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Decision Support for Energy-efficient Cooling Tower Operation using Weather Forecasts

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Cooling towers have a significant share in the consumption of electrical energy at chemical production sites and the optimal operation of these pieces of equipment has a large potential for energy savings. The properties of the cooling water that is provided by the cooling towers (temperature and pressure or flow rate) strongly influence the plants to which the cooling water is delivered. The cooling water supply usually has to fulfil certain requirements, e.g. a maximum temperature. In order to fulfil these requirements even under difficult conditions, like hot days in the summer, the cooling towers are overdesigned. If the operational regime is not properly adapted, the number of active towers or sections is higher than necessary which results in a too high consumption of electric power. To overcome this problem, an optimization and operator support system was developed in a collaboration of INEOS Köln and TU Dortmund, in the framework of the EU project MORE (“Real-time Monitoring and Optimization of Resource Efficiency in Integrated Processing Plants”). As a basis for the optimization, a cooling tower model that is based on lumped mass and energy balances was developed. The optimisation uses this model to compute a baseline which takes the ambient conditions and the specified cooling water quality into account. The current cooling tower performance is then rated versus the baseline and this reveals the potential for energy savings for the operators.
The first step of the decision support is the analysis of the trade-off between the cooling water temperature and the utilization of electric energy. The second step is the prediction of the cooling tower performance based upon an open online weather forecast. This enables the operators to act in anticipation and to foresee limitations in the cooling capacity. Consequently, the plants can shift production capacity to times where there is more available cooling power, e.g. to the night. The decision support system (DSS) will be set up as a web service at the production site of INEOS Köln and will be accessible to the operators and plant managers via standard web browsers, which provides a convenient and flexible utilisation.

1. Introduction

Cooling towers are among the most important equipment units in the processing industries, since they provide a vital utility for the operation of many production plants, chilled water. Due to the large amounts of electric power that the cooling towers consume to provide colling water of the specified temperature and flow rate, research was conducted towards the optimal design (Milosavljevic and Heikkilä, 2001) and selection (Couper, 2012) of cooling towers. Others studied the design of the cooling water network to optimise the water flow rate (Shenoy and Shenoy, 2013) or to find the best combination of the water return temperature and the pressure drop of the network (Sun et al., 2015) Mathematical models were created to determine influencing factors which are important for the operation of the towers, like chilled water throughput or fan speed of induced draft towers (Cortinovis et al., 2009) and the ambient conditions (He at al., 2014). Further studies focussed on the efficiency of cooling towers during operation (Marques et al., 2009). What is still missing is the transformation of these models and ideas to the online industrial application to provide decision support to the people who run the facility and who have to take the daily decisions. Although even relativ simple installations which provide feedback related to the current mode of operation can lead to a reduced electric energy consumption (Schultz et al., 2015).

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Often the water temperature at the tower outlets is not controlled and may be well below site standards which define an upper temperature limit. Consequently the way of operation is rarely optimal in the sense of minimal resource consumption and there is a large potential for savings, e.g., by reducing the number of active cooling towers or tower cells hereby increasing the water return temperature. There is a lack of supporting tools for the personnel on the site which has to ensure the quality specifications (temperature and flow rate) during the whole year. This is even more important when not only the cooling towers are considered isolated from the consumer plants, but the strong interaction with the production plants is taken into account. As the available cooling power and thus the cooling water temperature frequently is a limiting factor in the production, water temperatures below the site standard can be beneficial for the efficiency of the consumer plants, while the energetic performance of the cooling towers decreases. This trade-off is another challenge for decision support which is also addressed by the MORE project.

2. Cooling Tower Model

A detailed analysis of of the heat and mass transfer is available in the literature (Kloppers and Kröger, 2005). Based on these findings cooling towers models for the purpose of energy savings can be derived (Jin et al., 2007). However, in most real plant installations the measurements which are needed to employ such models online are not available. Therefore a cooling tower model was developed which is semi-empirical and takes into account the ambient conditions as well as the operational regime (Beisheim et al., 2015). The model is based on an integrated mass and energy balance and contains three empirical parameters to fit the model to the measured data. It is formulated as follows:

$$\dot{Q}_{calc} = z_1\, \dot{m}_{air,c}\, \Delta h_{air,\,max}{}^{z_2} \left(\frac{\dot{m}_{w,\,c}}{\dot{m}_{w,\,c,\,ref}}\right)^{z_3} \tag{1}$$

$$\Delta h_{air,\,max} = h_{air,in}(T_A, x_A, p_A) - h_{air,out}(T_{w,out}, x^{sat}) \tag{2}$$

where $\dot{Q}_{calc}$ denotes the heat transfer per cooling tower cell, $\dot{m}_{air,c}$ the air flow per cell, $\dot{m}_{w,c}$ the water flow, $\dot{m}_{w,c,ref}$ a reference flow, $h_{air,in}$ the enthalpy of the air inflow as a function of the temperature, humidity and pressure of the ambient air and $h_{air,out}$ the air outflow enthalpy as a function of the water outlet temperature ($T_{w,out}$) and the specific humidity of saturated air (x^{sat}) at this temperature. The model parameters z_i were fitted to a multicell cooling tower operating at the INEOS site in Köln. The developed model shows a much better match of the operational data over a broad range of cell loads compared to standard models as shown Figure 1.

Since only measurements of the ambient conditions as well as of the temperature and flow rates of the inlet and outlet cooling water are needed, the model can be implemented easily with the given instrumentation. In contrast to other performance models, the knowledge of the design parameters or of the degree of fouling is not necessary. Using this model, the performance can be compared to a baseline which accounts for the ambient conditions and indicates the number of cooling cells that are necessary to achieve the desired cooling water parameters. Fouling and other factors which influence the efficiency can be taken into account by updating the baseline (re-estimation of the parameters) to be able to evaluate the performance at the current operating conditions.

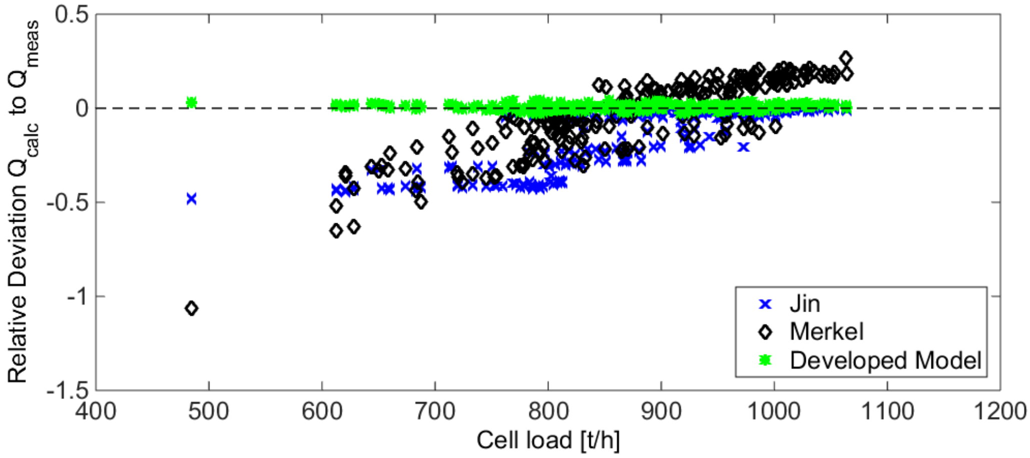

Figure 1: Calibration of the developed model and comparison to other models (Jin: Jin et al., 2007; Merkel: Kloppers and Kröger, 2005)

3. Decision Support

In many processes the environmental conditions, e.g., temperature, pressure and humidity of the ambient air, are an important factor that influences the overall performance significantly. Since cooling towers are an open system and the cooling is achieved by the evaporation of water into ambient air, the ambient conditions have a strong influence on the necessary air flow through the tower and therefore on the number of cooling cells and thus ventilators that have to be running at a given point in time. The higher the temperature of the incoming air, the more difficult it gets to chill the water. In summer it may even be impossible to achieve a desired water temperature at the cooling tower outlet. Hence, one aim of a decision support system is feedback to the operators to indicate the potential for efficiency improvements and limitations in the given situation.
At days when the air is warm or the humidity is high, the cooling power supplied might be insufficient to operate the production plant to which the cooling water is delivered at its desired load level. Consequently, another aim for the decision support is the prediction of the tower performance for the near future in order to estimate the possible production capacities and restrictions. The production of the consumer plants may then be adjusted in advance to the maximum performance of the cooling towers to increase the total productivity.
A prototypical interface for the decision support system is shown in Figure 2. In the upper left window, the current water temperatures and a forecast (for a fixed number of cooling cells) are displayed. Below the weather conditions are shown. The upper right graph shows a forecast of the number of required cells for two cases under the constraint to stay within the site wide limit for the cooling water temperature and under the constraint to achieve a certain temperature that is requested by the coupled production unit. The last figure displays the currently achievable water temperatures depending on the choice of the number of active ventilators.

3.1 Feedback

Feedback is given to the operators in the form of the cooling water temperatures that are achievable at the moment for the current ambient conditions. The graph in Figure 3 states a minimum cooling water temperature of circa 16 °C, when all cooling cells are working. The minimum number of cells in this case is eight in order to stay below the site limit of 25 °C. Thus it is easy for the operator to indentify the currently possible energy savings by the choice of the number of active ventilators. In addition, the operating personnel becomes aware of free cooling capacities that could be utilized by the production plants which consume the cooling water.

3.2 Forecast

The prediction is based on an open online weather forecast (www.openweathermap.org). The database can be polled to retrieve current weather information as well as a prognosis for the upcoming one to sixteen days. An example can be seen in Figure 4. Using this information trends for the future water temperatures are calculated under the condition that the number of active cells is fixed to the current value and the energy transfer is constant, resulting in a stationary temperature difference of the inlet and outlet streams. These predictions are displayed in Figure 5 as dashed and dotted lines.

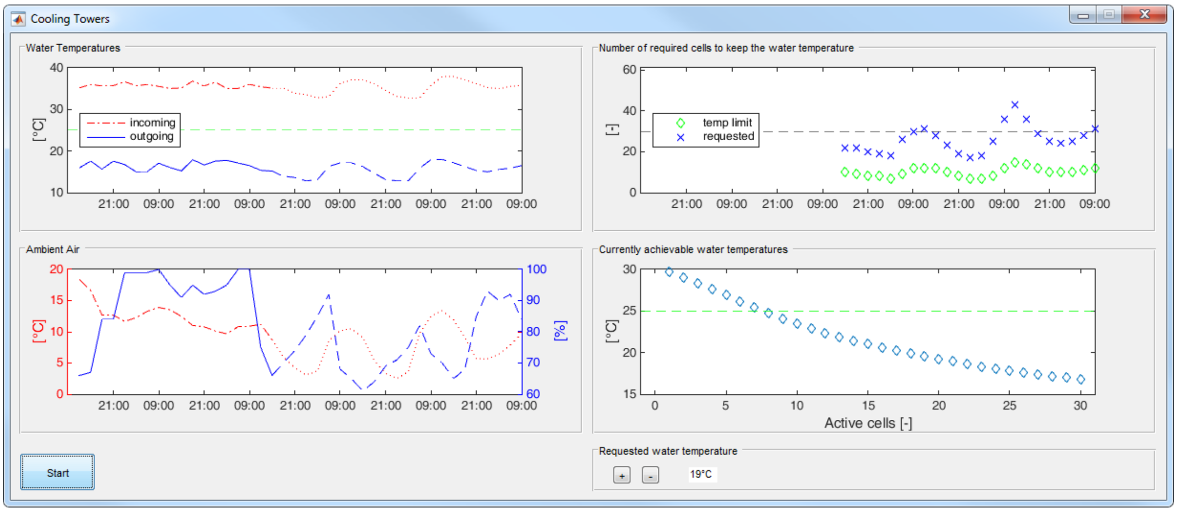

Figure 2: Prototypical interface of the decision support system

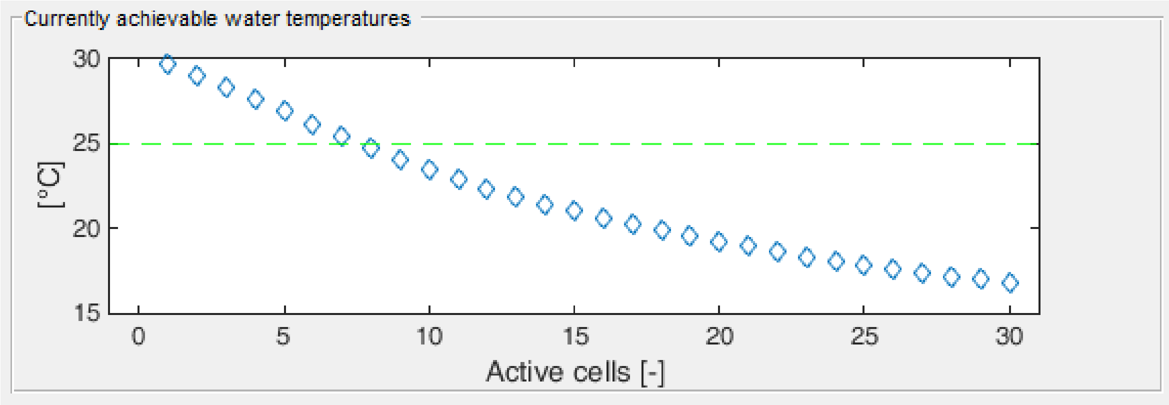

Figure 3: Feedback to the operator as about the achievable temperatures of the cooling water

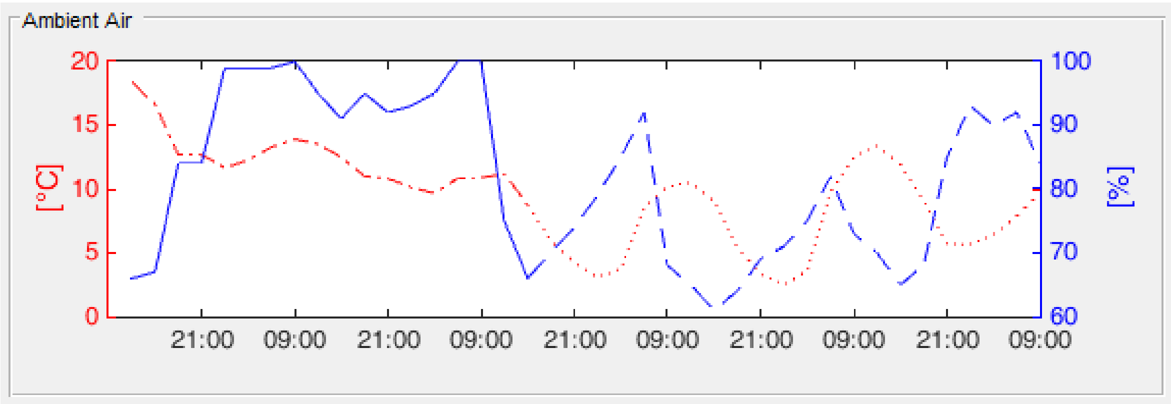

Figure 4: Conditions of the ambient air (past values on the left, forecast on the right)

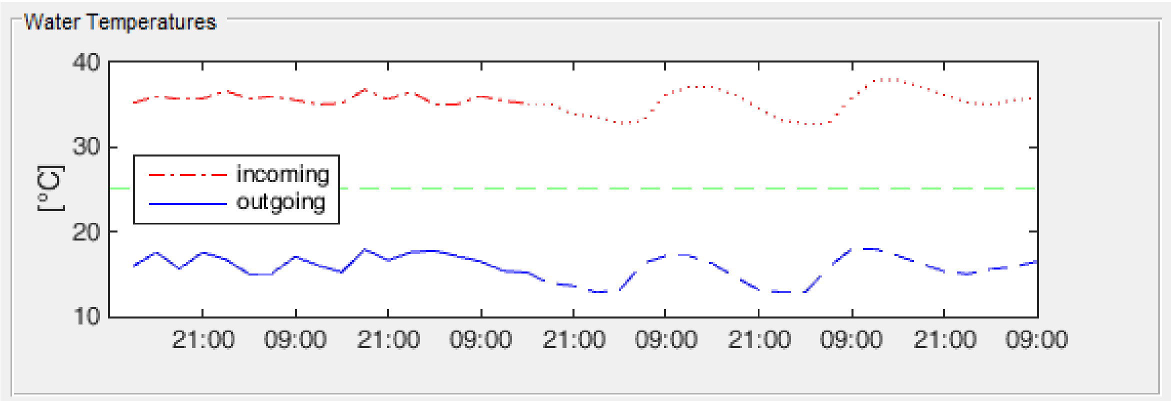

Figure 5: Measured and predicted temperatures of the incoming and outgoing water streams (the dashed line is the upper limit for the outgoing water temperature)

Finally the number of required cooling tower cells is predicted for two different goals. One goal is the minimum number of cells that is required to meet the site wide upper temperature limit and the other one is the number of active ventilators needed to achieve a desired temperature that the attached plants could ask for (cf. Figure 6). The former is especially important at hot summer days if the cooling capacity of the towers is not sufficient to satisfy the demand of the consumer plants which than have to reduce their throughput. In this case the forecast enables the decision makers to shift production capacities to less restricted times, e.g., to the night or the upcoming days, still achieving the overall production target. The same holds for the requested cooling water temperature.

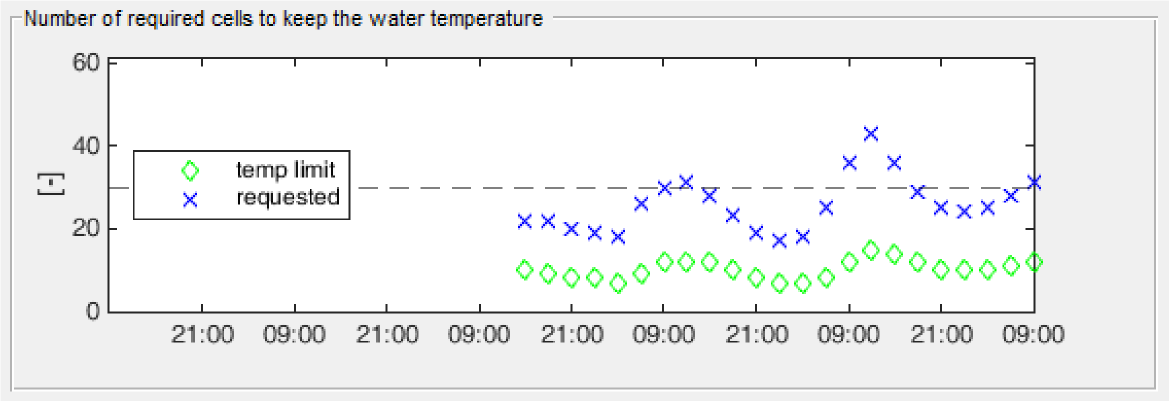

Figure 6: Prediction of the required number of cooling cells according to a site limit of the cooling water temperature and to a desired temperature (the dashed line being the installed number of cells)

An early knowledge of the cooling tower performance or limitation allows for proactive reactions. In the shown example, a problem would arise during the next two days around noon for both days. Even when all cooling cells are running it will not be possible to keep the water temperature at the desired level and to still dissipate as much thermal energy as required. This information can also be used for maintanance planning, since the number of not required tower cells is predicted some days ahead.

3.3 Installation on site

The decision support will be implemented at INEOS in Köln as a dashboard which gives timely feedback about the current status of the plant and visualises the forecast results. An already running dashboard shows the performance during the last hours and visualises the current condition of the cooling cells and pumps (actice, inactive, maintainance), but does neither give the detailed feedback presented here nor employs a prediction. However, since the operational personnel is used to this tool, some characteristics will serve as the basis for the decisions support system. Namely the graphical representation of the cooling towers and potentially the colour coding of graphs.
In contrast to the existing solution, the DSS will be implemented on a local webserver whereby the information are accessible via standard webbrowers on stationary PCs as well as mobile devices like tablet PCs or smartphones. Using web techniques offers a large flexibility in the design of the human-machine interface (HMI) and possiblities as e.g. the automatic scaling of the HMI for the screen size as well as a responsive design to allow the user to change the appearance easily (e.g. changing ranges of graphs).

4. Conclusions

Since standard literature models for cooling towers require data that are often not available in the industry for the given installation, a simple model was developed based on an integrated mass and energy balance that constains empirical factors that can be adapted to the individual plants. The new model needs less information from the real plant and shows a considerably better fit than standard literature models.
Based on this model a decision support tool was built which utilises a weather forecast in order to not only illustrate the past behaviour but to predict the future performance of the cooling towers. The tool provides information to the user to take the decision about the number of active cooling cells to fulfil the requirements. Simulation results illustrate the potential of energy savings when the ambient air conditions as an external influence are taken into account. Furthermore the DSS enables the decision makers to foresee limitations and to act in anticipation; for example by the shift of production capacities of the attached plants to periods of time with less restrictions or for planning of maintenance of the cooling towers.
Further work will integrate the optimization of the cooling towers with that of the plants to which the cooling water is delivered. The decision support system will then help to investigate and to utilise the trade-off between the energy consumption of the cooling towers and the efficiency of the production plants.

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