market, low load operation is now performed for longer periods of time. This paper focuses on improving low load operation for a specific power plant.

This section describes the system considered in this paper. Some of the details are specific to a particular plant and may not hold in general for once-through boilers. In particular, the recirculation system can be more or less complicated.

The boiler system considered is shown in Figure 1. In medium to high load, the boiler operates in once-through mode (OTM) meaning that the feed water passes through the high pressure pre-heater (HPPH), economiser to the evaporator where it fully evaporates into steam. The steam then passes to the superheaters, where it is heated before passing through the (fully open) turbine valve to the high pressure turbine.

The steam pressure after superheater 2, P_{sh}, is controlled by the fuel flow $\dot{m}_{fuel}$ to the furnace, whereas the steam temperature, T_{sh}, is controlled by the feed water flow $\dot{m}_{fw}$.

When the *load* (i.e. $\dot{m}_{out}$, the steam flow to the turbine) and hence the fuel flow is decreased, the feed water flow is also decreased in order to maintain the desired steam temperature. However, a certain flow $\dot{m}_{min}$ is required in order to prevent damage to the evaporator tubes. Thus, at some point the $\dot{m}_{fw}$ is maintained at $\dot{m}_{min}$ even though the steam temperature is lower than desired. This also means that the steam leaving the evaporator is not fully evaporated. The separator extracts the water, so that only steam is led to the superheaters. The extracted water is led to the bottle which acts as a small buffer. In recirculation mode (RCM) the water in the bottle is recirculated back to the feed water.

The main components of the recirculation system are the recirculation pump and the recirculation valve v_r. The pump operates at constant speed and the valve controls the recirculation flow $\dot{m}_r$. Since the water leaving the bottle is close to saturation, it is necessary to add coolant through the on/off valve v_{NPSH}, which is always open when the

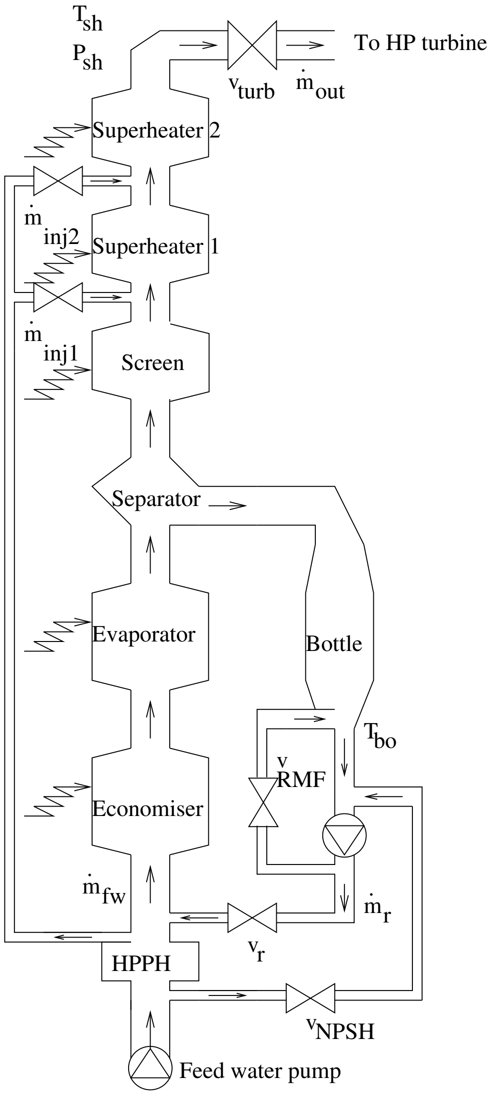

Fig. 1. *The high pressure steam system.*

pump is on. Furthermore, in order to maintain a sufficient flow in the pump, when the required $\dot{m}_r$ is low, some water can be returned to the bottle through v_{RMF}.

There is a significant difference in the dynamical behaviours of the system in OTM and in RCM. In particular, if the recirculated water is much warmer than the fresh feed water, non-minimum phase behaviour is introduced, since increased recirculation in order to lower the bottle level leads to warmer feed water, which in the short term increases the output flow from the evaporator, leading to an increased bottle level. Furthermore, the system in RCM is less controllable since the fresh water flow is bound by the minimum flow restriction, and less observable since the evaporator output temperature is given by the pressure and thus contains no information on the steam enthalpy.

A major point of concern in RCM is the temperature gradients of the metal in the bottle and separator. In this paper, we will focus on the outlet temperature, T_{bo}, of the water at the bottom of the bottle. Restricting the time derivative of this will help prevent stress in the bottle metal.

3. FLOW CONTROL LOOPS

The system dynamics can be roughly separated into two different time scales. The dynamics governing the water and steam flows are relatively fast, whereas dynamics from heat transfers are much slower. In this paper, we will focus on these slower dynamics. Furthermore, in RCM the system is open-loop unstable but can be stabilised by inner control loops maintainting flows at references provided by outer loops. Therefore, three flow control loops are built into the model, resulting in an open-loop stable model where it is possible to ignore flow loop dynamics when looking at a longer time scale. A feed water flow controller keeps $\dot{m}_{fw}$ at $\dot{m}_{min}$ $(91kg/s)$ and a bottle level controller keeps $\dot{m}_r$ proportional to the bottle level L. (Since the bottle is relatively small, there is not much to be gained from modifying this control.) In (Eitelberg and Boje (2004)) some issues regarding the stability of these loops are presented. This paper will not focus on these two flow control loops. They will be assumed to have been designed with a sufficient robustness and bandwidth. Furthermore, a control loop keeping the recirculation pump flow above the minimum $(32kg/s)$ through the v_{RMF} valve is also assumed.

4. SIMULATION MODEL

The controller is tested on a 22nd order nonlinear ODE model based on first principles (Trangbaek (2006)), which has been fitted to measurement data from low load operation of a 400 MW once-through boiler. The model is described in further detail in the appendix. Flow control loops as described in Section 3 are included in the model. These control loops are all assumed to have higher bandwidth than the sampling frequency used in the following. The model then has the following control inputs:

v_{turb}**:** Turbine valve.

$\dot{m}_{inj1}$ **and** $\dot{m}_{inj2}$ **:** The injection flows for the superheaters are also assumed to be controlled directly without delay.

$\dot{m}_{fw,ref}$**:** Feed water flow reference. In the traditional structure, this would be kept at $\dot{m}_{min}$ in RCM since the effects of an increase on the steady state are very small except for an increased power consumption in the recirculation system. However, in this paper we wish to explore if *temporary* increases can be useful during load transitions.

fuel: It is assumed that the fuel flow can be controlled directly without delay.

For other fuel types, the latter assumption may not be valid, and actuator dynamics must be incorporated in the model. The results in this paper could easily e extended to this situation.

Figure 2 shows step responses for selected inputs and outputs at three different loads. During the steps the inputs listed above are held constant, whereas the flow control loops are active. Notice how the feed water flow has almost no steady state effect on load or pressure in RCM.

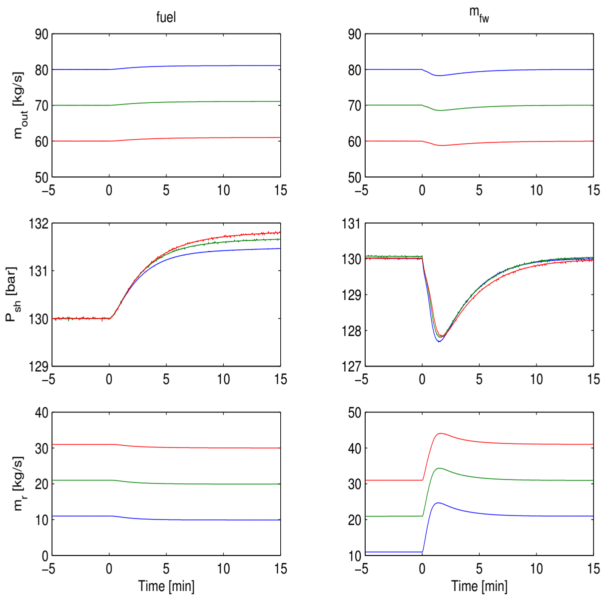

Fig. 2. Step responses of nonlinear simulation model at three different loads (applied at time zero). Left column: Small step on fuel flow. Right column: 10 kg/s step on feed water flow.

5. CONSTRAINED CONTROL

Model Predictive Control (MPC) encompasses a wide variety of linear and nonlinear control methods (Rossiter (2003); Bemporad et al. (2002)). In general, given a plant model, an MPC provides the optimal control signal that will satisfy given constraints on inputs, outputs and states over a certain future horizon. The MatLab toolbox MPT (Kvasnica et al. (2004)) provides an easy to use interface for designing MPCs for discrete time linear systems (and hybrid systems, but this will not be used in this paper).

The control design proceeds as follows; first the model discussed in Section 4 is linearised in an appropriate operating point and discretised, and the model order is reduced (balanced truncation) to 8. The sampling time is a compromise between precision and numerics. The linearised models contains an unpleasant mixture of fast and slow poles and zeros, and a short sampling time might be necessary in order to fully represent the dynamics. On the other hand, a long prediction in terms of samples is not desirable. A sampling time of 20 seconds is chosen together with a prediction horizon of 50 samples.

Integrators are added to the inputs allowing for (more or less) offset-free tracking by appending the reference to the state vector. This also allows for penalising the derivatives of the control signals.

Constraints are then set up for inputs, time derivatives of inputs, outputs, and time derivatives of outputs. MPT does not include an option for constraining the latter, so old versions of the relevant output signals are stored in the state vector. Thus, with original state space model given by

$$x_{k+1} = Ax_k + Bu_k, \; y_k = Cx_k + Du_k$$

the augmented state space system fed to the optimiser will be

$$\bar{x}_k = \begin{bmatrix} x_k \\ u_{k-1} \\ r_k \\ y_{k-1} \end{bmatrix}, \quad \bar{x}_{k+1} = \begin{bmatrix} A & B & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & I & 0 \\ C & D & 0 & 0 \end{bmatrix} \bar{x}_k + \begin{bmatrix} B \\ I \\ 0 \\ D \end{bmatrix} \Delta u_k$$

$$\bar{y}_k = \begin{bmatrix} e_k \\ u_k \\ \Delta y_k \\ y_k \end{bmatrix} = \begin{bmatrix} C & D & -I & 0 \\ 0 & I & 0 & 0 \\ C & D & 0 & -I \\ C & D & 0 & 0 \end{bmatrix} \bar{x}_k + \begin{bmatrix} D \\ I \\ D \\ D \end{bmatrix} \Delta u_k,$$

where r is the reference and e is the tracking error. The derivatives of y can now be constrained.

In Section 4, the choice of inputs was discussed. These are all assigned upper and lower limits as well as limits on the time derivatives. The chosen outputs are:

$\dot{m}_{out}$: The load. Tracking the load reference is the main objective. Therefore a high penalty is put on the tracking error of this signal in the quadratic performance index.

T_{sh}: The steam temperature must be kept within certain upper and lower limits. Furthermore, the time derivative must be less than 1 K/s.

P_{sh}: The steam pressure must be kept above a minimum (here $P_{min} = 130$ bar). In addition to this constraint, a medium sized penalty is put on the deviation from P_{min}. In steady state, the system will then be operating at this limit.

T_{bo}: The water outlet temperature at the bottom of the bottle. The bottle is sensitive to temperature gradients. Therefore, the time derivative of this signal is restricted to 0.1 K/s.

$\dot{m}_r$: The recirculation flow must be kept within certain upper and lower limits. Since this flow is proportional to the bottle level, this also constrains the bottle level.

The state is estimated by an LQG state observer designed with the same linearised model as used in the MPC. The model is appended with integrated noise on the load, resulting in offset-free tracking in the face of model inaccuracies and noise.

At each sample, k, the MPC solves the optimisation problem

$$\min_{\Delta u_k \ldots \Delta u_{k+N_c-1}} \sum_{i=0}^{N_p-1} \bar{x}_{k+i}^T Q \bar{x}_{k+i} + \sum_{i=0}^{N_c-1} \Delta u_{k+i}^T R \Delta u_{k+i}$$

subject to constraints on $\bar{x}$ and Δu over the horizon. $N_p = 50$ is the prediction horizon, $N_c = 4$ is the control horizon, which has to be short for computational reasons.

6. SIMULATION RESULTS

The constrained controller has been tested in a number of operating points with various sizes of load reference steps with good results. Here we will just show two of these, both illustrating the usefulness of allowing the controller to use the feed water flow as an input. The simulations are performed on the original nonlinear model.

Figures 3-5 show a load step from 70 to 50 kg/s (reference shown by the dotted line). The solid lines show the situation when the constrained controller is allowed to increase the feed water flow. The dashed lines show when the feed water flow is kept at the minimum. The constraints are shown by solid (red) lines.

A fast load decrease is achieved by closing the turbine valve and decreasing the fuel flow. Due to the various heat capacities this leads to a temporary pressure increase. Once the surplus energy has been extracted from the system, the pressure can be decreased to P_{min} again. It is noticed that the derivative of the bottle outlet temperature is a limiting factor during the load change.

It is also seen that a faster load transient can be achieved when the feed water flow is allowed to increase temporarily. It even allows for a smaller pressure increase. Loosely stated, this is because the increased flow leads to an increase in evaporator and economiser pressure and thus an increased water mass, yielding a storage capacity for the surplus energy.

Figures 6-8 show a similar load step, this time upwards from 75 kg/s to 85 kg/s. In this region, some water is fed back to the bottle through v_{RMF} in order to maintain the necessary flow in the recirculation pump. When the fuel flow is increased, the recirculation flow will drop, meaning that more coolant will be led to bottom of the bottle. It is indeed seen that a limiting factor during the load increase is the temperature gradient at the bottle outlet.

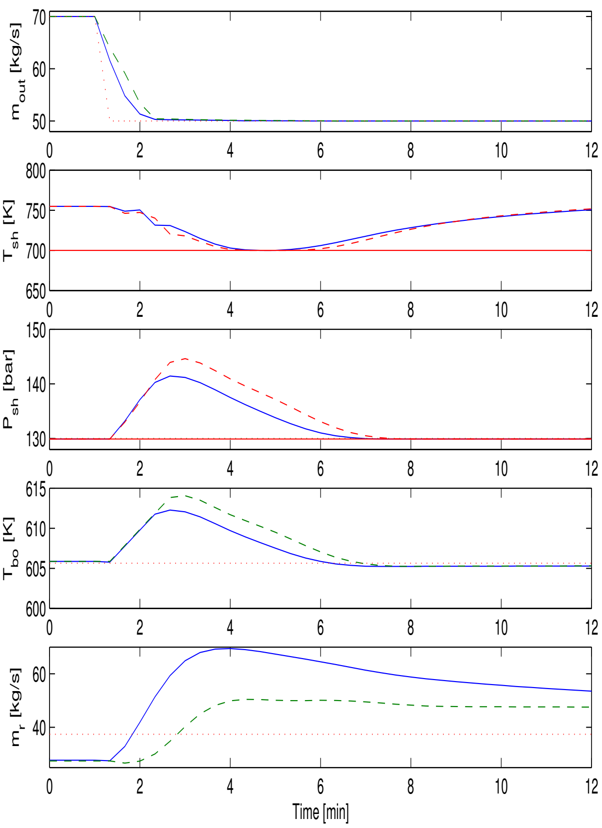

Fig. 3. Controlled outputs during a load step from 70 to 50 kg/s. From top to bottom: Output flow, steam temperature, steam pressure, bottle outlet temperature, and recirculation flow. Dotted lines show references.

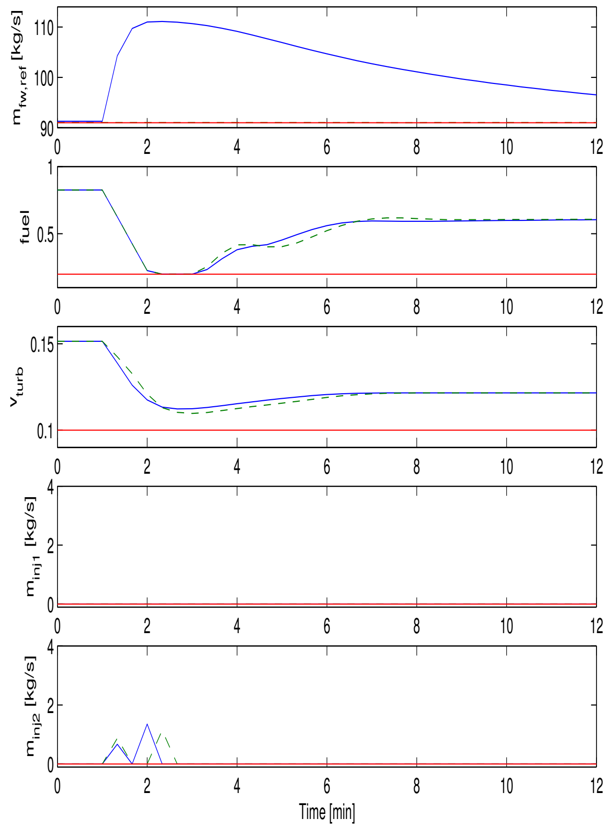

Fig. 4. Control signals during a load step from 70 to 50 kg/s. From top to bottom: Feed water flow, fuel flow, turbine valve position, injection flow 1 and 2.

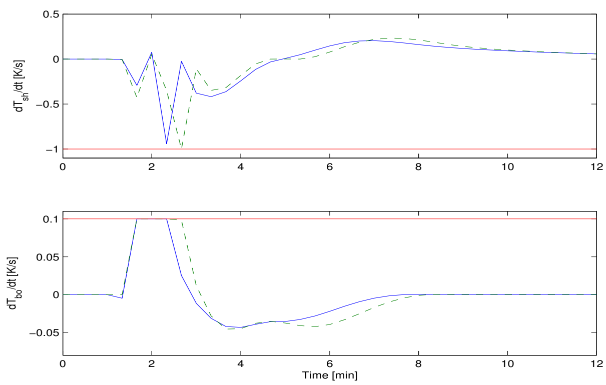

Fig. 5. Time derivatives of temperatures during a load step from 70 to 50 kg/s.

Again, the plots compare the situations when the feed water flow is allowed to increase (solid) and when it is not (dashed). To increase the turbine flow the turbine valve is opened. The increased flow makes the steam temperature drop and thus more fuel must be added. However, increasing the fuel flow leads to less recirculation and consequently a fast drop in the bottle outlet temperature. Thus, if $\dot{m}_{fw,ref}$ is not increased, the conflict between limiting the bottle temperature gradient and keeping the steam temperature within constraints leads to various undesired effects on the pressure and temperature, although the load reference is followed nicely. However, simply by allowing $\dot{m}_{fw,ref}$ to increase temporarily, the recirculation flow can be maintained, and a much smoother response is achieved.

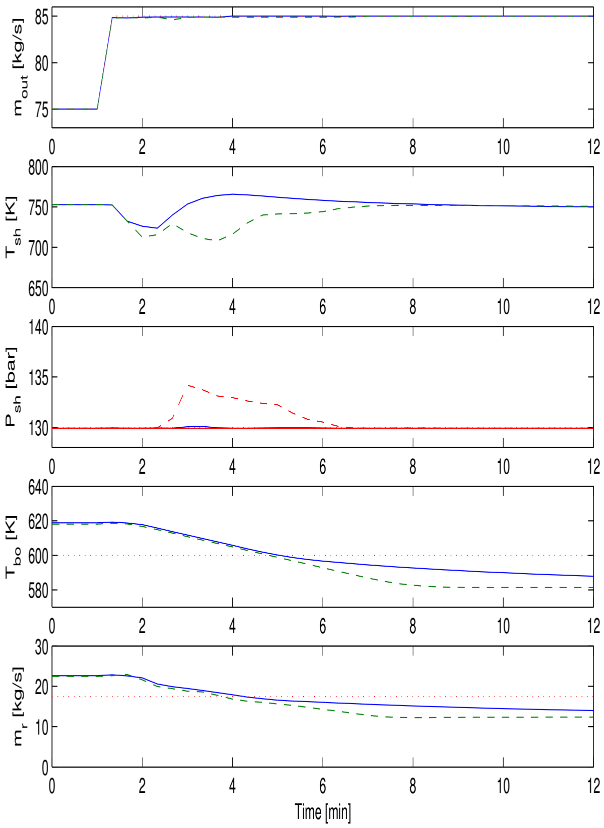

Fig. 6. Controlled outputs during a load step from 75 to 85 kg/s. From top to bottom: Output flow, steam temperature, steam pressure, bottle outlet temperature, and recirculation flow.

7. CONCLUSIONS

A constrained control strategy has been applied to a simulation model of a once-through boiler with recirculation. It was shown how the multivariable method allows for very fast load gradients without violating constraints, and how the feed water flow can be temporarily increased to improve performance in particular situations. It is expected that the method can be applied to most once-through boilers with bottle recirculation, but a significant amount of modelling work would have to be undertaken for each individual plant.

The linear MPC method used is only valid for recirculation mode, but since we are actually interested in load changes across wide regions, a nonlinear method should be explored in future work. A hybrid MPC approach to changing to and from recirculation mode has been developed and will be presented in future publications.

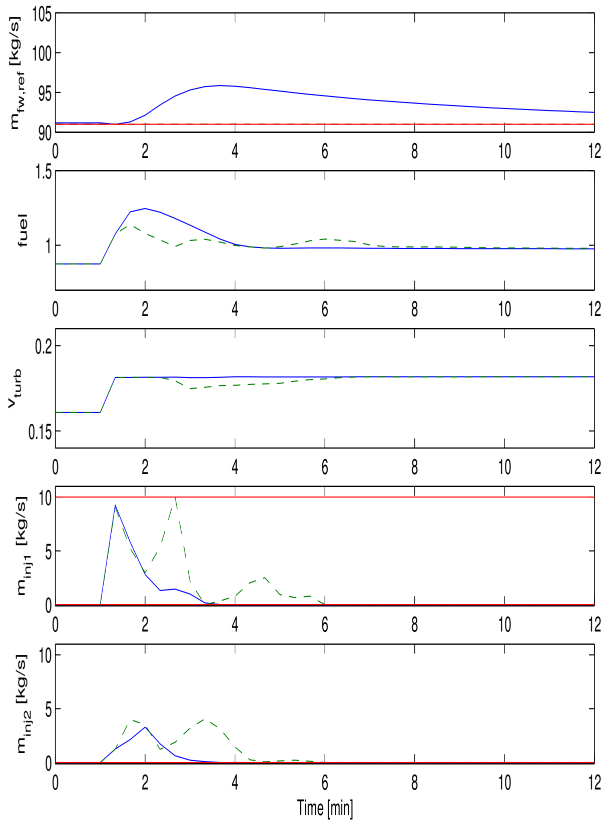

Fig. 7. Control signals during a load step from 75 to 85 kg/s. From top to bottom: Feed water flow, fuel flow, turbine valve position, injection flow 1 and 2.

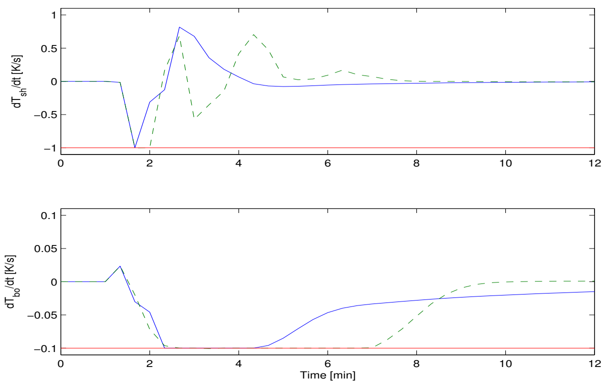

Fig. 8. Time derivatives of temperatures during a load step from 75 to 85 kg/s.

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Appendix A. SIMULATION MODEL

In (Trangbaek (2006)) a simulation model of the system in Figure 1 was considered. For completeness, this appendix contains some background details on this model, that are not essential to the developments in this paper.

The model operates from the lowest practical load (15%) to medium load (50%) and is able to handle transitions between RCM and OTM. Supercritical operation is not required.

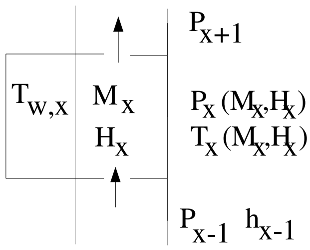

Fig. A.1. *A basic control volume.*

The economiser, evaporator and superheaters are each modelled by a lumped parameter control volume as shown in Figure A.1. A control volume x has three state variables, steam mass M_x, steam enthalpy H_x, and wall temperature $T_{w,x}$.

The steam pressure P_x and temperature T_x are determined by steam tables from the specific enthalpy $h_x = H_x/M_x$ and specific volume $v_x = V_x/M_x$ where V_x is the steam volume. The mass flow between two volumes is determined by the pressure difference between them, i.e $\dot{m}_{x\to x+1} = c_{x\to x+1}(P_x - P_{x+1})$, where c is some constant. In a sense, this means that the control volumes are split into a volume with a mass and energy balance and a pipe across which the pressure drop occurs. The specific enthalpy of the steam flow out of a control volume is given by the specific enthalpy in that particular volume, whereas the input flow will have an enthalpy specified by the preceding volume.

A further simplification is the heat input from the furnace to the wall. The energy flow is simply modelled as the fuel flow multiplied by a constant gain for each control volume. The choice of model structure of the separator and bottle is essential for the performance, but details cannot be included here. The separator flows are determined from pressure drops rather than an assumption on ideal separation. In order to model the temperature effects of recirculated coolant water on the bottom bottle, the bottle is modelled using two water/steam volumes.

Parameter adjustment

The model is adjusted to fit a set of closed-loop data from a 400 MW gas fired plant. The plant is an important part in compensating for changes in electricity consumption on the net, meaning that there is a dearth of steady state data, especially at low load. However, fitting the static characteristics accurately is less important than getting the dynamic behaviour right. A bigger problem is the closed-loop nature of the data, but since no open-loop data are available, a choice must be made on where to break the loop when simulating, i.e. which controllers should be included and what should act as external signals when trying to make a simulation fit the data.

In RCM the system is open-loop unstable, but is stabilised if a feed water flow controller keeps $\dot{m}_{fw}$ at $\dot{m}_{min}$ (or at some other reference, e.g. from a temperature control) and a bottle level controller keeps $\dot{m}_r$ proportional to the bottle level L. Therefore, all water flow controllers are applied in the simulation when tuning the parameters. As noted in (Eitelberg and Boje (2004)), these loops interact heavily and improper tuning can lead to instability. However, since the bandwidths of these loops are fairly high, this issue is not relevant in the frequency range of interest. In other words, any sufficiently fast and stabilising flow loop controllers will do.

Essentially the fuel flow, feed water flow, and turbine valve are used for controlling pressure, temperature, and flow at the outlet. These control signals contain both feedback parts from disturbance compensation and feed-forward parts from load changes.

When fitting to closed-loop data it is of course important to keep in mind that some measurements, e.g. superheater outlet temperatures, are in reality controlled outputs. If the controller is included in the simulation then of course the simulated output will fit the measurement. What should then be evaluated is if the control input, e.g. the feed water flow, looks like the measured input.

Since the objective is a model for controller design, it is chosen to let the three signals act as open-loop inputs in the simulation when fitting to data. Thus, the only part of the control system, which has been included in the model is the water flow loops. Acting as inputs (boundary conditions) are feed water flow reference, fuel flow, injection flows, and turbine valve setting.

The main parameters to adjust are the heat input gains, pressure drop to flow gains, steam volumes, and wall heat capacities, where the first two are mainly adjusted to fit steady state situations and the latter two are used for adjusting the dynamic behaviour.

In (Trangbaek (2006)) the model was shown to fit measurement data nicely.