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THE WORLDS' FIRST EVER COOLING TOWER ACCEPTANCE TEST USING PROCESS DATA RECONCILIATION

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ABSTRACT

The cooling capacity of cooling towers is influenced by multiple constructive and atmospheric parameters in a very complex way. This leads to strong variations of the measured cold-water temperature and causes unacceptable unreliability of conventional acceptance tests, which are based on single point measurements.

In order to overcome this lack of accuracy a new approach to acceptance test based on process data reconciliation has been developed by BTB Jansky and applied at a nuclear power plant.

This approach uses process data reconciliation according to VDI 2048 [1, 2] to evaluate datasets over a long period covering different operating conditions of the cooling tower. Data reconciliation is a statistical method to determine the true process parameters with a statistical probability of 95% by considering closed material-, mass- and energy balances. Datasets which are not suitable for the evaluation due to strong transient gradients are excluded beforehand, according to well-defined criteria.

The reconciled cold-water temperature is then compared, within a wet bulb temperature range of 5°C to 20°C to the manufacturer's guaranteed temperature. Finally, if the average deviation between reconciled and guaranteed value over the evaluated period is below zero, the cooling tower guarantee is fulfilled.

INTRODUCTION

The cooling capacity of cooling towers that are driven by natural ventilation is affected by multiple parameters in a very complex way. Not only constructive parameters have a high influence on the cooling performance, but also all parameters describing the atmospheric environment around the cooling tower. These parameters:

- Profiles of the air temperature and humidity at the inlet of the cooling tower.
- Interferences due to strong winds near the ground.
- Shearing of the wind towards the cooling tower outlet.
- Influence of the air temperature profile around the tower.
- Local topography.
- Thermal instabilities that cause turbulences in the air around the tower.

These parameters are not only essential for the cooling capacity, but also highly variable. Additionally, transient and dynamic conditions make the evaluation of the cooling capacity very difficult.

The variety of the parameters mentioned above, leads to a significant dispersion of the cooling water temperature measured at a cooling tower in operation. Therefore, conventional acceptance tests that are based on single-point measurements suffer from unacceptable unreliability because results are strongly influenced by coincidence.

To overcome this lack of accuracy, a new statistical approach to acceptance tests based on process data reconciliation according to VDI 2048 has been developed by BTB Jansky and applied at a nuclear power plant, in cooperation with the plant operating company, the cooling tower manufacturer and cooling technology consultants with many years of experience within this particular type of cooling tower.

The dispersion of the measured cooling water temperature is significantly reduced by evaluating process datasets over a sufficiently long period of time that covers all current states of operation of the cooling tower and different environmental scenarios. Additionally, non-suitable datasets are eliminated beforehand. These outliers are identified and excluded according to well-defined criteria in a separate pre-processing step. Thereby, more accurate conclusions about the cooling water temperature and the thermal load of the cooling tower, respectively the condensers are possible. At the same time, these results are not only more accurate, but also come with significantly reduced uncertainties. Figure 1 shows the probability density distribution of the thermal load of the cooling tower for different uncertainties. A similar result is obtained for the cold-water temperature (cooling water temperature at the inlets of the condensers) where a reduction of the uncertainties leads to a significantly more focussed probability distribution, **see APPENDIX 1.**

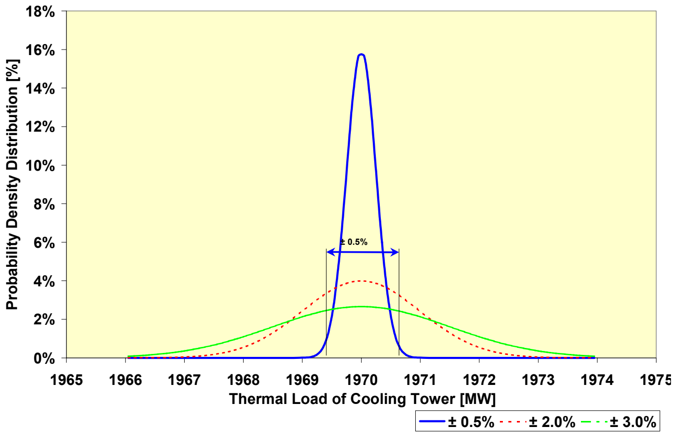


Figure 1: Increased accuracy of thermal load due to reduced uncertainties

Besides higher accuracy, there is another great advantage of this new approach. Process data reconciliation according to VDI 2048 [1, 2] uses standard measurement data from the process computer that is already installed on site. Additional measurement equipment and set-up on the primary and secondary side requiring high technical and personal effort is not necessary. On the tertiary side, only measurements of temperature, pressure and humidity of the air are required.

THEORETICAL BASIS

Process data reconciliation

Process data reconciliation is based on the Gaussian correction calculation, It provides the following advantages:

- quality control
- detection of serious errors
- the result confidence interval is the lowest possible and independent of the calculation method

As described in [1] corrections $\mathbf{v}$ are made to the measured values $\mathbf{x}$ according to equation (1), in order to obtain estimated values (reconciled values) $\bar{\mathbf{x}}$.

$$\bar{\mathbf{x}} = \mathbf{x} + \mathbf{v} \qquad (1)$$

The corrections $\mathbf{v}$ must be determined in a way that the quadratic error form

$$\xi_0 = \mathbf{v}^{\mathrm{T}} \cdot \mathbf{S}_{\mathbf{X}}^{-1} \cdot \mathbf{v} \Rightarrow \min \qquad (2)$$

becomes a minimum.

Quality control and detecting suspected tags (serious errors)

With a statistical probability of $p = 95\%$, ξ_0 is not greater than the 95% quantile of the χ^2 distribution from the degree of freedom r (number of auxiliary conditions) to be found in statistical tables [3]. If the condition

$$\xi_0 \leq \chi^2_{r,95\%} \qquad (3)$$

is not satisfied, the acquired data (measured values x) must be rejected because the contradictions are too great.

If the condition

$$\left| \frac{v_i}{\sqrt{s_{v,ii}}} \right| \leq 1.96 \qquad (4)$$

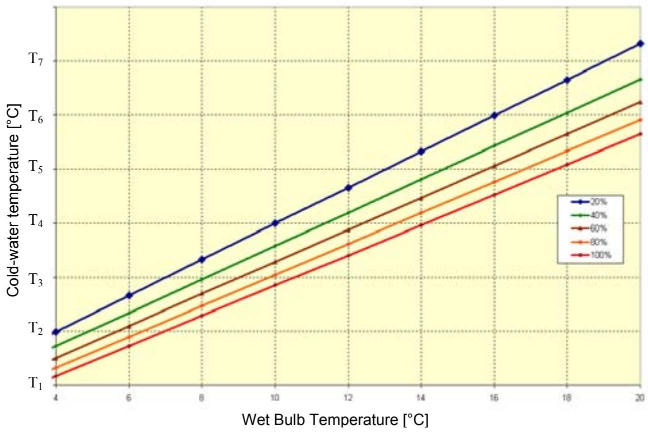
is not satisfied, the associated measured value x_i, or of the estimated value of the associated variance $s^2_{X_i}$, must be queried. In this way it is possible to obtain not only a general assessment of the acquired data, but also specific pointers to where serious errors or seriously inaccurate estimates of the measurement accuracy can be found.

EVALUATION OF GUARANTEE FULFILLMENT

To evaluate the reduction of the cold-water temperature guaranteed by the cooling tower manufacturer, measurement data sets over a constant period of several weeks are evaluated. For the acceptance test described here, a minimum number of 560 converging datasets is defined. The period covers a range of the air temperature between 5 °C and 20 °C. Also other quantities characterizing the environmental conditions like air pressure and humidity vary between certain limits. All these parameters are combined in the so-called “Wet Bulb Temperature” which is calculated according to von Iribarne und Godson [4], **see APPENDIX 2**.

Figure 2 shows an example of a guaranteed cooling tower characteristic where the guaranteed cold-water temperature is given over the wet bulb temperature depending on the humidity of the air at the cooling tower inlet.

Figure 2: Example of a guaranteed cooling tower characteristic



Extraction of suitable datasets for data reconciliation

There are different criteria for datasets which must be fulfilled to approve them for being included in the evaluation. Two of them define the general mode of operation of the tower:

- no datasets from the first 30 days after start-up of the new cooling tower
- regular operation mode without any by-passes or deactivations of any zones in the cooling tower

Also, there are certain conditions for the cooling water temperature to ensure a steady way of operation of the plant:

- standard deviation of the measured cold-water less than 0.2 K, respectively 0.5 k for the hot-water temperature

The incoming air at the inlet of the tower must be conform to the following criteria:

- standard deviation of the different temperature measurements less than 0.2 K, respectively 0.5 K depending on the type of measurement
- standard deviation of the measured relative humidity of the incoming air less than 3 %

Global environmental conditions need to adhere to the following criteria:

- wind velocity, measured at the meteo-tower, less than 5 m/s
- temperature difference between the measured air temperature at the top of the cooling tower (height: 110 m) and at the inlet between 0.2 K and 1.0 K.

The wet bulb temperature, which is a direct parameter for the cooling tower characteristics must not violate certain limits:

- wet bulb temperature between 5 °C and 20 °C
- wet bulb temperature should not change more than 0.5 K per hour

Filtering of suitable reconciled datasets

Because the guaranteed characteristic of the cooling tower is only valid for a thermal load of the power plant of about 100 %, no datasets with a reconciled value of the thermal load of the cooling tower below 1970 MW (equivalent to a thermal load of 99,8 %) are allowed.

Also according to VDI 2048 [1] [2] only reconciled datasets, which do not violate equations (3) and (4) can take part in the evaluation:

If both conditions of VDI 2048 are fulfilled, the calculated results are the “true” values and mirror the real state of the process with a statistical probability of 95 %.

In order to take into account the unsteady behaviour of the cooling tower for the evaluation, the number of datasets with increasing and decreasing wet bulb temperature (compared to the previous dataset) should be nearly equivalent.

Comparison of reconciled and guaranteed values

After successful reconciliation, by using VALI 4 [5] and filtering of the unsuitable datasets, the reconciled cold-water temperature T_{rec} is now compared to the guaranteed one (T_{guar}). The procedure contracted with the cooling tower manufacturer defines a point to point comparison between reconciled and guaranteed cold-water temperature with the wet bulb temperature ranging between 5 °C to 20 °C, which is the operating range the cooling tower is designed for. Now the average line of the obtained band of points over the wet bulb temperature is calculated.

$$delta = \frac{1}{N}\sum_{i=1}^{N}(T_{rec} - T_{guar}) \leq 0 \qquad (5)$$

If the average line is below zero for all values of the wet bulb temperature within the defined limits, the guarantee is fulfilled. To give an idea of a fulfilled guarantee, an example based on virtual measurements is given in **Figure 3**, where $(T_{rec} - T_{guar})$ and the average line are shown for different temperature ranges between 4 °C and 20 °C.

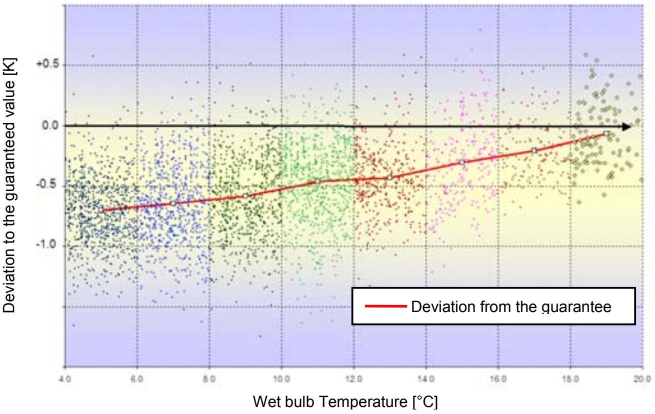


Figure 3: Example of a fulfilled guarantee based on virtual measurements

CONCLUSIONS

The integration of the tertiary side (cooling tower) into a data reconciliation model of the primary and secondary side clearly increases the accuracy of the obtained results. Uncertainties for the calculation of the thermal load of the cooling tower, respectively the condensers, as well as from the cold-water temperature are significantly reduced. In this way, it is possible to determine these quantities even though they cannot be detected reliably with standard measurement equipment because of high statistical variance. The described approach enables accurate acceptance tests as well as precise knowledge about the true state of the process.

REFERENCES

[1] VDI 2048 Part 1, “Uncertainties of measurement during acceptance tests on energy-conversion and power plants - Fundamentals”, October 2000.

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[3] Bronstein, Semendjajew, Musiol, Mühlig, “Taschenbuch der Mathematik” Verlag Harri Deutschland, Table 19.16, p. 814

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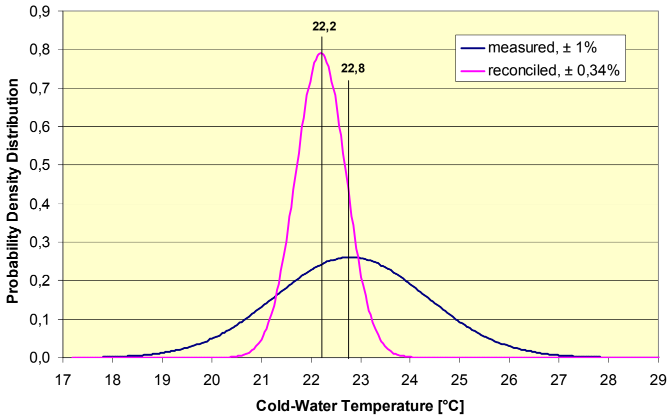
[5] VALI 4.0 USER GUIDE, BELSIM S.A., Liege, Belgium, December 2004



APPENDIX 1 : Probability Density Distribution of the Cold-Water Temperature

Saturation vapour pressure

$$e_s = \exp(C_{15} - C_1 T - \frac{C_2}{T}) \qquad (1)$$

Dewpoint vapour pressure

$$e_d = \exp(C_{15} - C_1 T - \frac{C_2}{T_d}) \qquad (2)$$

where $T_d = \dfrac{b - \sqrt{b^2 - C_3}}{C_4}$ (3)

with $e = RH \cdot e_s$ (4)

and $b = C_{15} - \ln(e)$ (5)

First guess: $s = \dfrac{e_s - e_d}{T - T_d}$ (6)

$$1st\_guess\_T_W = \frac{T \cdot f \cdot p + T_d \cdot s}{f \cdot p + s} \qquad (7)$$

Correction:

$$de = f \cdot p \cdot (T - T_W) - (e_W - e_d) \qquad (8)$$

as long as de < ew /10000:

$$der = e_W \left(C_1 - \frac{C_2}{{T_W}^2} \right) - f \cdot p \qquad (9)$$

Next guess: $next\_guess\_T_W = T_W - \dfrac{de}{der}$ (10)

From the above equations

- C_{15} = 26.66082
- C_1 = 0.0091379024
- C_2 = 6106.396
- C_3 = 223.1986
- C_4 = 0.0182758048
- L = latent heat of vaporization = ~2.54 x 10 6 (J/kg)
- p = pressure (mbar)
- T_w = wet bulb temperature (K)
- f = 0.0006355 = C_p/(L*epsilon) (1/K)
- C_p = 1004 (J/(K*kg))
- T = temperature (K)
- RH = relative humidity (ratio)
- T_d = dewpoint temperature (K)
- e_w = wet bulb vapor pressure (mb)
  = $\exp(C_{15} - C_1 T_w - C_2/T_w)$
- epsilon = mass of water vapor / mass of dry air = ~0.622

APPENDIX 2 : Calculation of the Wet Bulb Temperature