Natural Draft Cooling Tower Design and Construction in Germany - Past (since 1965), Present and Future

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Summary
In this paper, a brief overview of cooling tower design and construction in Germany is presented starting in the second half of the 1960’s (cooling tower Ibbenbüren 1965, STEAG cooling tower Lünen 1968) until today (Trianel cooling tower Lünen, 2010). As reference towers for the historical development, the two natural draft cooling towers located close to the city of Lünen are used.

The following aspects will be discussed with reference to the two natural draft cooling towers Lünen:
• Comparison of structural systems and constructive requirements.
• Design and analysis methods – structural models.
• New aspects such as flue gas duct (FGD) introduction and emission control (EMI platform).
• Construction of natural draft cooling towers – special aspects such as construction stages (erection of columns, lower ring beam, climbing through flue gas duct opening).
• Discussion: What has changed from 1968 until 2010?

The historical development of natural draft cooling tower design and construction is presented with reference to the two towers of Lünen. Special attention is paid to new structural aspects which have come up during the last years such as acid resistant concrete, flue gas duct introduction, EMI platforms. An outlook to cooling towers of heights up to 250 m is given which are currently in conceptual design phase for new power plant projects.

Keywords
Natural Draft Cooling Towers, Reinforced Concrete, Power Plants

Theme
Cooling Towers - Design – Construction – Past, Present, Future

1. Introduction
Natural draft cooling towers can be found at power plant sites where process water has to be cooled. Due to their large and slender double curved shell they represent one of the most fascinating and challenging civil engineering structure concerning design and construction. The actual cooling tower development and footrace against height in Germany has started in the year 1965 with the erection of cooling tower Ibbenbüren by company Heitkamp. In this project, a new and very innovative erection method using a climbing formwork has been used to erect this tower. With such a climbing formwork, the restrictions of regular formwork have been overcome. Unlimited tall structures (e.g. solar chimneys) could be built with such a climbing formwork if there were no restrictions concerning statics and construction logistics.

In this contribution, the historical development of cooling tower design and construction in Germany during the last 45 years is presented which is closely linked to construction company Heitkamp [1]. Hereby, special emphasis is put on the two natural draft cooling towers of Lünen as special representatives which represent this historical development and have been both erected by Heitkamp. Both towers are depicted in Figure 1.

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Special features of modern cooling towers such as flue gas duct introduction, EMI platform and concrete technology are explained with regard to design and construction issues. Further, an outlook is given to cooling towers which might be built in future.

Figure 1: Natural draft cooling towers Lünen – Steag tower 1968 and Trianel tower 2010

2. Historical overview
A historical overview of height development of natural draft cooling towers in Germany can be found in Table 1 according to [12]. Starting with cooling tower Ibbenbüren (height 100 m) in 1965, a continuous development in height can be observed. In Germany, height 160 m was reached for the first time by cooling tower Mülheim-Kärlich in 1976. Approximately 20 years later, the height 200 m has been reached for the first time with cooling tower Niederaußem K (built by Heitkamp) which is still the world wide highest tower [1]. Both cooling towers at Lünen – Steag tower 1968 and Trianel tower 2010 – have not been the highest towers in Germany at the time of their erection. However, they represent the historical development during the last decades quite well while they are located only some hundred meters away from each other and have been erected by the same construction company Heitkamp.
<table>
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<tr>
<th>Year/78</th>
<th>Site</th>
<th>Power [MWe]</th>
<th>Base Dia [m]</th>
<th>Height [m]</th>
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<td>86.00</td>
<td>117.00</td>
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<td>1967/68</td>
<td>Lünen (Steag)</td>
<td>345</td>
<td>77.50</td>
<td>109.30</td>
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<td>300</td>
<td>92.10</td>
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<tr>
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<td>98.00</td>
<td>128.00</td>
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<td>Meppen</td>
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<td>131.00</td>
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<tr>
<td>1974/75</td>
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<td>152.20</td>
<td>165.50</td>
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<tr>
<td>1995/96</td>
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<td>152.54</td>
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<tr>
<td>2008/10</td>
<td>Lünen (Trianel)</td>
<td>800</td>
<td>104.60</td>
<td>160.00</td>
</tr>
</tbody>
</table>

Table 1: Development of cooling tower heights in Germany and placement of NDCTs Lünen [12]

3. Cooling towers Lünen

3.1 STEAG tower 1967/68

STEAG natural draft cooling tower has been completed in 1968 with the following dimensions [4]:

- Total height above ground: 110.60 m
- Shell height: 103.10 m
- Shell base diameter: 75.20 m
- Shell throat diameter: 44.50 m
- Shell top diameter: 51.40 m
- Shell minimum thickness: 14 cm
- Shell thickness at bottom: 65 cm
- Concrete of shell: B 300, $f_{ck} \approx 16$ MN/m²
- Columns: 29 V-columns $\varnothing 60$
- Foundation: ring foundation b/h 2.20/2.30 on elastic soil separated with sliding film, prestressed
- Erection duration of shell: 5 months ($107/5/22 = 1$ m / day)

The shape of the tower is described by two hyperbolic shape functions, below and above the throat. Special for this tower is the ratio upper diameter / throat diameter = 51.40 / 44.50 = 1.15 so that the negative curvature in the upper part can be clearly seen from Figure 1 (left picture). Further, a speciality can be found in the prestressed ring foundation. Since the tower foundation is supported by sliding film, high tensile forces occur in the ring beam due to the missing contribution of soil friction. To compensate these tensile forces, the ring foundation has been prestressed. This special foundation has been used due to mining settlements. For the shell, a minimum thickness 14 cm applies.

The analysis of this tower has been conducted mainly by use of membrane theory for elementary load cases dead weight and wind. Bending action at lower and upper shell edge has been considered by shell bending theory using equivalent cylindrical shells as approximation [7]. Further considered action are temperature restraints and failure of single V-columns.
3.2 TRIANEL tower 2010

TRIANEL natural draft cooling tower has been completed in 2010 with the following dimensions:

- Total height above ground: 160.00 m
- Shell height: 151.60 m
- Shell base diameter: 98.40 m
- Shell throat diameter: 60.80 m
- Shell top diameter: 63.40 m
- Shell minimum thickness: 18 cm
- Shell thickness at bottom: 85 cm
- Concrete of shell: acid resistant concrete $f_{ck} = 70$ MN/m²
- Columns: 48-1 = 47 I-columns b/h 0.85/0.90 (top) b/h 0.85/2.10 (bottom)
- Foundation: ring foundation b/h 5.40/1.50 4 bore piles $\Phi 88$ below each column
- Erection duration of shell: 9 months (April 2009 – October 2009 $\approx 1$ m / day)

Also for this tower, a double curved geometry applies with two hyperbolic shape functions below and above the throat. The ratio upper diameter / throat diameter = 63.4 / 60.8 = 1.04 is much smaller than for the STEAG tower. The geometry above the throat is almost looking like a cylinder, although a very small negative curvature is provided, see Figure 1 (right figure). This speciality is due to the geometric property that the inner wall surface radius in the throat shall be equal to the inner wall surface radius of the upper ring beam.

The tower possesses a ring beam foundation without prestressing. However, a crack width limitation $w_k = 0.15$ mm applies for surfaces in contact with water which leads to high reinforcement ratios due to pure tension. Further, each meridional column is supported by a group consisting of 4 bore piles $\Phi 88$. The shell is erected with a special acid resistance high performance concrete so that no coating is necessary to protect the surface from acid due to flue gas duct introduction. A minimum wall thickness according to VGB-BTR 2005 [10] is met to ensure buckling safety and constructive requirements (minimum remaining section inner lever arm with consideration of high concrete cover 55 mm).

This tower shows 3 specialities which have become standard during the last few years:
   a) Missing of one single meridional column
   b) Huge shell opening for flue gas duct introduction
   c) EMI platform attached to shell below flue gas duct opening

Meridional column #35 is spared out since the inner part of the flue gas duct has to be introduced through this opening after the cooling tower has reached its final height. This special geometric situation has to be considered in the analysis which leads to stress redistribution in the lower part of the shell to adjacent columns.

The shell membrane behavior is further disturbed by the large shell opening for flue gas duct introduction. In this region, the shell is thickened in comparison with standard wall section at this height. Here, very high vertical and horizontal forces from flue gas duct have to be introduced into the shell.

The use of meridional I-beams provides a huge advantage in comparison to V-columns: after completion of columns, the lower shell edge is erected using slender precast beams so that the climbing process can start immediately after column erection with each climbing tower attached to one column.

Another speciality can be found in the EMI platform which is attached to the shell below the main flue gas duct opening. On the platform, a steel construction will be installed around the flue gas duct later. This platform is needed to provide controlling instruments for checking the cleanliness of flue gas. Here, very high vertical and
horizontal forces are introduced into the shell by the help of concrete brackets.

For the analysis of this tower, finite element method is used with the help of a global structural model including upper ring beam, shell, columns, ring foundation and pile foundation. Two different models are established:

1) Axissymmetrical model using finite element code ROSHE [8] which is based on finite ring elements. With this model, the structure is idealized and analysed as an axissymmetric shell of revolution. Discontinuities due to the shell opening, missing column #35 and discrete load introduction at bottom of shell are neglected in this model. However, very good design results are obtained with this model for the standard shell region, upper ring beam and column forces in standard regions with a restriction to only a limited number of governing load combinations.

2) Full 3D model using finite element code ROSHE3 [9] which is based on triangular shell elements with 36 degrees of freedom per element formulated in curved coordinate system. Within this model, all non-axissymmetric effects are considered. However, this model is quite complex and time-consuming concerning analysis, post-processing and design.

3.3 Comparison

Concerning erection procedure and erection time, no significant modifications can be observed during the last decades. Still the same climbing technique and climbing formwork principle are used. The main differences between the two towers must be seen in concrete technology, specialties due to flue gas duct introduction (opening, EMI-platform, missing meridional column) and computational capabilities which have been developed during the last decades with increasing computer power, especially mentioning the applied advanced expert systems ROSHE [8] and ROSHE3 [9] for cooling tower design. The use of such highly advanced expert systems is absolutely necessary since these modern cooling tower shell structures with their mentioned specialties due to flue gas duct introduction cannot be handled by simplified hand calculation methods based on membrane theory and substitution cylinders for consideration of bending action (as done for Steag cooling tower Lünen). They require highly advanced finite element analysis for shell structures with negative Gaussian curvature. Analysis and design aspects for natural draft cooling tower Lünen will be presented within the next chapter.

4. Design, analysis and construction of TRIANEL cooling tower Lünen

4.1 Finite element model

A detailed finite element model based on own tailored finite element code ROSHE3 is used for 3D modeling including all non-axisymmetric properties. This model is based on triangular elements formulated in curved coordinates. The structural model can be found in Figure 2.

Number of triangular shell elements: 4480
Number of 3D-beam elements (columns and ring foundation beam): 578
Number of translation springs (bore pile groups): 144
Number of rotation springs (bore pile groups): 144

Total number of system degrees of freedom 32182
4.2 **Elementary loadcases and combination of elementary loadcases – min / max design forces**

The following 97 elementary loadcases are analysed:

- LC 1: Dead weight of shell
- LC 2: Inner suction
- LC 3: Temperature operation
- LC 4: Temperature winter shut down
- LC 5: Shrinkage
- LC 6–21: Loads due to flue gas duct and EMI platform
- LC 22: Live load upper ring beam
- LC 23–25: Loads lower ring beam and ramp
- LC 26–61: Wind load positions 0° - 350°
- LC 62–97: Temperature Insulation 0° - 350°

Earthquake action is not considered due to geographical location of Lünen (see DIN 4149 [3]). These elementary loadcases are reduced to 12 governing load combinations for ultimate limit state and 12 governing load combinations for serviceability limit state.

\[
\text{ULS} \quad \sum_{j=1} \gamma_{G_{j}} \cdot G_{k,j} + \gamma_{Q_{j}} \cdot Q_{k,j} + \sum_{i>1} \gamma_{Q_{j}} \cdot \psi_{0,i} \cdot Q_{k,i} \quad \text{min / max} \quad n^{11}, n^{12}, n^{22}, m^{11}, m^{12}, m^{22}
\]

\[
\text{SLS} \quad \sum_{j=1} G_{k,j} + \psi_{1,j} \cdot Q_{k,j} + \sum_{i>1} \psi_{2,i} \cdot Q_{k,i} \quad \text{min / max} \quad n^{11}, n^{12}, n^{22}, m^{11}, m^{12}, m^{22}
\]

Safety factors \( \gamma_{0} \) and \( \gamma_{0} \) as well as combination factors \( \psi_{0}, \psi_{1}, \psi_{2} \) are provided in VGB-BTR 2005 [10] and VGB 602 [11]. With these governing design combinations, section resistance / required reinforcement amounts (ULS) and crack widths (SLS) are computed. Design checks are in accordance with DIN 1045-1 (2008) [2].
4.3 Buckling safety

A very important issue in natural draft cooling tower design is the check of buckling safety. According to BTR 2005, a minimum buckling safety $\gamma_B = 5.0$ must be provided for load combination Dead Weight + Wind + Inner Suction. Hereby, all possible wind directions must be analysed due to non-axisymmetric structural geometry. With this design check, the wall thickness of the shell is determined. However, since an acid resistant concrete is used with a very high Young modulus $E_{cm} = 35700$ MN/m², the minimum wall thickness $h = 18$ cm according to VGB-BTR 2005 [10] is sufficient to provide a buckling safety $\lambda_k = 7.9 > \gamma_B = 5.0$.

Figure 3: Lowest buckling eigenform for $7.9 \cdot (DW + W + WS)$

4.4 Construction issues

The Trianel natural draft cooling tower Lünen is founded on 48x4 bore piles $\varnothing 88$ with length $\approx 26$ m. The ring foundation and meridional columns are cast in situ. The first critical construction state is the erection of the lower ring beam. Here, the number of meridional columns is chosen in such a way that the field between two columns is bridged by slender precast elements and the climbing process can start immediately with each climbing tower attached to one column. The most critical state is the climbing of the flue gas duct opening. Here, one climbing tower is located directly in the opening. An auxiliary slender but highly reinforced wall is erected for climbing through this opening which is demolished after completion, see Figure 4. This wall receives an initial outward deformation to compensate the elastic deformation due to cantilever bending. After completing this opening, the climbing process can continue regularly. The construction state before completion of upper ring beam before hardening of concrete has to be checked with regard to buckling safety. The flue gas duct support bank and the EMI platform brackets are completed afterwards. Therefore, special reinforcement couplers are installed to connect these brackets to the shell. The construction state after climbing through the opening with different heights of individual climbing towers can be found in Figure 4. Further, site pictures and an erection movie will be shown during the conference presentation.
Conclusions

In this paper, the two natural draft cooling towers of Lünen have been compared which somehow represent the historical development during the last decades in cooling tower design and construction in Germany. While the erection principle has not changed significantly for the general shell part, new issues have been introduced such as flue gas duct opening and EMI platform which require special construction and design consideration. Significant improvements during the last few years have been achieved in concrete technology to create acid resistant concrete recipes for exposure class XA3 due to flue gas introduction so that coatings become unnecessary.

Cooling towers up to heights 200 m are built commonly as concrete shells without stiffening rings using the climbing procedure as described in this presentation. However, in near future higher cooling towers (height 230 m – 250 m) will be required (e.g. for nuclear power plants of third generation). For such towers, recent design studies conducted by the author showed that the possibility of horizontal stiffening rings needs to be taken into account again to achieve an optimum between dead weight, wall thickness and buckling safety. Similar studies with similar results have been already conducted by Zerna and can be found in [13].

References