COMBO-CFB: INTEGRATION OF CONCENTRATED SOLAR POWER WITH CIRCULATING FLUIDIZED BED POWER PLANTS

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Abstract – This paper addresses the problem of solar and conventional combustion thermal power plant integration. A brief overview of the achievements of a related project named COMBO-CFB is given, and (as one of the project's outcome) a general mathematical framework is presented which is to be utilized for process design including control aspects relying on the dynamical behavior of the hybrid plant. An application of the introduced approach is considered for a simple OTU boiler.

INTRODUCTION

In future's energy production portfolio renewable energy will occupy a significant share as energy production based on renewables represent a promising alternative towards the implementation of the "green living" which targets low (possibly zero) emissions and low ecological footprint. However, the trend adopting the green energy faces the fact that today's energy production is heavily governed by conventional combustion based units, hence the interaction between traditional and renewable production i.e. the hybridization is gaining much attention. A hybrid plant running on two different energy sources in synergy has unquestionable advantages over the standalone technologies. It solves the problem related to the intermittent (uncertain) nature of the renewable source while reduces the carbon footprint of the traditional power plant supporting the reach of the new emission performance standards just to mention few.

Among renewable sources, solar power has one of the greatest potential which is well supported by the rapid increase of Solar Thermal Power Plant installations worldwide. Solar thermal energy can be integrated into a conventional power plant at multi-points and multi-levels utilizing Concentrated Solar Power Technology (CSP). As outlined, the hybrid combines the advantages of the two different technologies: traditional Rankine cycle with relatively higher efficiency and concentrated solar power with relatively low temperature range. Having some overview on the key benefits, on the other hand, it must be emphasized that although the related standalone technologies are mature enough, hybridization involve numerous challenges related to (process) design and control.

The project entitled COMBO-CFB (Combination of Concentrated Solar Power with Circulating Fluidized Bed Power Plants) aims to provide methods and tools for the process design and control of the hybrid plant. The aim of this paper is (a) to give a brief summary of the results achieved under the COMBO-CFB project and (b) to introduce a process design approach which incorporates control aspects utilizing the dynamics of the hybrid plant. Besides theoretical considerations an application of the proposed approach for a simple OTU boiler is presented.

COMBO-CFB PROJECT – A BRIEF OVERVIEW

A project entitled COMBO-CFB funded by the Finnish Funding Agency for Technology and Innovation (TEKES) aims to provide methods, tools for the process design and control of the integrated plant to analyze and further improve interactions between intermittent renewable power generation and traditional power plants. The project is energized by the following goals: (a) increase centralized renewable solar energy that can operate with base and peak loads, utilize existing infrastructure and balance the distributed intermittent production (b) meet the new emission standards especially CO2 for power plant concepts (420-550 gCO2/kWh → combination of biomass, solar and gas with coal) (c) increase the share of intermittent renewable energy production (solar & wind) for better load change capabilities combined with maximal efficiency and low emissions throughout whole load range of traditional solid (fossil fuel) power plants (d) secure the competitive position of Finnish industry and manufactures related power plant ecosystem.

The project scheduled form 03/2014 - 12/2016 involved a close collaboration between the industrial partners: Foster Wheeler Energia Oy, Vaisala Oy, Telog Oy, Pöyry Oy, and research units VTT Finland, University of Oulu (Systems Engineering Research Group). The research and development work carried out under COMBO-CFB has been centered on the following topics: (a) modeling and simulation (Hakkarainen *et al.*, 2015a, Hakkarainen *et al.*, 2015b, Hakkarainen and Tähtinen 2015, Suojanen *et al.*, 2017) (b) forecasting (Hakkarainen *et al.*, 2015c) (c) control (Mikkonen *et al.*, 2016) (d) process design, integrated process and control design (Selek *et al*., 2016). A summary of the research outcomes is provided in (Suojanen *et al*., 2016).

Regarding integrated process and control design a general mathematical framework was derived which is to be utilized for process design including control aspects relying on the dynamical behavior of the hybrid plant. The derivation of this approach is considered throughout this paper.

SOLAR-COMBUSTION THERMAL PLANT INTEGRATION PRINCIPLE

In this section the key idea of plant hybridization is presented. First, the process of interest is introduced and later controllability aspects are addressed.

As work principle, thermal power plants implement the Rankine cycle which is utilized to convert heat to electric power. Considering water as work fluid, the cycle begins with the pumping unit which maintains the desired pressure and flow conditions. After pressurization the water is directed towards the steam generation unit where external heat is added and absorbed by the water producing high pressure high temperature steam which leaves the unit. The produced steam is passed through the turbine which drives the electric generator. After the generator the steam is condensed and the water leaving the condenser enters the pumping unit closing the cycle (see Figure 1).

In a hybrid configuration, the heat supplied to the steam generation unit is provided by two different sources: (a) furnace unit which produces heat by releasing the chemical energy of a given fuel through combustion and (b) a solar plant which directly utilizes the solar irradiation as energy source. Considering certainty, the furnace is recognized as a certain heat source (assuming that fuel is available) while in contrast, the solar share is considered as uncertain due to the intermittency of the solar irradiation and volatility of the weather conditions. The schema of the integrated solar-combustion thermal plant is depicted in Figure 1.

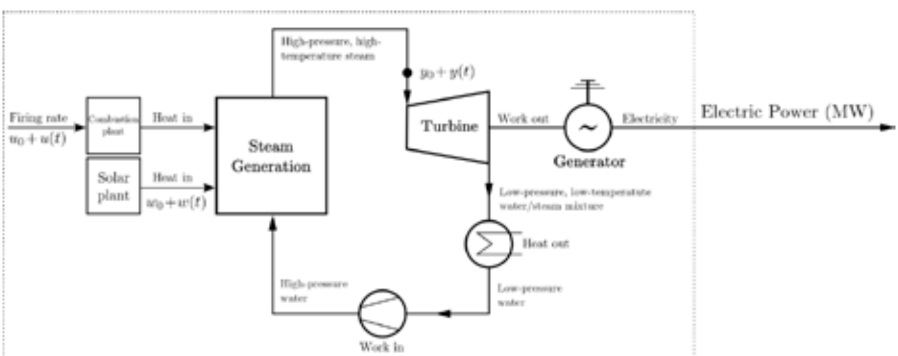

Fig. 1. Integrated solar-combustion thermal power plant

Thinking on the scale of fine details obviously there are numerous process configurations (designs) which can be considered for the hybrid plant. However, irrespective of the actual layout (topology) of the hybrid the operating principle is as follows: the nominal operation u_0 of the combustion unit together with the nominal heat output form the solar plant w_0 produces a given (nominal) steam "quality" y_0 at the inlet of the turbine. The physical units of the variables are problem dependent, however at this point the roles of the variables are to be fixed that is, u is considered as the manipulated variable, it determines the heat output of the furnace. Variable w describes the heat output of the solar plant and y denotes steam properties at the inlet of the turbine. From systems engineering perspective u and w are considered as process inputs while y is the process output which is determined by the inputs through a map (model). Regarding the solar share the following assumption is formulated:

Assumption 1. The heat output of the solar plant is varying (on a minute, hour timescale) subject to the conditions of solar irradiation.

This assumption highlights the main emphasis of this particular approach, that is, solar plants with supplementary role which cannot operate as standalone units (e.g. due to insufficient heat storage capacity) are the main focus for hybridization. Based on assumption 1, the output of the solar plant w is treated as a "disturbance" where the disturbance signal $w(t)$ describe the deviation form nominal condition w_0.

In this particular framework we focus on the nominal operation of the hybrid plant where - despite the changing conditions of solar irradiation - steady electric power production is desired. Steady production is assured by maintaining the nominal steam "quality" at the inlet of the turbine which requires that the deviation form nominal condition is zero i.e. $y(t) = 0$. Since the process output $y(t)$ is affected by both inputs $u(t)$ and $w(t)$ the effect of disturbance (changing conditions of solar irradiation) is to be compensated by the operation of the furnace such that the process output remains unchanged (i.e. nominal steam conditions are maintained at the inlet of the turbine).

In what follows, the certainty properties of the different heat sources magnify the need for proper control design for the integrated process. In this context integration may be viewed as introducing an uncertain heat source to a water-steam cycle empowered by a furnace where steady electrical power production is desired. Considering dynamic aspects, hybridization introduces and additional role to the process control which is required to handle the "disturbance" determined by the solar share to the thermal cycle.

Utilizing this controllability concept as an integration principle it is essential to understand that, the "effort" required to compensate the effect of disturbances is highly affected by the topology (design) of the integrated process. For example a solar power shut-down due to weather conditions requires less prominent reaction form the furnace (which means less fuel to be burnt and less emissions) for one particular process design than for the other due to the fact that the dynamic behavior of the different designs are different. With that said, the proposed principle for solar-combustion thermal plant integration is as follows:

The hybrid process to be designed so that the effort required by the operation of the furnace to compensate the effect of disturbances posed by the solar plant is minimal.

The key idea of the presented principle is to utilize the dynamics of the process for design. Given the design principle the related mathematical framework is introduced in the next section.

PROBLEM FORMULATION

In this section the mathematical problem related to process design considering control aspects is formulated. The mathematical model of the process around nominal conditions (u_0, w_0, y_0) is assumed to have the following form

$$y = F_\theta\langle u, w\rangle \tag{1}$$

where $F_\theta\langle . \rangle$ is a nonlinear, well-defined, one-to-one operator, $u(t)$ is the manipulated input of the process, $w(t)$ is the disturbance and $\theta \in \Omega$ is the design parameter describing the admissible configurations of the hybrid plant. To be able to formulate a meaningful mathematical problem let $\dot{u}(t)$ and $\dot{w}(t)$ are considered as process inputs. Using these, (1) becomes

$$y = F_\theta\langle I\dot{u}, I\dot{w}\rangle \tag{2}$$

where I defines the integral operator

$$(Ix)(t) := \int_0^t x(\tau)\, d\tau \tag{3}$$

In this context $\dot{u}$ and $\dot{w}$ can be interpreted as the time derivative of u and w signals. Regarding (2) the following assumption is formulated

Assumption 2. For the process model $y = F_\theta\langle I\dot{u}, I\dot{w}\rangle$ there exists a feed-forward compensator $\dot{u} = C_\theta\langle \dot{w}\rangle$ such that $F_\theta\langle (I \circ C_\theta)\dot{w}, I\dot{w}\rangle \equiv 0$ for all $\dot{w} \in W$.

The set W describes the domain of admissible (physically meaningful) disturbance signals. Assumption 1 ensures that the effect of solar heat share (for example a power drop) on the steam generation can be compensated by the operation of the furnace. Likewise, the analysis of the properties of the feed-forward compensator is of primary interest since this provides the coupling between the disturbance and compensator signals. Let us define the energy/effort of a signal (in notation $\|.\|_2$) as follows

$$\|x\|_2 := \left(\int_0^{\infty} x^2(t)\,dt\right)^{1/2}, \tag{4}$$

which is otherwise recognized as L2 norm. Using this, we are interested to examine the energy/effort balance of the feed forward compensator over the design parameter space Ω of the hybrid plant. Regarding this, let us consider the following scenario: given a disturbance signal $\dot{w}$ which effect on the process output (due to the feed-forward compensator) is cancelled by the input signal $C_\theta\langle\dot{w}\rangle$, that is, a signal with $\|\dot{w}\|_2$ energy is compensated by the corresponding effort $\|C_\theta\langle\dot{w}\rangle\|_2$. In this context, the fraction $\frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2}$ (referred to as L2 gain) describes how much the energy of the disturbance signal is required to be magnified by the feed-forward compensator to have its effect cancelled. Since the L2 gain (so as the feed-forward compensator) is the function of the design parameter θ it is natural to formulate the following question: which one of the process configurations minimize the L2 gain?

In real life however the disturbance cannot be characterized by a particular signal (disturbance cannot be forecasted with high accuracy). Correspondingly, in problem formulation the minimization of the L2 gain is performed over a set of disturbances W. To ensure that the problem is meaningful (e.g. disturbance signal has finite energy) the following assumption is considered:

Assumption 3. $W \subset L^2\backslash 0$, that is $\|\dot{w}\|_2$ is finite (well-defined) for all $\dot{w} \in W$.

The notation L^2 refers to the space of square integrable functions. We are interested to find the process parameters such that the disturbance can be compensated by minimal energy/effort. With that said, the corresponding mathematical problem is

$$\begin{aligned} \underset{\theta}{\text{minimize}} \quad & \left(\inf \frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2}, \left(\sup \frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2} - \inf \frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2}\right)\right) \\ \text{subject to} \quad & F_\theta\langle (I \circ C_\theta)\dot{w}, I\dot{w}\rangle \equiv 0 \\ & \dot{w} \in W,\ \theta \in \Omega \end{aligned} \tag{5}$$

Due to the fact that we are not dealing with one particular disturbance but rather a set of disturbances, the problem is formulated in a multi-objective manner where the primary objectives are (a) to minimize the best achievable L2 gain and (b) to minimize the "range" of the L2 gain over W.

APPROXIMATE PROBLEM

Rendering the solution to the outlined optimization problem is a challenging task. Depending on the complexity of the process model (1), the problem can be computationally intractable. In this section an approximate solution to the defined optimization problem is proposed. At first, the process dynamics is approximated by linear models as follows:

$$F_\theta\langle u, w\rangle \approx S_\theta^u u + S_\theta^w w \tag{6}$$

where S_θ^u and S_θ^w well-defined, one-to-one linear operators representing time invariant systems for all $\theta \in \Omega$. It is assumed that (6) well approximates the dynamics of the system around nominal conditions. With this assumption the feed-forward compensator is a linear (time invariant) operator as well, having the following form

$$C_\theta = -((S_\theta^u \circ I)^{-1} \circ (S_\theta^w \circ I)) \tag{7}$$

where $(.)^{-1}$ denotes the inverse map. Putting these together the approximate problem is defined as follows:

$$\begin{aligned} \underset{\theta}{\text{minimize}} \quad & \left(\inf \frac{\|C_\theta \dot{w}\|_2}{\|\dot{w}\|_2}, \left(\sup \frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2} - \inf \frac{\|C_\theta\langle\dot{w}\rangle\|_2}{\|\dot{w}\|_2}\right)\right) \\ \text{subject to} \quad & C_\theta = -((S_\theta^u \circ I)^{-1} \circ (S_\theta^w \circ I)) \\ & \dot{w} \in W, \theta \in \Omega \end{aligned} \tag{8}$$

CALCULATION OF THE OBJECTIVES

To render the solution to the approximate problem, the calculation of the objectives (L2 gain limits) for any $\theta \in \Omega$ is necessary. Since (8) is formulated such that the process dynamics is approximated by linear time invariant systems, the operator domain (Laplace transform) is exploited for such calculation. Using the operator domain, the solution process relies on the Parseval's theorem which states that the Laplace transform is unitary, that is, given a signal $x(t)$ in time domain and its Laplace transform $X(j\omega)$, then $\|x\|_2 = \|X\|_2$. Let $\hat{C}_\theta(j\omega)$ denote the Laplace transform of the feed-forward compensator. Applying Parseval's theorem we get,

$$\|C_\theta \dot{w}\|_2 = \left(\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\hat{C}_\theta(j\omega)\dot{w}(j\omega)\right|^2 d\omega\right)^{1/2} \equiv \left(\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\hat{C}_\theta(j\omega)\right|^2|\dot{w}(j\omega)|^2 d\omega\right)^{1/2} \quad (10)$$

where it is easy to see that

$$\inf\left|\hat{C}_\theta(j\omega)\right|\left(\frac{1}{2\pi}\int_{-\infty}^{\infty}|\dot{w}(j\omega)|^2 d\omega\right)^{1/2} \le \left(\frac{1}{2\pi}\int_{-\infty}^{\infty}\left|\hat{C}_\theta(j\omega)\dot{w}(j\omega)\right|^2 d\omega\right)^{1/2} \le \sup\left|\hat{C}_\theta(j\omega)\right|\left(\frac{1}{2\pi}\int_{-\infty}^{\infty}|\dot{w}(j\omega)|^2 d\omega\right)^{1/2} \quad (11)$$

Putting (10) and (11) together we get

$$\inf\left|\hat{C}_\theta(j\omega)\right| \le \frac{\|C_\theta \dot{w}\|_2}{\|\dot{w}\|_2} \le \sup\left|\hat{C}_\theta(j\omega)\right|, \quad \dot{w} \in W \quad (12)$$

It is well known that there exist signals for which the L2 gain is arbitrary close to the lower and upper boundaries defined by (12). Using this formula, the objectives for any $\theta \in \Omega$ are calculated by deriving the Laplace transform of the corresponding feed-forward compensator and calculating the infimum and supremum of its amplitude gain. In most of the cases, the Laplace transform of the feed-forward compensators is derived numerically.

BENCHMARK SYSTEM – SIMPLE OTU BOILER

The outlined approach was applied to simple OTU boiler model depicted in Figure 2. The boiler model consists of a water pump, a tube (circular pipe) and a turbine utilizing water as work fluid. The water pump is located at the inlet of the tube providing the desired pressure and flow conditions empowering the water/steam flow form the pump towards the turbine. The parameters specifying the geometry, mechanical, physical and thermodynamic properties are non-varying, e.g. pipe diameter, flow area, pipe wall thickness, heat exchange coefficients, etc. are considered as constant alongside the tube.

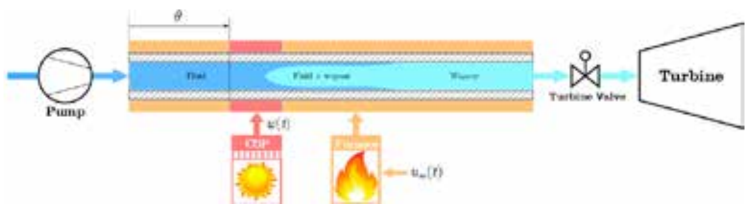

Fig. 2. Simple OTU boiler

The water/steam in the tube is in thermal interaction with the surrounding material (tube wall) and indirectly with the environment which consists of two different heat sources: (a) heat from furnace (brown) and (b) heat from a CSP plant (red). The heat sources interact with the tube on its total outer peripheral assuming a uniform heat flux (kW/m^2) under nominal conditions.

In this setup, the position of the CSP heat share (denoted by) is considered as design parameter. The magnitude of the heat flux provided by the furnace is considered as manipulated variable $u(t)$, while the magnitude of the heat flux of the CSP plant is treated as disturbance $w(t)$. The quality of the steam at the inlet of the turbine is quantified by its "power content" i.e.

$$y(t) := \dot{m}_{\text{out}}(t)h_{\text{out}}(t) \text{ (kW)} \quad (13)$$

where $\dot{m}_{\text{out}}$ (kg/sec) and h_{out} (kJ/kg) are mass flow and enthalpy of the steam respectively at the outlet of the tube.

The corresponding mathematical model (1) implements the two equation flow model representation (including mass and energy conservation) with finite volume approach. The tube is uniformly divided to 100 control volumes, the length of the solar share is considered to be 5% (i.e. 5 control volumes). Using this, the feedforward compensators for disturbance cancellation are determined numerically for the approximate problem, such that, the boundary conditions (water mass flow, temperature, enthalpy at the inlet and steam pressure at the outlet), pump speed and turbine valve opening degree remains unchanged.

The parameters of this simple model were determined by averaging out the corresponding parameters of an accurate process model which was implemented in APROS environment (e.g. the wall thickness of the tube represents the average wall thickness of the water pipes of the detailed OTU model).

RESULTS

The outlined optimization problem was numerically rendered for subcritical (40% load) and supercritical (80% load) operation modes. Since the corresponding problem has a one dimensional design variable the optimization problem was solved by enumeration i.e. utilizing the discretization scheme the L2 gain boundaries were calculated for each particular location. The disturbance set W characterizes the set of mathematically meaningful disturbance signals.

Figures 3 and 4 depict the L2 gain extremes (min and max) versus the position of the solar heat share. The design parameter is normalized; the variable *position* (%) indicates the location of the solar heat share alongside the tube.

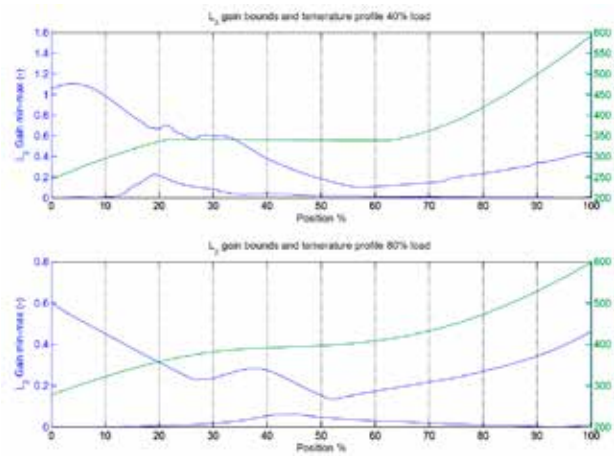

Fig. 3. Extremes of the control effort as a function of the position of solar share and the nominal temperature distribution of water-steam alongside the tube for subcritical (top) and supercritical (bottom) conditions

The result presented in figure 3 can be interpreted as follows: regarding the position of the solar heat share the effort required to compensate the effect of a given (mathematically meaningful) disturbance signal lies between the blue curves, however the exact position between the boundaries (effort) depends on the actual realization of the disturbance signal. Using this, figure 4 depicts the best possible effort (Figure 4, left) and the range of the effort (Figure 4, right). The results presented on figure 4, (left) show that there exists disturbance signals which can be compensated by minimal effort in case the solar heat share is positioned at the inlet and outlet (95% of the total length) of the tube.

On the other hand, in real life it cannot be assured that only these particular disturbance signals are received form the CSP plant. Consequently, it is required that the compensation effort must be robust against a range of uncertainties. Focusing on robustness the range of the effort (L2 gain range) is of high importance.

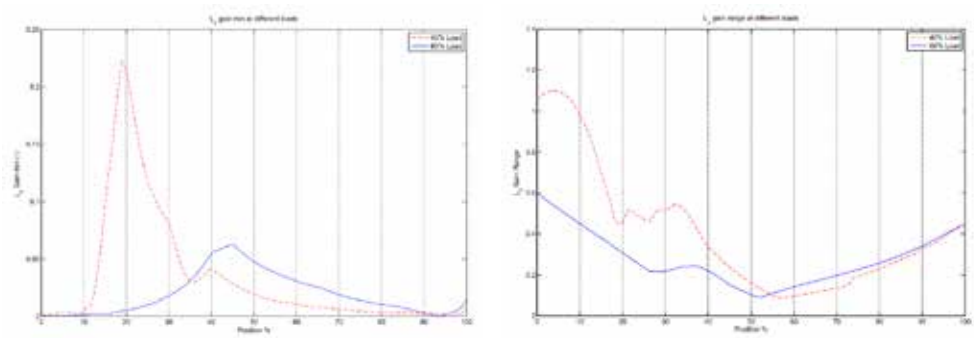

Fig. 4. Best achievable compensation effort (left) and range of the compensation effort (right) as a function of the position of the solar heat share alongside the tube

Figure 4 (right) shows that the range of the L2 gain is minimal if the solar heat share is positioned at (about) the middle (50% - 60% of the total length) of the tube while at other locations (especially at the inlet and outlet of the tube) the variation of the compensation effort is much higher. This practically means that at inlet and outlet locations the compensation effort might be very sensitive to the actual realization of the disturbance signal while at the middle of the tube this sensitivity is less significant. Furthermore it can be seen that, during the evaporation phase there are remarkable differences between sub and supercritical cases considering compensation effort (best achievable and range). The difference is less prominent when pure steam is present in the tube (~ 65 – 100% of tube length).

On the other hand, (as defined by the optimization problem) it is aimed to simultaneously minimize the best achievable and the range of the compensation effort. In the ideal case (0,0) is achieved which would mean that practically no effort is required to compensate the effect of the heat output fluctuations of the CSP plant regardless of the realization of the disturbance signal. On the other hand, figure 4 highlights that the best achievable and the range of the compensation effort are conflicting objectives, that is the improvement of one objective induces the deterioration of the other and vice versa.

In such case, it is not possible to declare one particular candidate solution (process configuration) as optimal. Indeed, finding a tradeoff between the objectives is of primary focus. Starting from the inlet of the tube, figure 5 plots the objectives for each particular discrete position.

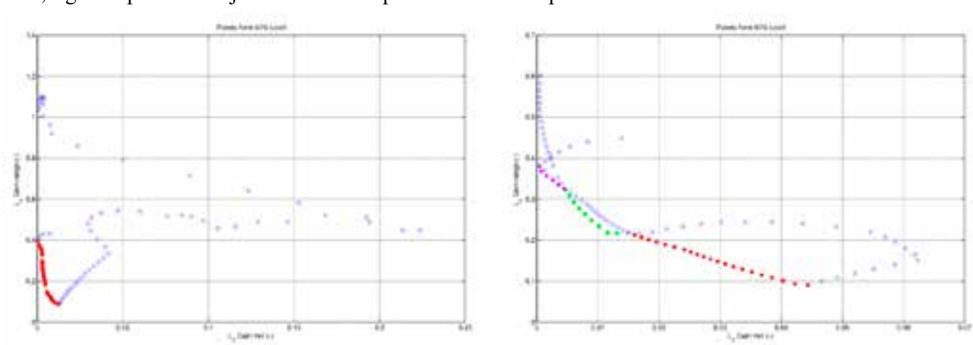

Fig. 5. Multi-objective plots of control efforts for subcritical (left) supercritical (right) conditions. The optimum in Pareto sense is colored.

Using the Pareto optimal solutions highlighted in figure 5, figure 6 depicts the corresponding optimal positioning of the solar heat share for subcritical and supercritical conditions. The results show that considering disturbance cancellation aspects the solar share should be positioned towards the end of the tube.

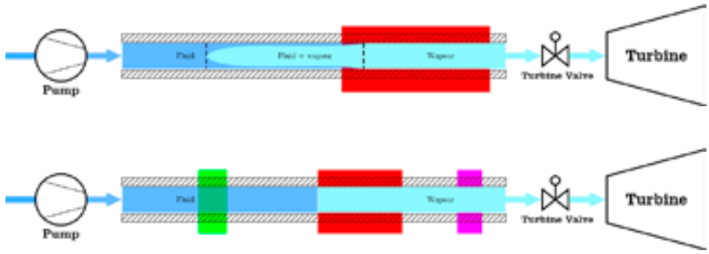

Fig. 6. Pareto optimal solutions for subcritical (top) and supercritical (bottom) conditions.

SUMMARY AND CONCLUSIONS

This paper addresses the problem of solar and conventional combustion thermal power plant integration. It provides an introduction and a brief summary of the results achieved under the COMBO-CFB project. Besides these, an application of an integrated process and control design approach developed under COMBO-CFB for once through boilers was presented applying a control oriented model. The approach provides guidelines for the design of the integrated process including control aspects utilizing the dynamics of the underlying process.

The proposed approach was applied to a simple OTU boiler model involving a process design problem: the positioning of the solar heat share of a once-through hybrid plant alongside a tube. Due to the simplicity of the model the obtained results are preliminary however surprising and unexpected as well. The Pareto optimality criteria of the corresponding optimization problem revealed that the solar heat share should be positioned to the middle, preferably towards the outlet of the tube which is somehow completely against the engineering intuition. All things considered the presented approach seems to have a potential but requires further development and examination on more realistic models.

ACKNOVLEDGEMENTS

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