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# Close loop optimisation of large CHP based on approximation model

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**Abstract.** Complex optimization of CHP plants becomes a very important issue in research and implementation, particularly in the context of increasing environmental requirements. The process in industrial CHP plants could be decomposed into several subprocesses, which could be optimized individually using dedicated solutions. The article presents the results of work of complex, multi-modular optimization project of one CHP plant located in petrochemical and refinery plant in Poland. The scope of the project is economical load dispatch optimizer aimed to increase economical profit of CHP operation, combustion optimization for boiler efficiency increase and NOX emission reduction, steam temperature advanced control for improved control quality, sootblowing optimization for reduction of steam demand for sootblowing process. The solution includes also measurement validation and correction system, which is based on data reconciliation algorithm and on-line performance monitoring system.

## 1 Introduction

The fossil fuel heat and power generation industry faces nowadays demanding environmental regulations as well as accent on economical profit. Both conditions request investments in modernization of exiting plants in terms of low emission and emission reduction technologies like new burners or air staging, flue gas desulfurization and selective catalytic or no-catalytic reduction of NOX emission. From economical profit point of view steam generation boilers and steam turbines are modernized in the way to reduce losses and to improve efficiency of the process. Once either industrial CHPs or municipal CHPs reach a high level of modernization with best available technologies new solutions for better utilization of the plants are applied. In most model based advanced control and optimization software solutions are used.

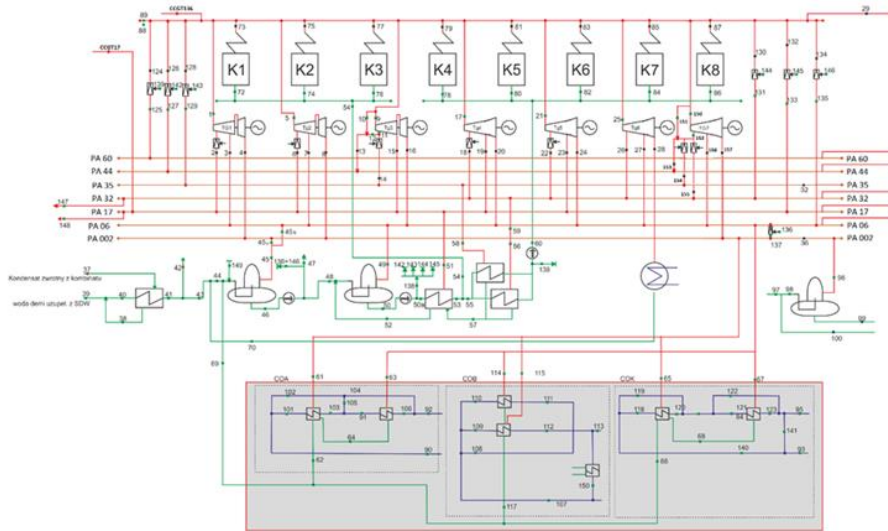
This paper presents solution and implementation results of model based advanced control and optimization in PKN Orlen CHP plant located in refinery and petrochemical plant in Plock, Poland. Design of the solution responds to design of the CHP plant and, in most, conditions of process steam supply. The process in the plant had been decomposed into subprocesses, where a benefit could be achieved, so the solution integrates the economical load dispatch optimizer, combustion optimizer, steam temperature advanced control, sootblowing optimizer, measurement validation and reconciliation system, performance monitoring system.

All systems in the solution operate in on-line mode. The economical load dispatch optimizer [0], [2], [3] is a closed-loop system, that based on the thermodynamic and economical model of the plant calculates load demand individually for boilers and turbines, to improve

economical profit of the plant. In other words the system maximize electricity generation and minimize fuel consumption. The combustion optimization system [4], [5] is a closed-loop system that, based on the combustion empirical model calculates proper amount of air and air distribution. Goal of the system is to maximize boiler efficiency and minimize NOX emission, while respecting constraints of key process parameters like steam temperatures and O<sub>2</sub> content in flue gases. The steam temperature advanced control [6] is to improve control quality of steam temperatures, what means minimize difference of steam temperature and its setpoint. The sootblowing optimizer [7], [8] operates in advisory mode and the goal of the optimization is to save steam for sootblowing process, what consequently saves fuel energy. The measurements validation and reconciliation system [9] is the system, that monitors mass and energy flow and correct the measurements in the way to have balanced mass and energy of the plant as well as individual units like boilers, turbines pressure reduction stations etc. The performance monitoring system is on-line system, that based on measurements calculates key performance parameters of the process like boiler and turbine efficiency, boiler losses, turbine performance coefficients etc.

## 2 The CHP plant description

The Orlen CHP plant is located in refinery and petrochemical plant in Plock, Poland. It is composed of eight oil and gas boilers and seven steam turbine generators.



**Fig. 1** - The CHP plant model

Three boilers are with the capacity of 320 t/h and five boilers are with the capacity of 420 t/h of steam generation. All boilers are able to fire simultaneously different types of oil and gas fuels.

The boilers are equipped with twelve burners, installed in there vertical levels on all four walls. Most burners are able to fire either oil or gas fuel. The steam temperature is controlled by attemperators installed on left and right side before second and third superheaters of each boiler. Boilers are equipped with sootblowing system and sootblowers are installed on steam superheaters, SCR, economizer and air heaters.

The are 6 extraction-backpressure turbines and one extraction-condensing turbine with capacities ranging from 320 t/h of inlet steam flow and 55 MW to 420 t/h of inlet flow and 70 MW. All turbines are able to control MW. Turbines 1, 2, 4 and 5 are able to control pressure on second extraction and on outlet. Turbines 3, 6, and 7 are able to control pressure on first and second extraction and on outlet. Simplified model of the CHP plant is presented in the **Fig. 1**.

The model presents boilers, process steam collectors and pressure of each, turbines extractions pressure and feedwater system.

The main purpose of the CHP plant is to satisfy demand of process steam. Number of boilers, turbines and steam reduction stations in operation depends on process steam demand but considering ability of responding of rapid changes of process steam demand. In other words the CHP plant must be ready, at any time to reduce or increase load according to demand of the process steam.

### 3 The economical load dispatch optimization

The economical load dispatch optimizer is aimed to control the CHP plant in closed-loop mode to maximize the economic profit of the plant operation. The system composes of three main components: thermodynamic and economic model of the plant, calculation engine for

searching optimal solution graphical user interface for system tuning and monitoring. The model is a combination of first-order thermodynamic model, where mass and energy balance is modelled and empirical models of efficiency of boilers and turbines. Efficiency of boilers and fuel demand is calculated with the following formulas:

$$\eta = f(t, m) \quad (1)$$

$$Q_b = \frac{m(i_{steam} - i_{water})}{3600} \quad [MW] \quad (2)$$

$$Q_{fuel} = \frac{Q_b}{\eta} \quad [MW] \quad (3)$$

where:

- $\eta$  – boiler efficiency [-],
- $t$  – ambient temperature [°C],
- $m$  – steam generation [t/h],
- $Q_b$  – boiler heat demand [MW],
- $i_{steam}$  – enthalpy of steam generated [kJ/kg\*K],
- $i_{water}$  – enthalpy of feed water [kJ/kg\*K],
- $Q_{fuel}$  – fuel demand [MW].

Turbine performance coefficients and turbine power are calculated with the following formulas:

$$u1 = f(m_{in}, m_{out}, i_{in}, m_{u2}) \quad (4)$$

$$u2 = f(m_{in}, m_{out}, i_{in}, m_{u2}) \quad (5)$$

$$out = f(m_{in}, m_{out}, i_{in}, m_{u2}) \quad (6)$$

$$eff = f(m_{in}, m_{out}, i_{in}, m_{u2}) \quad (7)$$

$$P_{el} = \left( \frac{m_{u1}}{u1} + \frac{m_{u2}}{u2} + \frac{m_{out}}{out} \right) * eff \quad (8)$$

where:

- $m_{u1}$  – steam flow at first extraction [t/h],
- $m_{u2}$  – steam flow at second extraction [t/h],
- $m_{out}$  – steam flow at outlet [t/h],
- $m_{in}$  – steam flow at turbine inlet [t/h],
- $i_{in}$  – enthalpy of steam at inlet [kJ/kg\*K],
- $u1$  – performance parameter at first extraction [t/MW],
- $u2$  – performance parameter at second extraction [t/MW],
- $out$  – performance parameter at outlet [t/MW],

$eff$  – turbine mechanical efficiency [-],  
 $P_{el}$  – power generation [MW].

The economical model is expressed by the following formula:

$$Income = \sum_i P_{ee} \cdot P_{el}^i - \sum_j P_{fuel} \cdot Q_{fuel}^j \quad (9)$$

where:

$P_{ee}$  – electricity price [PLN/MWh],  
 $P_{el}^i$  – energy production of i-th turbine [MWh],  
 $P_{fuel}$  – fuel price [PLN/MWh],  
 $Q_{fuel}^j$  – energy in fuel demand of j-th boiler [MWh].

Every optimization step the calculation engine searches for a solution that on one hand satisfies the demand of process steam and on the other hand is most effective from economical point of view. The calculation engine is based on constrained optimization by linear approximation – COBYLA. The COBYLA algorithm is numerical optimization solution for the problems that have constraints and derivative of the goal function is not known. The algorithm is designed to solve non-linear problems with linear approximation. The goal function of the economical load dispatch is non-linear because the empirical models of boiler efficiency are second degree polynomials and models of turbine performance coefficients are third degree polynomials. Optimization is executed every 60 seconds. A solution for certain optimization step is a vector of load individually boilers and turbine's extractions and outlets. The solution must fulfill certain conditions like:

1. To satisfy the demand for process steam,
2. To satisfy minimum and maximum constraints for boiler load,
3. To satisfy minimum and maximum constraints for turbine extractions and outlet flow – distinguishing between extractions/outlets in pressure control mode and extractions/outlets in standard mode, turbine inlet flow and turbine MW.
4. To satisfy maximum gas temperature at SCR inlet for each boiler.
5. To satisfy maximum pressure difference in live steam manifold.
6. To satisfy minimum and maximum load of power supply sections.

Once a solution is found control algorithm calculates values of boiler master control, turbine load and turbine valve positions in order to reach the optimum point. The control algorithm is based on PID algorithm. The control algorithm is significantly slower than tuning of PID controller of pressure in process steam collectors implemented originally in DCS logics. This design allows to reach optimal point without influencing process steam pressure significantly.

## 4 The combustion optimization

The task of the combustion optimization system is to perform an on-line optimization of a current process operating point. The optimizer is implemented above a base control layer, which is DCS. The system calculates setpoints or setpoints corrections for

controllers that operate in a base control layer. Control systems of processes in CHP plants are based on PI (Proportional-Integral) controllers. These controllers controls sub-processes that have an influence on a main optimized MIMO (Multi Input Multi Output) process (i.e. combustion process).

In specific the combustion optimization system is aimed to calculate proper amount of air for the combustion and air distribution. The goal for the system is to increase boiler efficiency and reduce NOX emission while considering a number of constraints. The system utilizes artificial intelligence algorithm, which is artificial immune system. The algorithm has self-learning and auto-adaptive abilities. The system is equipped with several algorithms but there are two main: learning algorithm and optimization algorithm. The learning algorithm is responsible for monitoring the combustion process and collecting knowledge about the process at certain operating point. This allows the optimization algorithm to work with the most updated knowledge. The optimization algorithm uses the knowledge database calculates linear model of the combustion process. Once a boiler changes operating point, for example load or fuel mix, the optimization algorithm automatically searches for new knowledge units that represent new operating point and basing on these calculate new model.

The optimisation module allows to define the goal function with the following formula. For each optimization signal the formula consists of two main parts linear and square. This feature allows to change optimization priority once one of optimization goals differ from the setpoint significantly. In other words, if value of one of optimization signals exceeds square insensibility level, the penalty of the signal increases over penalties of other signals significantly so the optimizer changes the priority order.

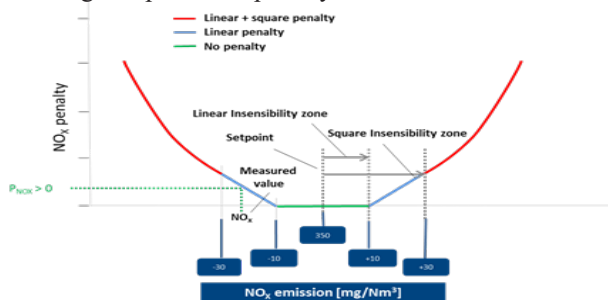
$$J = \sum_{k=1}^{n_m} \left[ \alpha_k (|\tilde{m}_k^c - \tilde{m}_k^c| - \tau_k^{lm})_+ \right] + \left[ \beta_k (|\tilde{m}_k^c - \tilde{m}_k^c| - \tau_k^{sm})_+^2 \right] + \sum_{k=1}^{n_y} \left[ \gamma_k (|\tilde{y}_k - \tilde{y}_k| - \tau_k^{ly})_+ \right] + \left[ \delta_k (|\tilde{y}_k - \tilde{y}_k| - \tau_k^{sy})_+^2 \right] \quad (10)$$

where:

$\alpha_k$  – linear penalty coefficient for k-th manipulated variable,  
 $\beta_k$  – square penalty coefficient for k-th manipulated variable,  
 $\gamma_k$  – linear penalty coefficient for k-th monitored process output,  
 $\delta_k$  – square penalty coefficient for k-th monitored process output,  
 $\tau_k^{lm}$  – insensibility zone for linear penalty for k-th manipulated variable,  
 $\tau_k^{sm}$  – insensibility zone for square penalty for k-th manipulated variable,  
 $\tau_k^{ly}$  – insensibility zone for linear penalty for k-th monitored process output,  
 $\tau_k^{sy}$  – insensibility zone for square penalty for k-th monitored process output,

$(\cdot)_+$  – “positive” operator  $(x)_+ = \frac{1}{2}(x + |x|)$ ,  
 $\tilde{m}_k^c$  – current value for k-th manipulated variable,  
 $\tilde{y}_k$  – current value for k-th monitored process output,  
 $\tilde{m}_k^d$  – demand for k-th manipulated variable,  
 $\tilde{y}_k^d$  – demand value for k-th o monitored process output.

The **Fig. 2** presents visual representation of example penalty function of NOX emission. The green zone is the range, within which no penalty is applied, so the parameter is within optimum point. The blue zone is linear penalty zone, which means the emission is either too low or too high, so optimizer calculates setpoint changes in the way to reduce the penalty. The red zone is square penalty zone, which elevates priority of certain signal automatically, so the optimizer focuses on reducing this particular penalty.



**Fig. 2** - Graphical presentation of penalty function

During optimization the optimization algorithm is searching for a solution with the following formula:

$$\min \left\{ \sum_{k=1}^{n_m} \left[ \alpha_k (|\tilde{m}_k^c + \Delta m^d - \tilde{m}_k^c| - \tau_k^{lm})_+ \right] + \sum_{k=1}^{n_y} \left[ \gamma_k (|\tilde{y}_k + \Delta m^d K_k - \tilde{y}_k| - \tau_k^{ly})_+ + \delta_k \left( (|\tilde{y}_k + \Delta m^d K_k - \tilde{y}_k| - \tau_k^{sy})_+ \right)^2 \right] \right\} \quad (11)$$

where:

$\Delta m^d$  – optimal change vector of manipulated variables,  
 $K_k$  – matrix of the automatically identified input-output gains of the process.

The  $K_k$  matrix represents static gains in mathematical model. It is automatically identified at each optimization period basing on the most recent knowledge gathered in the knowledge database.

The calculated change of manipulated variables must satisfy the following constraints:

$$\Delta m_{low}^d \leq \Delta m^d \leq \Delta m_{hi}^d \quad (12)$$

$$m_{low}^c \leq \tilde{m}^c + \Delta m^d \leq m_{hi}^c \quad (13)$$

where:

$\Delta m_{low}^d$  – low constrain vector of control variables in single optimization step,

$\Delta m_{hi}^d$  – high constrain vector of control variables in single optimization step,

$\tilde{m}^c$  – current values vector of control variables,

$m_{low}^d$  – low constrain vector of absolute values of control variables,

$m_{hi}^d$  – high constrain vector of absolute values of control variables.

First constrain formula refers to the allowable range of decision variable change in single optimization step and the second refers to absolute range of decision variable.

## 5 The steam temperature advanced control

The steam temperature advanced control system is a MPC solution, that is aimed to improve control quality of steam temperature. A significant change of controlled value could be caused by a change of disturbance signal – boiler load. The steam temperature advanced control is to minimize the side effect of changing boiler load. The system basing on dynamic model of the process calculates correction of setpoints of steam temperature control in on-line and closed-loop mode.

Standard control of steam temperature is based on two PID controllers working in cascade mode. The steam temperature advanced control calculates a correction of setpoint to the lower PID. The correction is calculated with the following formula:

$$\Delta u = - \frac{\sum_{i=1}^N G_{1,i} \Delta v_i}{G_2} = - \sum_{i=1}^N \frac{G_{1,i}}{G_2} \Delta v_i \quad (14)$$

where:

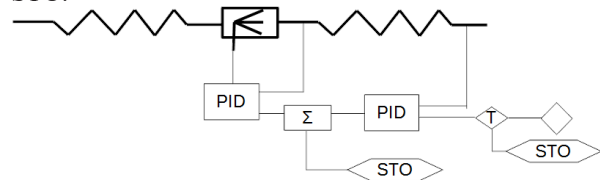
$\Delta u$  – correction of setpoint,

$G_1$  – transfer function of disturbance change e.g. load change,

$G_2$  – transfer function of control change e.g. PID setpoint,

$\Delta v$  – disturbance change e.g. load change.

The general effect of the steam temperature advance control is improved control quality of steam temperatures. The system calculates the control trajectory in the most efficient way to minimize control error. The PID is to balance inaccuracy of the model. Second goal for the system is to balance load of steam attemperators between two levels of steam control. The algorithm monitors if the second level of steam control is out of range, e.g. spray valves are closed and modifies the setpoint for first level of steam control, e.g. increases the temperature after the first attemperators. This feature of the system allows for better operation of the first algorithm. The **Fig. 3** presents design of base control change with steam temperature advance control signals – STO.



**Fig. 3** - Base control modification with steam temperature advanced control

One signal is a setpoint correction of lower PID and second signal is a replacement of setpoint of upper PID, which corresponds of two algorithms described above.

## 6 The sootblowing optimizer

The sootblowing optimization system is an advisory mode system that monitors the sootblowing performance and activates the sootblowing according to certain optimization goals. In a standard procedure, the sootblowing is activated every fixed period with all sootblowers. The main feature of the system is calculation and monitoring of heat fluxes of the boiler heat exchange sections and decide, when and which sootblowers to activate. The optimization goal is to maintain cleanliness of boiler heat exchange sections with lowest steam consumption for the sootblowing. The cleanliness factor is calculated as a ratio of current heat flux and the theoretical heat flux at current operating conditions and clean boiler sections. The current heat flux is calculated with standard thermodynamics laws basing on steam flow, temperature and pressure measurements. The theoretical heat flux is empirical models, that depends on boiler load, enthalpy of steam in to section and type of fuel.

$$CF = \frac{Q_{current}}{Q_{theoretical}} \quad (15)$$

$$Q_{current} = \dot{m}(H_{out} - H_{in}) \quad (16)$$

$$Q_{th} = f(\dot{m}, H_{in}, \frac{oil}{gas} ratio, oil\ type, gas\ type) \quad (17)$$

where:

$\dot{m}$  – steam flow kg/s,

$H_{wy}$  – enthalpy of steam out of section [kJ/kg],

$H_{we}$  – enthalpy of steam in to section [kJ/kg].

The sootblowing optimizer calculates the time for activation of two groups of sootblowers – steam superheater, SCR and economizer group of sootblowers and air preheaters group of sootblowers. The algorithm that calculates the time considers following conditions:

1. Minimize steam consumption for the sootblowing.
2. Maintain cleanliness of boiler heat exchange sections.
3. Minimize flue gas temperature at SCR.
4. Maintain general cleanliness of the boiler to not exceed limits for SCR temperature in case a rapid increase load of is needed.

The time is displayed on the process graphic, so operators are informed when to activate certain group of sootblowers. The time is calculated in on-line mode and could be adjusted if operating conditions are changing, e.g. boiler load change or fuel mix changed.

## 7 The measurement validation and reconciliation system

The measurement validation and reconciliation system is aimed to monitor and to correct measurements considering mass and energy balances, thermodynamics laws etc. Each measurement has an error. When considering a complex design of a plant with number of measurements a proper mass and energy balance is a challenge. This could be solved with the reconciliation algorithm.

The reconciliation algorithm calculates corrections of measurements or not measured values that, with the highest probability, are representing real values. The algorithm is basing on mathematical and thermodynamic model of the plant. Each measurement is described with a parameter that represents the accuracy of the measurements. The specific value of accuracy coefficient is defined considering quality of measurement and experience, but a good estimation would provide analysis of the standard deviation and the variance of the measurement. When estimating the accuracy the measurements are divided into three groups: top accuracy measurements which are MW measurements or steam flow measurements at CHP/plant connections, standard accuracy measurements which are superheated steam or water measurements, which accuracy is relatively high, low accuracy measurements which are wet steam measurements or the measurements with low reliability.

The reconciliation algorithm searches for a minimum of the following goal function:

$$J(\hat{y}, \hat{z}) = (y - \hat{y})^T V^{-1} (y - \hat{y}) \quad (18)$$

$$F(\hat{y}, \hat{z}) = 0 \quad (19)$$

where:

$y$  – raw measurements,

$\hat{y}$  – corrected measurements,

$\hat{z}$  – not measured values,

$V$  – covariance of measurements,

$F$  – conditions matrix – mass and energy equations.

Additionally, the system is equipped with algorithm for correcting raw measurements according to density. The density correction factor is calculated with the following formula:

$$c = \sqrt{\frac{\rho}{\rho_{cor}}} \quad (20)$$

where:

$\rho_{cor}$  – density at standard conditions,

$\rho$  – density at current conditions.

## 8 Results

The general goal of the project was to improve the efficiency/economical profit of operation of CHP plant with closed-loop and advisory mode with artificial intelligence, machine learning, model based IT solutions. Specific goals for specific systems were defined if the following way:

- Economical load dispatch:
  - 6 100 MWh increased electricity generation,
  - 56 000 GJ reduced fuel consumption.
- Combustion optimization with steam temperature advanced control:
  - 0.2% increased boiler efficiency,
  - 5-15% reduced NOX emission.
- Sootblowing optimization:
  - Boiler K2 – 8800 GJ reduced fuel consumption,
  - Boiler K5 – 5900 GJ reduced fuel consumption,
  - Boiler K7 – 5900 GJ reduced fuel consumption,

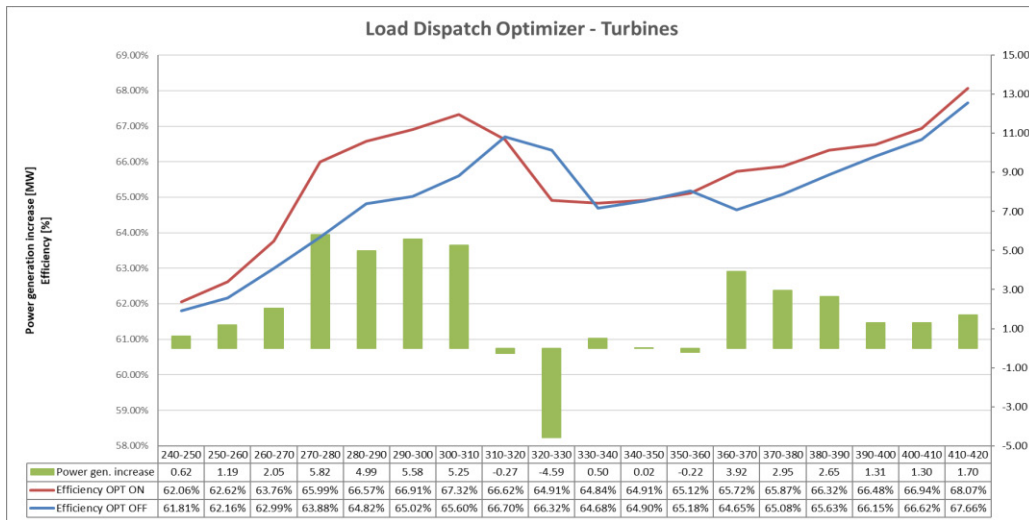


Fig. 4 - Economical load dispatch optimizer – turbines

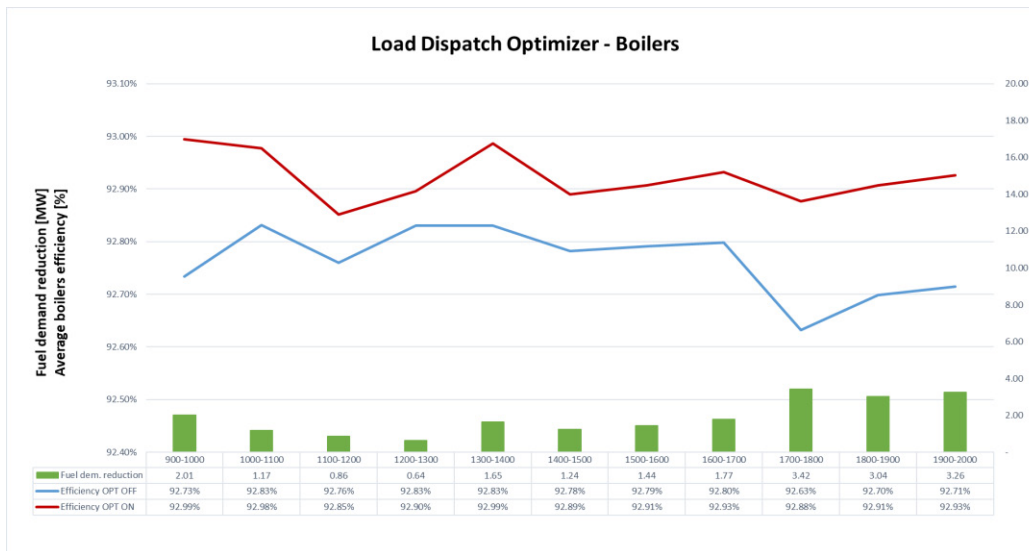


Fig. 5 - Economical load dispatch optimizer – boilers

### 8.1 The economical load dispatch optimization - turbines

The effects of economical load dispatch optimization are calculated based on historical data from central SCADA system for the period of January 2019 – June 2019. The Fig. 4 presents effect of the optimization on the turbines.

The optimization effect is calculated basing on analysis of average isentropic efficiency of all turbines T1-T7. The average isentropic efficiency is a ratio of total MW and total isentropic MW. The isentropic MW is a total of isentropic expansion and steam flow for each turbine’s extraction and outlet. The formula is presented below:

$$\eta_{isentr} = \frac{P_{CHP}}{P_{isentr}} \cdot 100\% \quad (21)$$

$$P_{CHP} = \sum_{i=1}^7 P_{MW_i} \quad (22)$$

$$P_{isentr} = [\dot{m}_{PA44} \cdot (i_{PA136} - i_{PA44_s}) + \dot{m}_{PA32} \cdot (i_{PA136} - i_{PA32_s}) + \dot{m}_{PA17} \cdot (i_{PA136} - i_{PA17_s}) +$$

$$\dot{m}_{PA06} (i_{PA136} - i_{PA06_s}) + \dot{m}_{PA002} \cdot (i_{PA136} - i_{PA002_s})] / 3600 \quad (23)$$

where:

- $\eta_{isentr}$  – average isentropic efficiency [%],
- $P_{CHP}$  – total CHP MW production [MW],
- $P_{isentr}$  – total isentropic MW production [MW],
- $P_{MW_i}$  – MW production of i-th turbine [MW],
- $\dot{m}_{PA44}$ ,  $\dot{m}_{PA32}$ ,  $\dot{m}_{PA17}$ ,  $\dot{m}_{PA06}$ ,  $\dot{m}_{PA002}$  – stem flow to certain process steam collectors PA44, PA32, PA17, PA06 and PA002 [t/h],
- $i_{PA136}$  – enthalpy of live steam [kJ/kg\*K],
- $i_{PA44_s}$ ,  $i_{PA32_s}$ ,  $i_{PA17_s}$ ,  $i_{PA06_s}$ ,  $i_{PA002_s}$  – enthalpy of steam of theoretical isentropic expansion PA44, PA32, PA17, PA06, PA002 [kJ/kg\*K].

As a result of optimization the average increase of isentropic efficiency increase 0.621%, what results 1.93 MW of higher MW production. The total increase of electricity generation annually is 16 245 MWh.

The highest result has been recorded for lower load of the CHP plant, but lower results are for within minimum and maximum range of total load of the CHP. This is influenced mostly by constraints, which limits optimization decisions for minimum and maximum load of the CHP.

### 8.2 The economical load dispatch optimization - boilers

The effects of economical load dispatch optimization for boilers are calculated based on historical data from central SCADA system for the period of January 2018 – June 2019. The presents **Fig. 5** effect of the optimization on the boilers.

The optimization effect is calculated basing on analysis of average efficiency of all boilers. The efficiency is calculated basing on polish and European standards – PN-EN 12952-15. The average boiler efficiency of the CHP plant is a weighted average of boiler load, calculated with the following formulas:

$$\eta_B = \frac{1 - \sum S_i^*}{1 + \frac{Q_{rad} + Q_{sootbl} - Q_{XL} \sum S_i^*}{Q_{use}}} \quad (24)$$

$$\eta_{avg} = \frac{\sum_{i=1}^8 \dot{m}_{Bi} \eta_{Bi}}{\sum_{i=1}^8 \dot{m}_{Bi}} \quad (25)$$

where:

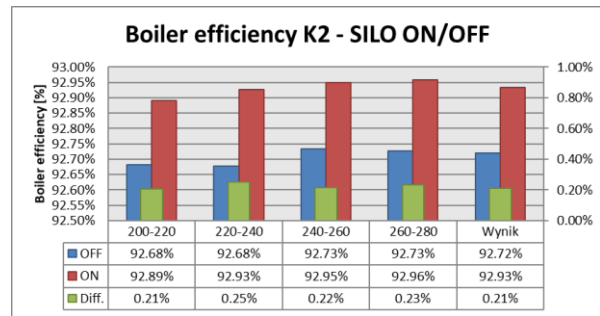
- $\eta_B$  – boiler efficiency [%],
- $\sum S_i^*$  – total boiler losses [kJ/kg\*K],
- $Q_{rad}$  – heat loss of the radiation [kJ/kg\*K],
- $Q_{sootbl}$  – heat loss for sootblowing [kJ/kg\*K],
- $Q_{XL}$  – heat to steam air heaters [kJ/kg\*K],
- $Q_{use}$  – useable heat [kJ/kg\*K],
- $\eta_{avg}$  – weighted average of steam generation [%],
- $\dot{m}_{Bi}$  – steam generation of i-th boiler [t/h],
- $\eta_{Bi}$  – boiler efficiency [%].

As a result of the optimization average increase of total boiler efficiency is 0.158% what results in 1.86 MW reduction of fuel demand. The total reduction fuel consumption annually is 56 421 GJ.

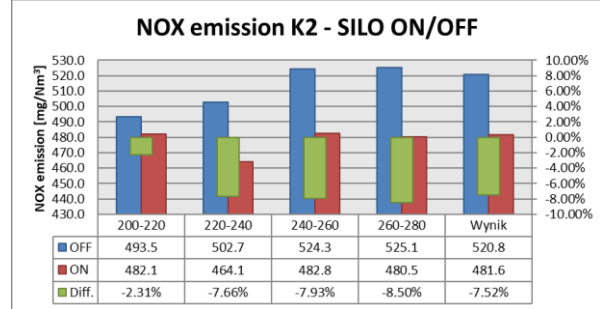
### 8.3 Combustion optimization

The effects of combustion optimisation for boilers are calculated based on historical data from central SCADA system for the period of January 2018 – June 2019.

The **Fig. 6b** presents effect on boiler efficiency and **Fig. 6b** presents effect on NOX emission of the combustion optimization for boiler K2.



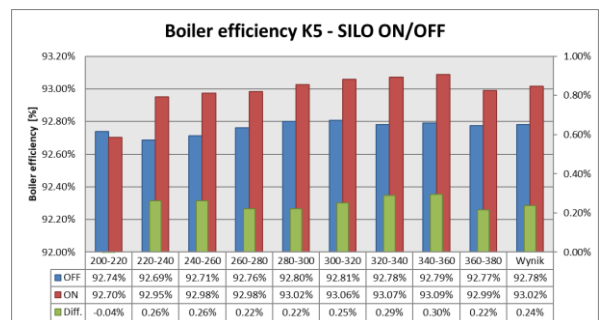
**Fig. 6a** - Combustion optimization for boiler K2 – efficiency



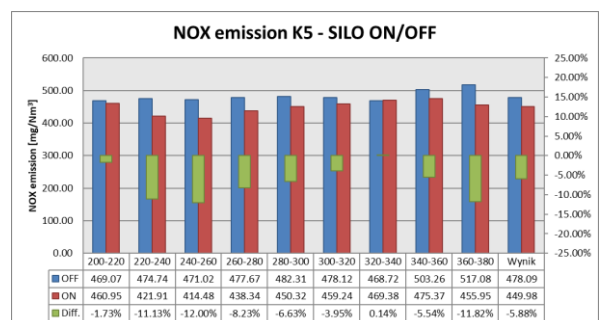
**Fig. 6b** - Combustion optimization for boiler K2 –NOX emission

The average increase of boiler efficiency is 0.21 % reduction of NOX emission is 7.52%. The main factor is reduction of excess air and air distribution with respect of constraints like minimum of steam temperatures – 530 °C, minimum of O2 in flue gas – 1.85% or maximum of CO emission – 15 ppm. The lowest efficiency gain is recorded for lower boiler load, which is caused by lower steam temperatures, which require higher excess air.

The **Fig. 7b** presents effect on boiler efficiency and **Fig. 7b** presents effect on NOX emission of the combustion optimization for boiler K5.



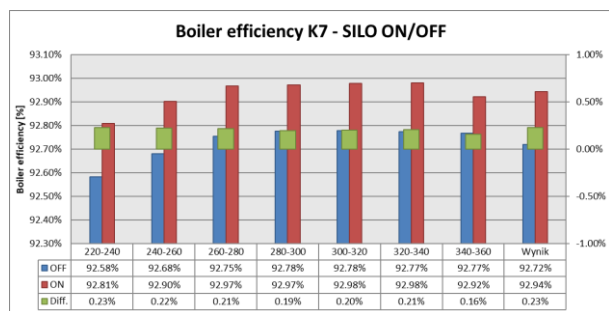
**Fig. 7a** - Combustion optimization for boiler K5 – efficiency



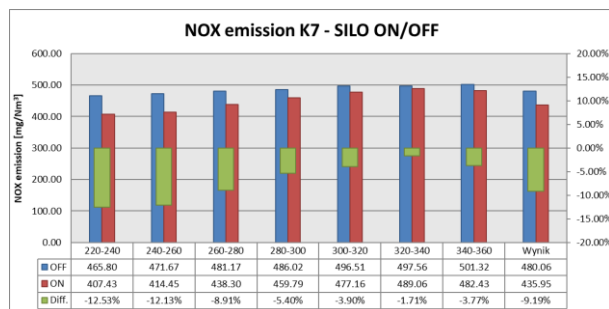
**Fig. 7b** - Combustion optimization for boiler K5 – NOX emission

The average boiler efficiency increase is 0.24 % and reduction of NOX emission is 5.88%. The main factor is reduction of excess air and air distribution with respect of constraints like steam temperatures, O<sub>2</sub> in flue gas or CO emission. The lowest efficiency gain is recorded for lower boiler load, which is caused by lower steam temperatures, what requires higher excess air. An insignificant drop of efficiency within minimum load range is a result of changing order optimization priorities in the way to increase steam temperatures.

The **Fig. 8b** presents effect on boiler efficiency and **Fig. 8a** presents effect on NOX emission of the combustion optimization for boiler K7.



**Fig. 8a** - Combustion optimization for boiler K7 – efficiency

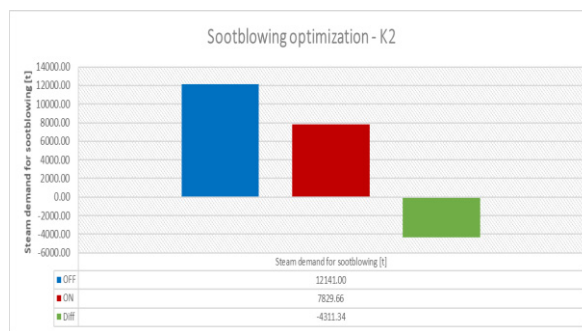


**Fig. 8b** - Combustion optimization for boiler K7 – NOX emission

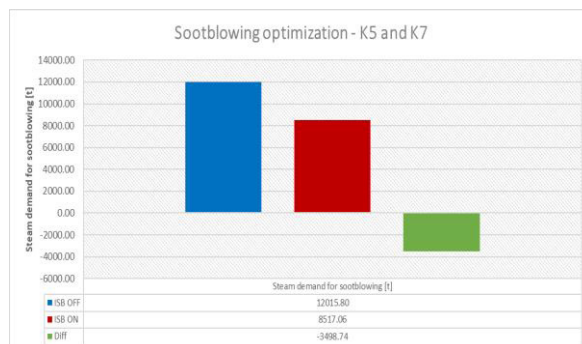
The average boiler efficiency increase is 0.23 % and reduction of NOX emission is 9.19%. The main factor is reduction of excess air and air distribution with respect of constraints like steam temperatures, O<sub>2</sub> in flue gas or CO emission. The lowest efficiency gain is recorded for lower boiler load, which is caused by lower steam temperatures, what requires higher excess air.

#### 8.4 The sootblowing optimization

The sootblowing optimization results in sootblowing steam reduction of 4311 t for boiler K2 and 3498 t for boiler K5 and K7 individually. This allows for annual reduction of fuel consumption respectively 11662 GJ for boiler K2 and 8421 GJ for boilers K5 and K7 individually. The optimization effects are presented on **Fig. 9a** and **Fig. 9b**.



**Fig. 9a** - Sootblowing optimization of boiler K2



**Fig. 9b** - Sootblowing optimization of boiler K5 and K7

## 9 Conclusions

The project has a positive influence on the process efficiency and economical profit of the CHP plant. The model based optimization and control allows for more efficient calculation of process control setpoints and control trajectory. The system respects constraints what allows to maintain the necessary range for base process control. The constraints management feature combined with balanced mass and energy brings a new quality. Depending on the solution systems operate with 1-5 minutes resolution supporting process operators with their duty. In other words the systems support operators to work in more efficient way and generally, the plant operates respecting standard procedures, defined by CHP management board.



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