

## Utilization of Drum Boilers' Storage Capacity for Flexible Operation

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**Abstract:** Due to increasing amount of intermittent and uncontrollable renewable energy production and reducing amount of stabilizing inertia in power systems, requirements for improved dynamic performance of controllable steam boilers will increase remarkably. Load tracking capacity of steam boilers consists of utilization of fast responding energy storages in boiler structures and change rate of available combustion power. This paper presents results of a simulation based dynamic analysis of the transient operation of a steam boiler exposed to fast load change. The results are evaluated against the requirements set by the maximum allowed thermal stresses in boiler structures and stability of steam parameters set by steam turbine operation. This project is a part of the FLEXe (Flexible Future Energy Systems) research program coordinated by CLIC Innovation Ltd and funded by the Finnish Funding Agency for Innovation TEKES.

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### 1. INTRODUCTION

In future energy systems, the value of flexible operation and controllability of thermal power plants will increase remarkably due to increased amount of intermittent and uncontrollable renewable power generation. Intermittent renewable generation disturbs the generation-consumption balance in power systems and at the same time it replaces controllable thermal generation capacity. Thus the increased need of controllable generation capacity shall be supplied by fewer thermal power plants, at least until somebody introduces a dynamically flexible and economically viable large capacity storage system for electric energy.

In order to make this power system balancing problem not too easy, increased capacity of renewable generation will also reduce the stabilizing inertia of power systems. Both wind turbines and solar PV plants are connected asynchronously to power systems via power converters having no inertia. In synchronous generators based production, rotational energy stored in the massive rotors of turbine-generator systems is the first reserve utilized during load transients. Rotating loads, such as electric AC-motors, are also an essential part of the system inertia. However, increased use of energy efficient frequency converter based drives as well as increased amount of non-rotating loads, e.g. data centres, are reducing the inertia of power systems as well.

The fastest generation based frequency restoration capacity is activated within app. 5 – 10 seconds. This is the time needed for hydro power plants and thermal power plants engaged to primary frequency control, to react to the imbalance in the system. How severe the frequency deviation will be before the activation of the restoration capacity depends on the amount of rotating inertia in the system. There is an

increasing risk that typical disturbances in the power systems will lead to that size of frequency deviations, which will activate automatic load dispatching procedures causing severe disturbances to the normal operation of the power systems.

Due to these issues, it is evident that more quickly responding generation capacity is needed to keep the power systems running. One option to increase the controllability of power plants is the extended utilization of energy storages of steam boilers. This paper presents the results of an analysis of the transient behaviour of a steam boiler. The analysis is based on dynamic simulation. Dynamic simulation is a commonly used tool for system evaluating and control design, see e.g. (Kataja, 2007), (Majanne, 2006, 2011, 2013), (Mills, 2011), (Yli-Fossi, 2011), (Gude & Vazquez, 2011).

The goal of this study is to evaluate the amount of available energy in boiler structures and how the utilization of those energy storages will effect on the expected life time of the boiler-turbine system. The results are based on dynamic simulations made with a model validated against real process measurements. The content of the paper is structured as follows: Section 2 introduces the applied simulation model. Section 3 introduces the boiler process and energy storages integrated with the process structures. Section 4 introduces the utilization of boiler's storage capacity for rapid load changes. Section 5 evaluates the effects of active utilization of storage capacity to thermal stressing of boiler components, Section 6 evaluates effects of utilization of storage capacity to stabilizing controls, and Section 7 concludes the results and evaluates the feasibility of this approach to be actively applied as a part of the boiler load control during fast transients.

## 2. SIMULATION MODEL

The dynamic simulation model for a circulating fluidized bed (CFB) boiler is built by using a model component library developed by Tampere University of Technology and boiler manufacturing company Valmet Technologies. The modelling software environment is Matlab/Simulink. The water/steam side of the model is modelled using developed general heat transfer blocks suitable for evaporation and superheating in subcritical boilers as well as for heat transfer in supercritical boilers (Yli-Fossi 2011). Heat transfer coefficients for model blocks can be tuned automatically according to boiler design data or actual process measurements if available. (Yli-Fossi 2014)

Fig. 1 shows the structure of the heat transfer model applied in boiler model. The heat transfer surface consists of an optional refractory lining and a tube wall. The refractory wall is installed only in the bottom part of the furnace walls and in the separation cyclone. Refractory wall model is divided into five layers and tube wall model into two layers to shape the system dynamics.

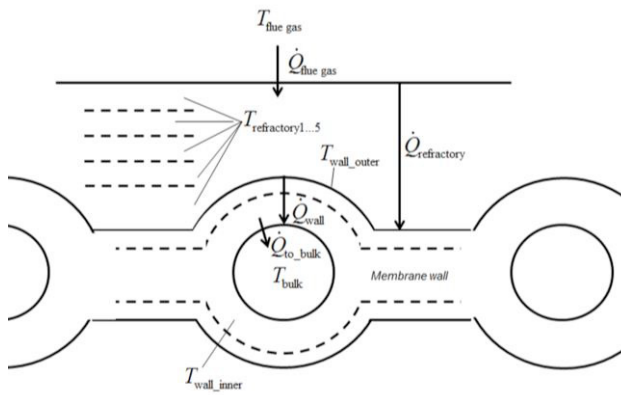


Fig. 1. Heat transfer model structure for boiler walls.

Pressure point calculation is based on equation (1) for single phase and (2) for water/steam mixture flows (Yli-Fossi 2016)

$$\frac{dp}{dt} = - \frac{(\dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q) - [\rho / (\partial \rho / \partial h)]_p + h}{V [1 + \rho (\partial \rho / \partial p)]_h / (\partial \rho / \partial h)]_p} (\dot{m}_{in} - \dot{m}_{out}) \quad (1)$$

$$\frac{dp}{dt} = \frac{(\dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} + q) - \left[ \frac{(\rho' h' - \rho'' h'')}{(\rho' - \rho'')} (\dot{m}_{in} - \dot{m}_{out}) \right]}{V' (X') + V'' (X'')} \quad (2)$$

$$X' = \rho' \frac{dh'}{dp} + \frac{\rho'' (h'' - h')}{\rho' - \rho''} \frac{d\rho'}{dp} - 1$$

$$X'' = \rho'' \frac{dh''}{dp} + \frac{\rho' (h'' - h')}{\rho' - \rho''} \frac{d\rho''}{dp} - 1$$

where  $\dot{m}$  is mass flow,  $h$  is enthalpy,  $q$  is heat flow,  $\rho$  is density and  $V$  is control volume. For two phase mixture'

denotes liquid and '' vapour. Mass flow between pressure control points is calculated according to Eq. 3,

$$\frac{d\dot{m}}{dt} = \frac{p_{in} - p_{out} - \Delta p}{L / A} \quad (3)$$

where  $p_{in}$  and  $p_{out}$  are calculated pressures in control points,  $\Delta p$  is pressure drop across the flow element,  $L$  is element length and  $A$  pipe diameter.

## 3. ENERGY STORED IN BOILER STRUCTURES

A steam boiler consists of a series of interconnected energy conversion and storage systems. The structure and the properties of the system depends on the applied combustion method and the structure of the water-steam system. The analysed process in this work is a multifuel (coal, biomass, peat) fired CFB drum boiler operated at fixed live steam pressure.

At first fuel is fed into the furnace where chemical energy is converted to thermal energy. Unburned fuel in the furnace forms a chemical energy storage. Dynamics and the capacity of this storage depends on the combustion rate and the rate of fuel feed into the boiler. E.g. in pulverized coal combustion the reaction time is some hundreds of milliseconds while in fluidized bed combustion for crushed and moist coal it is over 100 seconds (Basu, 2015).

After the combustion, the released thermal energy is transferred from flue gases and flame radiation to an inert sand bed circulating in the hot loop of the CFB-furnace and further to heat exchange surfaces in the furnace and separation cyclone walls, and superheater tubes in the convection pass. In CFB-boilers the bottom part of the furnace and the separation cyclone is lined with a refractory wall protecting tubes from erosion. This refractory wall forms an energy storage. In the upper part of the furnace with no refractory lining, heat power is transferred directly to heat exchangers' tube walls. These metal structures form next energy storages in the boiler.

From metal tubes heat is transferred to water-steam cycle of the boiler. In drum boilers the water-steam system consists of an evaporator loop and a super heating section separated from each other by a steam drum. In the evaporator, water and saturated steam mixture circulates injecting thermal energy from tube walls. In the drum saturated steam is separated from water and led to superheaters. Superheater tubes form the next massive energy storage. Also the steam drum operating at the evaporator temperature is an energy storage. In addition, water-steam fluid stored in the evaporator and superheaters forms energy storages. Fig. 2 shows the relative capacities and distribution of energy storages in the case boiler operating at 90% of its nominal load. Here, reference temperature for heat storages is 0°C. "Fuel inventory" shows the energy content of the unburned fuel stored in the furnace (coal with 120 s. combustion time), "Flue gas & air" the energy stored in combustion air and flue gases inside the boiler, "Bed material" energy content of the inert bed material, "Refractory" energy content of the refractory lining.

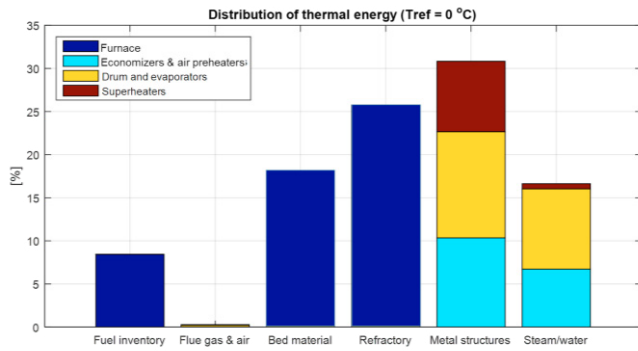


Fig. 2. Energy storages of a CFB drum boiler.

“Metal structures” shows the total amount of energy stored in tube and drum walls and how it is distributed to economizer and air preheater, drum and evaporator, and superheaters. “Steam water” shows the amount of stored energy in water and steam.

#### 4. UTILIZATION OF BOILER’S STORAGE CAPACITY

Fig. 2 does not tell anything about the availability of these boiler’s energy storages for load control purposes. Utilization of energy storages in fixed pressure operated drum boiler can be illustrated by the steam storage capacity of the boiler. The steam storage capacity  $C_e$  of the boiler is defined as how much extra steam power a boiler can momentary generate with a constant combustion power as a function of unit pressure drop in a steam drum.  $C_e$  is defined as

$$C_e = \frac{\int_{t_1}^{t_2} [h(t) q_m(t) - h(t_1) q_m(t_1)] dt}{p(t_1) - p(t_2)} \quad (3)$$

where  $h$  is enthalpy,  $q_m$  mass flow and  $p$  pressure of live steam.  $t_1 \dots t_2$  is the period during which the generated steam flow differs from the steady state value. During the pressure drop, saturated water in the evaporator and drum starts to evaporate due to pressure drop caused lowered evaporation temperature. Latent energy needed for additional evaporation is extracted from evaporator and drum walls. Tube wall temperatures drop and after a while the system is stabilizing to a new steady state with a lower fluid pressure and temperature at constant fuel feed. Thus, energy storage in the boiler is discharged by producing some extra steam resulting to dropped steam pressure and temperature in the evaporator and the drum. Measured behaviour of steam flow from the case boiler during the storage capacity test is shown in Fig. 3.

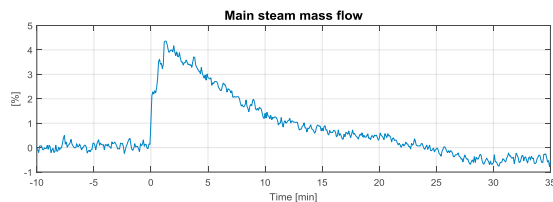


Fig. 3. Measured steam flow in the case boiler induced by a 5% pressure drop caused by a quick turbine valve opening during constant fuel flow.

A rule of thumb for a control design of industrial steam boilers and networks says that during abrupt load changes it is allowed to let boiler’s live steam pressure fluctuate  $\pm 5\%$  from its nominal value in order to utilize the boiler’s storage capacity. In the analysed boiler, the capacities of energy storages at 5% pressure drop, resulting to 5°C temperature drop, are shown in Fig. 4. Figure shows that in this case the inventory of unburned fuel forms the biggest energy storage in the system, almost 90% of the total capacity. However, this storage is not affected by the evaporator pressure and thus has no effect on the steam storage capacity of the boiler. The biggest energy storages connected with the drum pressure are the metal structures of the evaporator and the drum and water-steam fluid in these components. Economizer structures contain also a big energy storage, but their availability depends on, if feed water is evaporated in the economiser during the pressure drop or not. Even if the evaporation in the economizer would be beneficial to boiler’s storage capacity, it will cause control problems with the drum level.

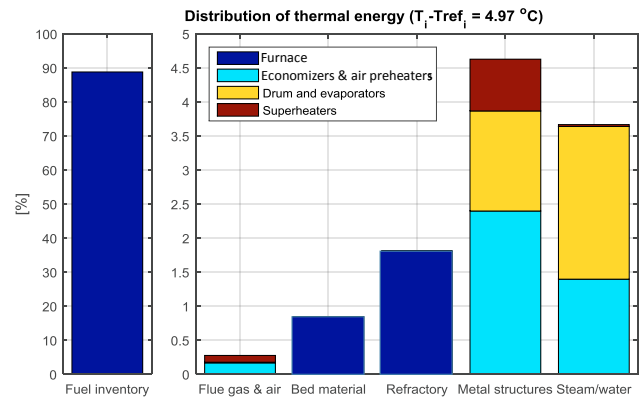


Fig. 4. Available energy storages related to 5% pressure change change in the evaporator.

#### 5. CHARACTERISTICS OF TRANSIENT OPERATION

Controlled utilization of boiler’s storage capacity during fast load changes is conducted by the coordinating master control of the boiler-turbine process. In case of the fixed pressure operation, the boiler-turbine unit control must be realized as a boiler-follow structure, that is, unit load is controlled by the turbine control valve and boiler pressure by fuel feed.

In order to utilize the storage capacity of the boiler, the operation of the turbine and the boiler should be synchronized so, that a tolerable change in live steam pressure is conducted producing extra steam to speed up the load change. However, fluctuation of steam pressure has several consequences. In the evaporator filled with a mixture of saturated water and steam, system pressure is directly connected with system temperature, and due to fluctuating pressure boiler structures are exposed to thermal stressing. For this reason, the behaviour of the boiler and the turbine during rapid load changes must be analysed to be able to set the operation limits for the coordinating control (Henderson, 2014).

5.1 Boiler side effects

The steam drum is the biggest thick walled pressure vessel exposed to evaporator temperature changes. Due to the thermal stresses, the temperature change rate and the temperature difference across the drum wall should be maintained inside the acceptable limits. The lower part of the drum is filled with saturated water and the upper part with saturated steam. Heat exchange from water to wall is more efficient than that from steam to wall. This will result to asymmetric temperature response in the upper and lower parts of the drum. In the analysis, the model of the 100 mm thick drum wall is divided into four layers to catch the main dynamics and temperature differences inside the drum wall. Simulated 5% pressure drop induced temperature transients of saturated water and steam inside the drum and in different wall layers are presented in Fig. 5. Solid lines describe temperatures of water-covered wall parts and dashed lines parts contacted with saturated steam.

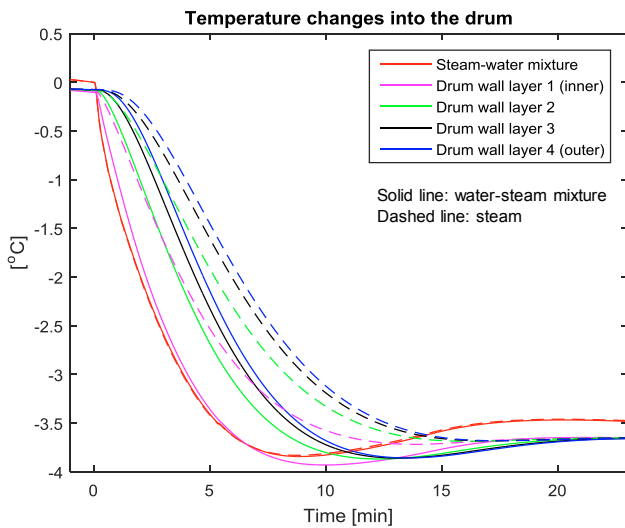


Fig. 5. Temperature transients inside the drum wall during 5% pressure drop in the evaporator.

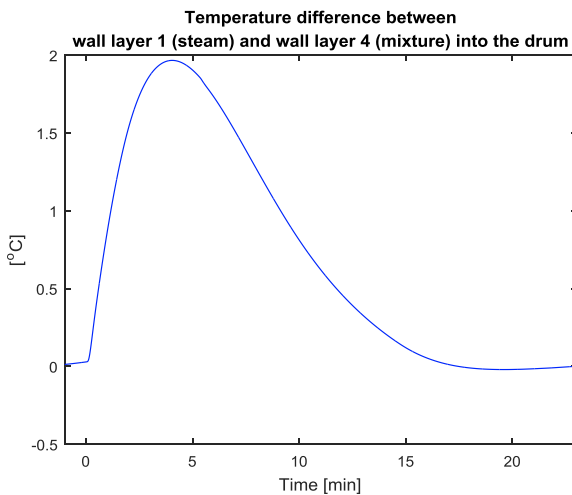


Fig. 6. Transient of the maximum temperature difference across the drum wall in the border line of water and steam.

Fig. 6 shows the maximum temperature difference inside drum wall during the transient between the outermost layer in the steam side and innermost layer in the waterside. The maximum detected temperature change rate is 3°C/min in the inner layer of the water-covered area.

According to discussions and calculations made by boiler material experts, the detected temperature differences and change rates have no essential effect to the expected lifetime of the metal structures of the boiler. The results show that from the boiler material side, the maximum allowed pressure change to utilize the boiler storage capacity could be increased up to 10% from nominal pressure. This would approximately double the temporary excessive steam flow from the boiler.

5.2 Steam turbine side effects

From the steam turbine side, the most important process variables are live steam and reheated steam temperatures. During a normal operation, when a steam turbine is operating at a thermal equilibrium, the allowable load change rate is defined according to curves shown in Fig. 7. Regarding to our case turbine, the maximum “Sudden change range” varies from 50% (at low loads) to 40% (at high loads) from the rated power (distance between “Directrix” and “Boundary” lines). Outside from this “Sudden change range” the boundary line constrains the maximum allowed load increase rate to 5%/min from the rated power. This result is valid with constant live steam temperature during the load change. However, that is usually not the case, but steam temperature is typically changing during transients. The maximum allowed change and change rate of steam temperature is defined by turbine manufacturer provided temperature curves shown in Fig. 8 (for decreasing steam temperature).

Steam temperature should stay within the limits defined by  $\pm\Delta T$  available. For our case turbine, the  $+\Delta T$  is 25°C and  $-\Delta T$  is -20°C. For decreasing steam temperature, the change rate

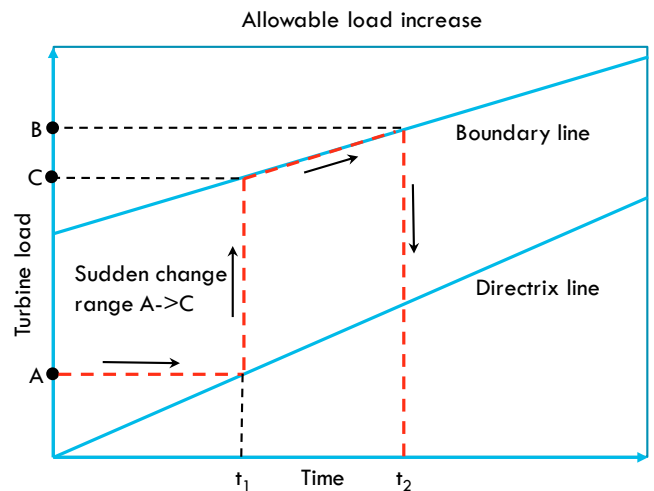


Fig. 7. Loading change rate curve for a steam turbine operating at a thermal equilibrium. Time needed for a load change from point A to B takes time  $t_2 - t_1$ .



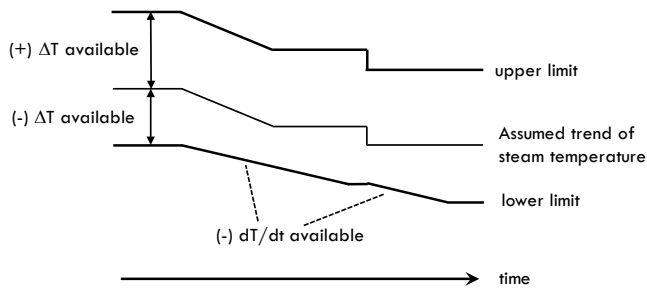


Fig. 8. Allowed steam temperature range in steam turbine input in case of decreased temperature. When the actual  $-\Delta T$  is less than the maximum available  $-\Delta T$ , the lower limit value is changed with the change rate  $-dT/dt$ .

$-dT/dt$  for the minimum allowed steam temperature is  $-1.5^\circ\text{C}/\text{min}$ . Thus in case of dropping temperature, steam temperature is allowed to decrease, until it intersects with the lower limit line.

Besides steam temperatures, also material temperature differences in thick-walled turbine valves and casings are limiting the operation of steam turbines due to thermal fatigue in structures. In addition, temperature differences between different parts of the turbine cylinders are monitored to avoid seizing between moving rotor parts and static part in turbine casings.

Figure 9 shows the simulated live steam temperature transient during 5% pressure drop in the case boiler. With uncontrolled steam temperature, temperature dropped  $7^\circ\text{C}$ . With controlled steam temperature the maximum change was limited to  $5^\circ\text{C}$ . In this case simulation, the temperature controllers were not especially tuned for this experiment, but the response shows a generic effect of temperature control to transient response. Comparing the simulated process responses to turbine manufacturers' defined operation limits, it is clear that utilization of boiler storage capacity in this extend for load control has no essential impact on the operation and expected life time of steam turbines. From the turbine side it can also be presumed that the storage capacity of the boiler can be utilized more than this 5% drop from nominal pressure.

### 5.3 Combustion Control

Future needs for power plant load tracking operation are focused both to quick responding for frequency control, and fast load ramping to balance the fluctuations originated from

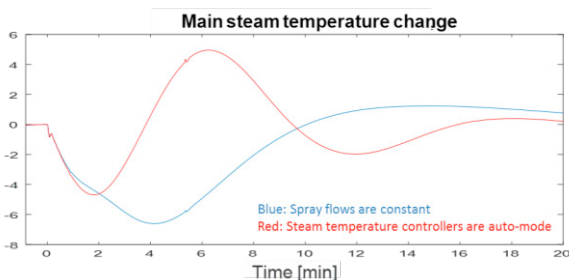


Fig. 9. Live steam temperature responses (controlled and uncontrolled) during a 5% pressure drop in the boiler.

intermittent renewable power production. Utilization of boiler's storage capacity supports the fast responding frequency control, but for load ramping also improved combustion control is required.

As discussed in Section 3, CFB boiler may have a big amount of unburned fuel circulating in the hot loop. In our example, the applied fuel is slowly reacting coal forming a big energy storage. In case of using highly reactive biomass, the capacity of energy storage formed by unburned fuel is much smaller. In both cases, the improved load ramping performance requires new methods for combustion control, among other things to keep combustion related emissions and thermal efficiency in the acceptable level. Overfiring of the boiler for fast load ramping will obviously effect on the temperature distribution in the furnace and may cause thermal stressing related problems in evaporator and superheater structures. One problematic area is the refractory lining at the bottom of the furnace. Fast temperature changes may easily crack the linings.

In order to avoid these type of problems, more detailed information about the operation circumstances is required. We have an ongoing project to analyse the transient behaviour in the furnace by Computational Fluid Dynamics (CFD) modelling based dynamic simulation. Information produced from this project will be utilized in the development of improved combustion control for fast and efficient load ramping control in CFB boilers.

## 6. STABILIZING CONTROLS

As concluded in the previous section, utilization of boiler's storage capacity for improved load control is not expected to cause material problems either in boiler or in turbine side, as the estimated temperature variations caused by studied pressure changes fulfil both the boiler and turbine manufacturers' requirements for safe operation. It is expected that the limiting factors for extended utilization of boiler's storage capacity for load control come from the stabilizing controls of sub-processes.

The conventional solutions for stabilizing controls are developed for slower dynamic requirements compared with the situation we are facing in future. Especially the extended operation ranges and fast ramping from minimum load to maximum load are features, which are not supported by the conventional control structures. New types of stabilizing controllers are needed to keep boiler's subsystems at desired operation points during excessive transient operations.

Obvious targets for improved stabilizing controls are the drum level control and the steam temperature control. The shrink and swell effect caused non-minimum phase type response of drum level will be increased due to the extensive utilization of boilers storage capacity. Besides the shrink and swell effect in the evaporator, feed water may start to boil in the economizer increasing the swelling effect in the drum. It is quite obvious that a conventional three element drum level control cannot handle this case satisfactorily. To be insensitive for extended shrinking and swelling in the drum, the level compensation of the three element controller should

be tuned so slow that the controller would not be capable to operate satisfactory during load ramping. Thus, an improved feed water control system for the boiler is required.

The other expected problem is superheated and reheated steam temperature controls. Conventional cascade structure with feed forward compensation from fuel feed cannot handle temperature control when steam flow is changing due to pressure change in the evaporator. In the first step, steam temperature drop caused by increased steam flow should be compensated by reducing attemperation flows. The size of temperature drop is increased due to the situation that heat power released in the furnace is not increased along with the increased evaporation. In the second step, when combustion control starts to increase the fuel feed due to pressure drop in the boiler, the attemperation flows should again be increased to compensate the effect of increased thermal power to superheaters. A successful control of this type of operation is not possible with the conventional cascade control structure, but more advanced method is required. Overfiring of the boiler during load ramping make this even more difficult due to nonlinearly changing temperature distribution to different heat exchangers in the furnace and flue gas passes.

Dynamically faster combustion control will effect to combustion air control, emission control and furnace pressure controls. Their operation should be improved to keep the process on its optimal operation trajectory. In practice, this means that the whole control system must be redesigned for the improved dynamic performance of steam boilers.

## 7. CONCLUSIONS

Increased requirements for the dynamic performance of steam power plants put the requirements for boiler control design in a totally new framework. Improved load change rate capacity is produced by utilizing the internal energy storages of the boiler and improved combustion control for flexible production of thermal power. The improved load tracking control is a trade-off between load change rate, expected life time of the power plant, thermal efficiency of the generation, and harmful flue gas emissions produced from the process. To be able to manage all these issues, an advanced coordinating control system is needed to optimize and coordinate the operational objectives of all sub processes involved with the power plant operation.

The focus of this paper was to analyse the usability of boiler's storage capacity for quick responding first step load changes of a drum boiler. Dynamic effects of drum pressure changes induced additional generation of live steam that was evaluated against the restrictions set by thermal stressing of boiler and turbine components. The result was that the effects caused by a 5% pressure change from nominal value have no major impact on the expected life time of process components. Even a 10% pressure change could be possible. The limiting factor for the utilization of boiler's storage capacity is the performance of stabilizing control loops keeping the process in the devoted operation point. Extended use of boiler's energy storages and fast wide range load ramp control requires a totally new design both for coordinating and stabilizing control levels.

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