BRITISH STANDARD

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# Heat exchangers — Method of measurement and evaluation of thermal performances of wet cooling towers

The European Standard EN 14705:2005 has the status of a British Standard

ICS 27.060.30; 27.200

British Standards

# National foreword

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The UK participation in its preparation was entrusted to Technical Committee RHE/30, Heat exchangers, which has the responsibility to:

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- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
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English version

# Heat exchangers - Method of measurement and evaluation of thermal performances of wet cooling towers

Echangeurs de chaleur - Méthode de mesure et évaluation des performances thermiques des aéroréfrigérants humides

Wärmeaustauscher - Verfahren zur Messung und Bewertung der wärmetechnischen Leistungskenndaten von Nasskühltürmen

This European Standard was approved by CEN on 24 March 2005.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CEN member.

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EUROPEAN COMMITTEE FOR STANDARDIZATION
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EUROPÄISCHES KOMITEE FÜR NORMUNG

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## Contents

# Foreword

This European Standard (EN 14705:2005) has been prepared by Technical Committee CEN/TC 110 “Heat exchangers”, the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by December 2005, and conflicting national standards shall be withdrawn at the latest by December 2005.

This document includes a Bibliography.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

## 1 Scope

This European Standard specifies requirements, test methods and acceptance tests for thermal performances pumping head verification of wet cooling towers and plume abatement for wet/dry cooling towers.

This European Standard is applicable to natural draught wet cooling towers (see in 3.1.2.2) fan assisted natural draught cooling tower (see 3.1.2.3), wet/dry cooling towers (see 3.1.2.4) and "Mechanical draught cooling towers", except series ones.

It specifies the test methods, the apparatus required, the limitation of errors and the method for results examination.

The acceptance testing covers the verification of the thermal performance data and pumping head of the cooling tower as specified in the contract between the supplier and the purchaser. If these tests are required then this should be recognized at the time of the contract, as additional fittings, and preparations for the test may be required.

Deviations from the rules laid down below as well as additions need special agreement between purchaser and supplier and should be documented.

This standard does not apply to mechanical draught series wet cooling towers which are dealt with in EN 13741.

NOTE Terms like "design", "values", "guarantee" and "acceptance" used in this standard should be understood in a technical but not in a legal or commercial sense.

## 2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

EN 306, *Heat exchangers - Methods of measuring the parameters necessary for establishing the performance*

EN 872, *Water quality - Determination of suspended solids - Method by filtration through glass fibre filters*

EN 60751, *Industrial platinum resistance thermometer sensors (IEC 60751:1983 + A1:1986)*

EN ISO 5167-1, *Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 1: General principles and requirements (ISO 5167-1:2003)*

ISO 1438-1, *Water flow measurement in open channels using weirs and Venturi flumes - Part 1: Thin-plate weirs*

ISO 2975-3, *Measurement of water flow in closed conduits - Tracer methods - Part 3: Constant rate injection method using radioactive tracers*

ISO/TR 3313, *Measurement of fluid flow in closed conduits - Guidelines on the effects of flow pulsations on flow-measurement instruments*

# 3 Terms, definitions and symbols

## 3.1 Terms and definitions

For the purposes of this European Standard, the following terms and definitions apply.

**3.1.1**
**cooling tower**
apparatus in which water is cooled down by heat exchange with ambient air

**3.1.2**
**wet cooling tower**
cooling tower in which the heat exchange between the water and the air is achieved by a direct contact

**3.1.2.1**
**mechanical draught wet cooling tower**
wet cooling tower where the air circulation is produced by a fan

**3.1.2.1.1**
**series type mechanical draught wet cooling tower**
mechanical draught wet cooling tower, the design of which is fixed and described in the manufacturer's catalogue and for which the performance data are available, which allows tests evaluation over the defined range of operating conditions

**3.1.2.1.2**
**non series type mechanical draught wet cooling tower**
mechanical draught wet cooling tower, the design of which is project dependent and for which the performance data and test evaluation at specific operating conditions may be subject to agreement

**3.1.2.2**
**natural draught cooling tower**
wet cooling tower where the air circulation is produced only by a density difference between the cold air outside the cooling tower and the hot air inside

**3.1.2.3**
**fan assisted natural draught cooling tower**
natural draught cooling tower with the addition of fan to boost the draught

**3.1.2.4**
**wet/dry cooling tower (reduced plume cooling tower)**
cooling tower comprising two parts. In the first part, the heat exchange between the water and the air is achieved by direct contact and through a tight wall in the second part

**3.1.2.4.1**
**reduced plume wet/dry cooling tower**
wet/dry cooling tower designed for plume abatement

**3.1.2.4.2**
**water conservation wet/dry cooling tower**
wet/dry cooling tower designed for water conservation

**3.1.3**
**air flow**
total quantity of air, including associated water vapour flowing through the tower

**3.1.3.1**
**counterflow**
where air and water flows are in opposite direction in the filling

**3.1.3.2**
**cross flow**
where air flows perpendicular to the water in the filling

**3.1.4**
**ambient wet (dry) bulb temperature**
wet (dry) bulb temperature of air measured windward of the tower and free from the influence of the tower

**3.1.5**
**approach**
difference between recooled water temperature and inlet air wet bulb temperature

**3.1.6**
**inlet water flow**
quantity of hot water flowing into the tower

**3.1.7**
**cold water basin**
device underlying the tower to receive the recooled water from the tower and direct its flow to the suction line or sump

**3.1.8**
**cooling range**
difference between the hot water temperature and the recooled water temperature

NOTE The term "range" is also applied to this definition, but is regarded as a non-preferred term.

**3.1.9**
**drift loss**
water lost from the tower as liquid droplets with the same chemical characteristics as the circulating water, entrained in the outlet air

**3.1.10**
**heat load**
rate of heat to be removed from the water within the tower

**3.1.11**
**hot water temperature**
temperature of inlet water

**3.1.12**
**inlet air wet (dry) bulb temperatures**
average wet (dry) bulb temperatures of the inlet air; including any recirculation effect

**3.1.13**
**make-up**
water added to the circulating water system to compensate for water loss from the system by evaporation, drift, purge and leakage

**3.1.14**
**purge (blow down)**
water discharged from the system to control concentration of salts or other impurities in the circulating water

**3.1.15**
**recooled water temperature**
average temperature of the water at the cold water basin discharge excluding the effect of any make-up entering the basin or at the exhaust of the exchanger for wet/dry cooling tower

**3.1.16**
**recirculation**
portion of the outlet air that re-enters the tower

**3.1.17**
**interference**
intake of outlet air of adjacent cooling towers

**3.1.18**
**tower pumping head**
total head of water required at the inlet to the tower, to deliver the inlet water through the distribution system

**3.1.19**
**surfacic flow**
inlet water flow expressed in quantity per unit of plan packing area of the tower

**3.1.20**
**wet (dry) bulb temperature**
the temperature indicated by an adequately ventilated and wetted (non-wetted) thermometer in the shade and (where applicable) protected from any radiation effect

**3.1.21**
**atmospheric gradient**
air dry bulb temperature variation with altitude expressed in degree Celsius per 100 m

## 3.2 Symbols

For the purposes of this European Standard, the symbols of Table 1 shall apply.

**Table 1**

| Symbols | Designated parameters | Units |
|---|---|---|
| $A$ | Transfer surface per unit of volume | $m^{-1}$ |
| $a$ | Angle of an elbow | degree |
| $ap$ | Approach ($t_C$ - $t_W$) | K |
| $C$ | Heat coefficient | - |
| $CEV$ | Evaporation coefficient related to the difference in water content | $kg{\cdot}m^{-2}{\cdot}s^{-1}$ |
| $C_F$ | Load loss coefficient | - |
| $CFV$ | Evaporation coefficient related to the difference in water content | $kg{\cdot}m^{-2}{\cdot}s^{-1}$ |
| $C_S$ | Specific water consumption | $kg{\cdot}J^{-1}$ |
| $c_{pa}$ | Mass heat capacity of the air at constant pressure | $J{\cdot}kg^{-1}{\cdot}K^{-1}$ |
| $c_{pe}$ | Mass heat capacity of the water | $J{\cdot}kg^{-1}{\cdot}K^{-1}$ |
| $c_{pv}$ | Mass heat capacity of the vapour at constant pressure | $J{\cdot}kg^{-1}{\cdot}K^{-1}$ |
| $D_{10}$ | Direction of the reference wind in relation to the north | degree |
| $d$ | Hydraulic diameter | m |
| $F_p$ | Fan motor power | kW |
| $F_{pG}$ | Guaranteed fan motor power | kW |
| $g$ | Gravity acceleration | $m{\cdot}s^{-2}$ |
| $H$ | Draught height | m |
| $h$ | Mass enthalpy of the air | $J{\cdot}kg^{-1}$ |
| $h_1$ | Mass enthalpy of the air at the air inlet calculated from $p_a$, $t_s$ and $\varphi$ | $J{\cdot}kg^{-1}$ |
| $h_2$ | Mass enthalpy of the saturated hot air at the air outlet downstream from the drift eliminators | $J{\cdot}kg^{-1}$ |
| $h_s$ | Mass enthalpy of the saturated moist air at the water temperature | $J{\cdot}kg^{-1}$ |
| $h_{s1}$, $h_{s2}$ | Mass enthalpy of the saturated moist air at the water temperature with 1 = inlet, 2 = outlet | $J{\cdot}kg^{-1}$ |
| $k$ | Number of tests | |
| $\frac{KAV}{q_{me}}$ | Merkel number | - |
| $L_{vt}$ | Water vaporization latent heat at temperature t | $J{\cdot}kg^{-1}$ |
| $m$ | Circulating water volume flow rate at the cooling tower inlet | $m^3{\cdot}s^{-1}$ |
| $m_b$ | Calculated blow-down water volume flow rate | $m^3{\cdot}s^{-1}$ |
| $m_{bm}$ | Measured blow-down water volume flow rate | $m^3{\cdot}s^{-1}$ |

*(to be continued)*

**Table 1** *(continued)*

| Symbols | Designated parameters | Units |
|---|---|---|
| $m_E$ | Evaporated water volume flow rate | $m^3 \cdot s^{-1}$ |
| $m_m$ | Make-up water volume flow rate | $m^3 \cdot s^{-1}$ |
| $m^0$ | Number of a wind velocity class | |
| $m_p$ | Volume flow rate of water entrained by drift losses | $m^3 \cdot s^{-1}$ |
| $N$ | Characteristic index of nominal pattern | |
| $n$ | Constant exponent of the exchange law | |
| $n^b$ | Number of tests per $m^0$ class | |
| $n^b$m | Number of recorded values for each test | |
| $P$ | Thermal load | kW |
| $p_a$ | Atmospheric pressure | Pa |
| $p_{vs}$ | Saturating vapour pressure | Pa |
| $p_s$ | Static pressure | Pa |
| $p_v$ | Partial pressure of vapour in the air | Pa |
| $q_{mas}$ | Dry air mass flow rate | $kg \cdot s^{-1}$ |
| $q_{me}$ | Circulating water mass flow rate at cooling tower inlet | $kg \cdot s^{-1}$ |
| $q_{VF}$ | Recooled water recuperation system leaking water volume flow rate | $m^3 \cdot s^{-1}$ |
| $q_{Vi}$ | Local volume flow rate | $m^3 \cdot s^{-1}$ |
| $q_{VPC}$ | Volume flow rate of circulating pumps | $m^3 \cdot s^{-1}$ |
| $S_i$ | Flow section corresponding to the measurement point i | $m^2$ |
| $S_1$, $S_2$ | Cross sections perpendicular to the pressure taps on the water circuit | $m^2$ |
| $S_F$ | Exchange body front surface | $m^2$ |
| $T$ | Test starting time | h, min |
| $t$ | Temperature | °C |
| $t_a$ | Dry temperature of the ambient air | °C |
| $t_b$ | Blow-down water temperature | °C |
| $t_c$ | Mean temperature of the recooled water immediately above the plane of the cold water basin (rain water cooling tower) or immediately above the plane of the water in the troughs (water recuperator cooling tower) | °C |
| $t_{c,i}$ | Mean temperature of the recooled water for the test i | °C |

*(to be continued)*

**Table 1** *(continued)*

| Symbols | Designated parameters | Units |
|---|---|---|
| $T_{cG,i}$ | Guaranteed mean temperature of the recooled water for the test i | °C |
| $t_e$ | Mean temperature of the cold water at the cooling tower outlet (mixture of cooled water and make-up water) | °C |
| $t_h$ | Mean temperature of the hot water in the cooling tower inlet | °C |
| $t'_h$, $t''_h$ | Mean temperatures of the hot water in the inflows | °C |
| $t_k$ | Local temperature | °C |
| $t_m$ | Make-up water temperature | °C |
| $t_w$ | Wet bulb temperature at the air inlet | °C |
| $t_{wa}$ | Wet bulb temperature of ambient air | °C |
| $t_s$ | Dry bulb mean temperature at the air inlet | °C |
| $T_V$ | Basin cold water renewal time | min |
| $V$ | Total volume of the exchange body | $m^3$ |
| $v_D$ | Mean frontal velocity of the air at the exchange body inlet | $m \cdot s^{-1}$ |
| $v_i$ | Local flow velocity | $m \cdot s^{-1}$ |
| $v_1$, $v_2$ | Water velocities perpendicular to the measurement sections | $m \cdot s^{-1}$ |
| $v_{W10}$ | Reference wind velocity 10 m above ground level | $m \cdot s^{-1}$ |
| $x$ | Difference in level between the spray hole nozzle outlet and the water plane of the cold water basin | m |
| $\gamma$ | Coefficient of correction in the Merkel integral | - |
| $\tau$ | Student coefficient | - |
| $x\varphi$ | Absolute humidity of the ambient air | $\frac{\text{kg water}}{\text{kg dryair}}$ |
| $x\varphi_1$ | Absolute humidity of the air at air inlet | $\frac{\text{kg water}}{\text{kg dryair}}$ |
| $x\varphi_2$ | Absolute humidity of the air at cooling tower outlet | $\frac{\text{kg water}}{\text{kg dryair}}$ |
| $\varphi$ | Relative humidity of the ambient air | % |
| $\varphi_1$ | Relative humidity of the ambient air at air inlet | % |
| $\varphi_2$ | Relative humidity of the ambient air at cooling tower outlet | % |
| $\Phi$ | Fan power influence factor | K/% |
| $\rho$ | Density of the air | $kg \cdot m^{-3}$ |

*(to be continued)*

**Table 1** *(concluded)*

| Symbols | Designated parameters | Units |
|---|---|---|
| $\rho_e$ (t) | Density of the water of the circulating water circuit at temperature t | $kg \cdot m^{-3}$ |
| $\rho_1$ | Density of the air entering the cooling tower | $kg \cdot m^{-3}$ |
| $\rho_2$ | Density of the hot air at the outlet, downstream from the drift eliminators | $kg \cdot m^{-3}$ |
| $\sigma$ | Standard deviation of the wind velocity at 10 m ($V_{w10}$) during the test | $m \cdot s^{-1}$ |
| $\alpha_r$ | Weighting coefficient of the class r reference wind velocity | |
| $\Delta p$ | Circulating water pressure loss | Pa |
| $\Delta p_s$ | Differential static pressure measured on the water circuit between sections $s_1$ and $s_2$ | Pa |
| $\Delta t$ | Weighted difference on the recooled water temperature | K |
| $z$ | Difference in temperature on the water between the cooling tower inlet and outlet (Cooling range) | K |
| $t_{cK}$ - $t_{cG}$ | Difference to the guarantee on the recooled water temperature for a test | K |
| $\Delta t_r$ | Recooled water temperature difference for the class r reference wind velocity | K |
| $\theta$ | Instantaneous temperature of the recooled water | °C |
| $\lambda$ | Universal load loss coefficient for water conduits | |
| $\mu$ | Coefficient $\mu = \frac{h_2 - h_1}{h_{s1} - h_1}$ | |
| $\nu$ | Coefficient $\nu = \frac{h_{s1} - h_{s2}}{h_2 - h_1}$ | |

## 4 Performance tests – General

The performance tests forming the subject of this standard shall be carried out, unless otherwise specified, in the contract at least after three months of continuous operation and definitely after commissioning. It concerns the following performances:

- pumping head - flow rates and pressure loss (see 6.4.5);
- thermal performances - determination of the recooled water temperature at measured conditions (see 6.4.4.4);
- emission performances (drift losses);
- plume characteristics at the outlet (only for wet/dry cooling towers).

The method described in this standard for the verification of thermal performances apply to all cooling towers defined in the scope.

# 5 Guarantee

## 5.1 General

Prior to the contract the supplier shall have submitted performance documents available setting out the guaranteed properties as a function of the admissible influence parameters in order to document the guaranteed properties of the cooling tower supplied.

## 5.2 Guarantee documents

The supplier of a cooling tower shall guarantee:

a) the cooling tower pumping head;

b) the mean recooled water temperature ($t_c$) as a function of;

. dry bulb temperature, $t_s$

. relative humidity, $\varphi$ or wet bulb temperature $t_w$

. cooling range (*z*), or hot water temperature $t_h$

. water flow rate ($m$ or $q_{me}$)

and where applicable as a function of other parameters such as

. fan power consumption, $F_p$

. interference factor

. recirculation factor

. ambient (atmospheric) pressure, $P_a$

. atmospheric (vertical) temperature gradient, G

However for natural draft cooling towers extended tests checking wind effect at site on tower performance may be performed subject to the contract. If so, the supplier shall guarantee the average temperature of the recooled water $t_c$ as function of

. wind velocity, $V_{10}$

. wind direction, $D_{10}$

The guarantee documents can be in the form of spread sheets, curves, analytical expressions, computer program etc.

Performance curves should be presented in the format shown in Annex A, however other formats or appropriate formulas as acceptable provided they give the same information.

Curves shall have reading accuracy of 0,1 K. The area in which acceptance tests are permitted shall be indicated as per 5.3.2.

If correction curves are provided for the effect of other parameters (e.g. wind speed, atmospheric gradient, plume abatement, atmospheric pressure, interference factor, recirculation factor), they shall be used subject to contract.

c) For hybrid cooling towers the outlet air status has to be predicted for all specified boundary conditions:

. dry bulb temperature, $t_s$

. relative humidity, $\varphi$ or wet bulb temperature $t_w$

Other parameters may be guaranteed subject to the contract.

## 5.3 Validity conditions for measurements

### 5.3.1 General

The measurement results obtained during the course of the tests shall only be taken into account if the requirements mentioned below are met.

### 5.3.2 Acceptable operating conditions

a) During the tests:

The values of the following quantities may differ from the design values of the percentages shown below:

| | | |
|---|---|---|
| — | circulating water volume flow rate $m$: | ± 10 % of the design volume flow rate $m_N$, |
| — | cooling range $t_h - t_c$: | ± 20 % of the design temperature rise $t_h - t_{cN}$, |
| — | thermal load $P$: | ± 20 % of the design thermal load $P_N$, |

b) During the hour finishing at the end of the measuring period, the following gradient conditions shall be fulfilled:

- water flow rate $\leq \pm 2$ % per hour;
- heat load $\leq \pm 5$ % per hour;
- ambient wet bulb temperature $\leq 1$ K/hour.

### 5.3.3 Water conditions

The quality of the circulating water flow as well as that of the make-up water shall be within the range of the specification defined in the contract.

In particular dissolved and suspended solids, oil and organic components concentration shall be checked.

The total dissolved solid shall not exceed the greater of the following:

a) 5000 ppm;

b) 1,1 time the design concentration.

The circulating water shall contain not more than 10 ppm of oil, tar or fatty substances.

For measuring methods, see EN 872 for solids.

### 5.3.4 Other conditions

### 5.3.4.1 Equipment-related requirements

The whole cooling tower shall be in proper operating condition. In particular, the water distribution system, the drift eliminators and the exchange body shall not contain a quantity of foreign bodies likely to interfere with the normal flow of the water and air.

In order to establish that the cooling tower operates well, it shall be visited by both parts of the contract together before testing.

### 5.3.4.2 Climatic conditions-related requirements

The climatic conditions shall be within the normal operating ranges, these being defined by agreement between the customer and the manufacturer.

If the wind conditions are agreed by contract, the average wind velocity and peak wind velocity shall lie within the design limits specified in the contract. In that case, wind effect shall be provided by the cooling tower manufacturer, as mentioned in 9.3.2 or as shown in Annex A.

If no limits are defined in the contract, the average wind velocity shall not exceed 3 $m.s^{-1}$. The wind stability condition shall be that the standard deviation $\sigma$ of the wind speed ($m.s^{-1}$) of the reference wind shall not exceed a limit value during the half hour (30 min) preceding and during the measurements, whatever the duration of the test period may be.

$\sigma < 0,5 + 0,2\ V_{mean}$ for all cases

Furthermore, during the test, the atmospheric conditions shall comply with the following conditions:

- no rain, snow or hail;
- no fog, the difference between the dry temperature $t_a$ and the wet temperature $t_W$ shall be greater than 0,1 K;
- in the event of high obstacles (other cooling tower, machine room, ...) being in the vicinity of the cooling tower, only those tests for which the wind does not come from the direction of these obstacles are taken into account.
- the wet bulb temperature of the ambient air averaged at the air inlet $t_W$ shall be greater than or equal to 2 °C:

  $t_W \geq 2$ °C

Mainly for natural draught cooling towers it is essential to control the atmospheric gradient during the test since it affects the inlet air density which is part of the driving force that makes the cooling tower perform. If the atmospheric gradient is agreed by contract, the average gradient measured up to twice the cooling tower height shall be in the range of specification. If the atmospheric gradient is not defined in the contract the average gradient shall be negative and over -1 K per 100 m.

An indicator of the gradient may be the absolute difference between the dry mean temperature in the cooling tower air inlet $t_s$ and the dry temperature of the ambient air $t_a$. Between -1 K and 0 K corresponds in most cases to an atmospheric gradient between + 0 K per 100 m and -1 K per 100 m.

The difference between the dry temperature of the ambient air $t_a$ and the dry mean temperature in the cooling tower air inlet $t_s$ shall be such that:

$-1 < t_s - t_a < 0$ K

Another indicator of the cooling tower vertical dry bulb gradient shall be the difference in dry bulb between ground level and the top of the air inlet. For an acceptable test, the average dry bulb at or near the top of the air inlet shall be at least 0,15 °C less than the average dry bulb measured 1,5 m above grade level.

In suspicion of inversion (positive atmospheric gradient), whatever the indicator may be, performance tests can only be continued by agreement between all parties involved.

#### 5.3.4.3 Operating configuration-related requirements

The cooling tower shall be in its normal configuration, anti-freeze system out of service, by-passes closed.

#### 5.3.4.4 Conditions concerning the instrumentation

Prior to conducting the tests, the measuring probes employed and the measuring devices in the case of the use of an indirect method for determining a flow rate, shall be calibrated.

## 6 Test procedure

### 6.1 Test parameters

Table 2 summarises the parameters influencing the thermal test for each type of cooling tower within the scope of this European Standard.

**Table 2 — Parameters influencing the thermal test for each type of cooling tower**

| Type of cooling tower | Air temperature | Atmospheric gradient | Wind effect | Fan power | Other |
|---|---|---|---|---|---|
| Natural draught | Dry bulb (inlet)<br>Wet bulb (ambient) | X | X | - | |
| Fan assisted natural draught | Dry bulb (inlet)<br>Wet bulb (ambient) | X | X | X | |
| Mechanical draught (except series) | Wet bulb (inlet) | - | X | X [a] | X |
| Wet/dry plume abatement | | | | | Extra-plume verification |
| Natural draught | Wet bulb (ambient or inlet)<br>Dry bulb (inlet) | X | X | | |
| Mechanical draught | Wet bulb (ambient or inlet)<br>Dry bulb (inlet) | | X | X | |

[a] Recirculation is not part of the guarantee.

### 6.2 Quantities to be measured

The quantities to be measured for each of these performances shall be as follows:

a) Thermal performances:

- reference wind velocity measured 10 m above the floor;
- direction of the reference wind measured 10 m above the floor (only if certain sectors are to be taken into account);
- pluviometry (if necessary);
- atmospheric pressure, $p_a$;
- wet bulb temperature of the ambient air, $t_{wa}$, measured 10 m above the floor or alternatively relative humidity of the ambient air $\varphi$;
- dry bulb temperature of the ambient air, $t_a$, measured 10 m above the floor;
- dry bulb mean temperature of the air in the cooling tower inlet, $t_{s1}$;
- wet bulb mean temperature of the air at tower inlet, $t_w$, or alternatively relative humidity of the air at tower inlet $\varphi_1$;
- cold water temperature, $t_e$;
- hot water mean temperature of the circulating water (if applicable), $t_h$;
- make-up water temperature, $t_m$ (if necessary)[1) ;
- blow-down water temperature, $t_b$ (if necessary)[1);
- volume flow rate of the circulating water entering the cooling tower $m$;
- volume flow rate of the make-up water, $m_m$ (if necessary)[1);
- volume flow rate of the blow-down water, $m_b$ (if necessary)[1).

b) Cooling tower pumping head:

- pressure in water intake of the refrigerant inlet (or the limit of supply).

c) Drift loss performance:

- Volume flow rate of water with the same chemical characteristics as the circulating water entrained by drift losses, $m_p$.

d) Plume abatement:

- Wet bulb temperature at tower outlet $t_{w2}$ or relative humidity $\varphi_2$;
- dry bulb temperature at tower outlet $t_{s2}$ .

e) Atmospheric vertical gradient G;

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1) These temperatures and flow are only necessary if the corresponding auxiliary water flow rate enters or exits between the hot and cold water temperature measurement section.

f) Fan power consumption.

## 6.3 Quantities to be determined

The quantities to be determined by calculation are as follows:

- water mass flow rate in the cooling tower inlet;
- cooling range $t_h$ - $t_c$;
- transferred thermal load $P$;
- evaporated water volume flow rate $m_E$ (can be measured);
- recooled water mean temperature, $t_c$,

## 6.4 Measurements and calculation of the mean quantities

### 6.4.1 Measurements of atmospheric parameters

### 6.4.1.1 Measurements of the reference wind velocity and direction

The measurements of the wind velocity $v_{W10}$ and wind direction $D_{10}$ shall be conducted by means of cup-type anemometers and weather vanes or by means of anemometer/vane assemblies.

One measuring device is sufficient. However three measuring devices are required when extended tests checking wind effect at site on tower performance are performed.

For open field the measuring device shall be at a height of 10 m above the mean level of the ground and the location of the measurement support mast shall be defined as a function of wind sectors selected for the test and shall be if possible in an open spot at a minimum distance of 300 m from any sizeable obstacle (cooling tower, machine room relief, etc.). Should this be impossible an agreement shall be made between the manufacturer and the customer.

### 6.4.1.2 Measurement of the dry bulb temperature of the ambient air $t_a$ and wet bulb temperature $t_w$ or relative humidity and atmospheric pressure

If necessary, the dry bulb temperature and wet bulb temperature or relative humidity of the ambient air and the atmospheric pressure shall be measured at 10 m above the ground, in the vicinity of the location where the wind velocity and direction measurements were made using temperature probes and barometer.

Where necessary, the average vertical ambient dry bulb temperature gradient shall be measured in the surrounding of the cooling tower between the elevation of the centre of air inlet and up to twice the height of the cooling tower.

The probe(s) shall be protected from the sun's rays and from the rain.

### 6.4.1.3 Detection of rain

It may be carried out using a bucket-type pluviometer or indicate presence or rain (e.g. rain detector) or by visual examination.

#### 6.4.1.4 Measurements of the air inlet dry bulb temperature $t_s$ and wet bulb temperature or relative humidity

For undisturbed cooling tower's environment, air inlet dry bulb temperature $t_s$ and air inlet wet bulb temperature $t_w$ (or relative humidity) shall be measured close to the air inlet, at a maximum distance of 1,5 m of the air inlet.

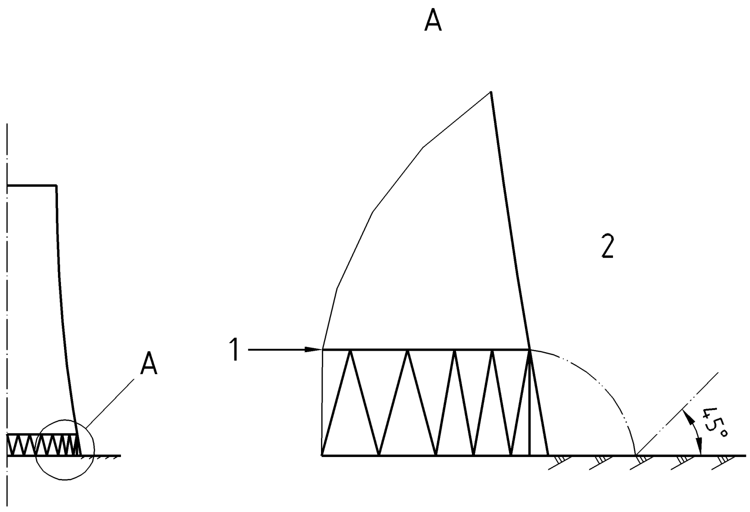
The minimum number of probes shall be $n_c \times n_v$, where $n_c$ = number of probes around the circumference, $n_v$ = number of probes along the height of air inlet (see Table 4).

Where several probes are used they shall be spread out at regulars intervals both in circumferential and vertical directions.

If the probes are located at only one level, they shall be preferably installed at the middle of the air inlet.

The probes shall be protected from possible projections of water and from the sun's rays.

The undisturbed cooling tower is identified by the fact that there are no obstructing elements protruding in the area limited by a circle the radius of which is the height of the air inlet and a line inclined at 45°, as shown on Figure 1.



**Key**

1 Higher level of the air outlet

2 Zone without obstructing element

Figure 1 — Zone without obstructing element at the air inlet

If these conditions are not fulfilled special boundaries conditions are necessary and shall be agreed by the parties involved. Where additional measuring points are used the results shall be weighted by the surface they represent.

### 6.4.2 Measurement and calculation of the absolute and relative humidities of the ambient air ($x\varphi$ and $\varphi$)

**Measurements**

The measurement of the ambient humidity shall be conducted either using three suction psychrometers or three hygrometers (for example dew point). This apparatus, protected from the sun's rays and the rain, is placed at a height of 10 m above ground level in the vicinity of the wind velocity and direction measurement points.

The psychrometer measurements of the dry and moist temperatures allow to determine the relative humidity of the ambient air as well as the absolute humidity for which one uses the formulae given in 8.2.3.

In the case of the use of hygrometers, the combined measurements of the relative humidity and dry temperature allow to calculate the wet bulb temperature, then the value of the absolute humidity of the ambient air using these same formulae.

### 6.4.3 Measurement of the atmospheric pressure ($P_a$)

The atmospheric pressure shall be measured using an absolute pressure sensor protected against the effects of the wind.

### 6.4.4 Water temperature

#### 6.4.4.1 Determination of the hot water temperature $\bar{t}_h$

Where possible the test shall be conducted with make-up and blow-down water circuits shut off.

If it is not possible temperatures shall be measured as in 6.4.4.2 and 6.4.4.3.

a) Measurement of the circulating water temperature on reaching the cooling tower:

- the hot water temperature shall be measured in the riser or in the water distribution of the cooling tower;
- in the case of two water inlets, the temperature shall be measured in each riser or in the water distribution;
- the measuring device shall comprise at least 3 probes per riser or water distribution.

b) Calculation of the mean temperature of the hot water:

- hot water intake: the mean temperature $\bar{t}_h$ is equal to the arithmetical mean of the temperatures measured at each point;
- two hot water intakes: the mean temperature of the hot water shall be calculated by weighing the temperatures by the corresponding flows

#### 6.4.4.2 Determination of the make-up water temperature $t_m$

The make-up water temperature shall be measured at the entry into the cooling water circle.

The measuring device comprises three probes.

The mean temperature of the make-up water is equal to the arithmetical mean of the measured temperatures.

#### 6.4.4.3 Determination of the blow-down water temperature $t_b$

The blow-down water temperature shall be measured in the blow-down discharge structure, at the boundary of the cooling tower.

The measuring device shall comprise three probes.

The mean temperature of the blow down water is equal to the arithmetical mean of the measured temperatures.

#### 6.4.4.4 Determination of the recooled water temperature $t_c$

##### 6.4.4.4.1 Measurement of the temperature of the circulating water leaving the cold water basin

###### 6.4.4.4.1.1 General

The circulating water temperature shall preferably be measured inside the pipes, at cooling tower outlet structure and upstream the (cold water) pump (s) or directly in the water discharge structure. Measurements may also be performed down stream the pump but in that case correction of recooled water measured temperature shall be made to take account of heat input from the pump and precautions are needed to prevent damage (e.g. thermometer break).

###### 6.4.4.4.1.2 Measurements inside the pipes

In the case of several outflows, the temperature shall be measured in each of them.

The minimum number of probes at one outflow shall be 2,5 $(q_{me}.10^{-3})^{1/2}$ where $q_{me}$ is expressed in kg·s$^{-1}$. They shall be located as indicated in EN 306.

###### 6.4.4.4.1.3 Measurements in the water discharge structure

The minimum number of probes shall be 2,5 $(q_{me}.10^{-3})^{1/2}$, where $q_{me}$ is expressed in kg·s$^{-1}$.

Where the depth of water exceeds 1,5 m, two levels of probes shall be used.

NOTE If the temperature at at one or more measuring points differs by more than 1 K from the average, a first step to reduce the uncertainty should be to double the number of sensors installed.

In the case the uncertainty remains unacceptable, it should be necessary to weight the temperature by local velocity (to be measured).

In this case, it is necessary to draw up velocity charts for the water perpendicular to the measurement section if the average temperature at one or more measuring point varies by more than 1 K during measuring period per outlet. These charts enable one on the one hand to define the minimum number of probes to be installed and their location and furthermore to carry out, if necessary, on the basis of the conditions described, the weighting of the temperatures by the velocities.

Where make-up circuit is not shut off precautions shall be taken e.g. measures of the velocity field to prevent heterogeneous flows to be undetected.

### 6.4.5 Water flow rates

#### 6.4.5.1 General

There exist two types of water flow rates which enter and leave the cooling tower:

a) Time-invariant flow rates (flow rates produced by pumps, without adjusting mechanisms on the circuit).

NOTE 1 Precautions should be taken to ensure that pressure losses are constant during the test (clean lines).

b) Flow rates which are variable as a function of the settings (water level, valves, thresholds,...).

NOTE 2 The measurements of such flow rates are conducted on a continuous basis during the performance tests.

#### 6.4.5.2 Measurement of the circulating water volume flow rate at the cooling tower inlet $m$

Depending on the type of cooling circuit, this flow rate is invariant or variable.

In the first case, the measurement shall be conducted for each configuration of the pumps to be tested in operation using the velocity area method, the constant flow injection method using radioactive tracers (ISO 2975-3), or any other equivalent method.

When conducting thermal performance tests, the configuration of the pumps in operation shall be checked in order to determine the total flow rate.

In the second case, one shall use either an absolute method by standardized pressure-reducing appliances (see EN ISO 5167-1 and ISO/TR 3313) or by a standardised overflow (see ISO 1438-1), or an indirect method which requires preliminary calibration.

#### 6.4.5.3 Measurements of the make-up water volume flow rate $m_{\mathrm{m}}$

If the make-up circuit is not shut off during the test, $m_{\mathrm{m}}$ shall be measured.

The measurement shall be conducted either by an absolute method by standardised pressure-reducing appliances (EN ISO 5167-1 and ISO/TR 3313) or by a standardised overflow (see ISO 1438-1), or an indirect method which requires preliminary calibration.

#### 6.4.5.4 Measurement of the blow-down water volume flow rate $m_{\mathrm{bm}}$

If blow-down water circuit is not shut off during the test $m_{\mathrm{bm}}$ shall be measured.

The measurement shall be conducted either by an absolute method by standardized pressure-reducing appliances (EN ISO 5167-1 and ISO/TR 3313) or by a standardized overflow (see ISO 1438-1), or an indirect method which requires preliminary calibration.

#### 6.4.5.5 Cooled water recuperation system leaking water volume flow rate $q_{\mathrm{VF}}$

This quantity is calculated at the time of the thermal performance tests.

The leakage flow rate value shall be obtained from the measured or predetermined volume flow rates ($m_{\mathrm{bm}}$ and $m_{\mathrm{m}}$), and the calculated volume flow rates ($m_{\mathrm{b}}$ and $m_{\mathrm{E}}$).

The uncertainty inherent to this method only allows to verify that the leakage flow rate is below the imposed contractual threshold.

#### 6.4.5.6 Circulating water circuit mechanical load loss $\Delta p$

##### 6.4.5.6.1 Hydraulic conditions

During the tests, the mechanical pressure loss of the water shall remain below the threshold specified at the time of ordering.

#### 6.4.5.6.2 Measurement method

The mechanical pressure loss shall be determined from:

- a differential static pressure $\Delta p_s$ measurement carried out using a differential pressure probe;
- the measurement of two relative pressures carried out using two probes.

The terminals of the probes shall be connected up to two static pressure taps, one being installed in a hot water inlet pipe, the other in a cold water outflow pipe.

The calculation of the mechanical pressure loss uses in addition the following data:

- the areas of the cross sections of the water inflow and outflow pipes perpendicular to the pressure taps;
- the difference in level between the nozzle outlet of the spray nozzles and the water plane of the cold water basin.

The pressure measurement sections shall be sufficiently remote from the downstream and upstream pipe irregularities, so that there is not too much interference in the velocity area. The measurement sections may be located inside or outside the structure.

The water level in the cold water basin shall be kept at the nominal value throughout this test.

#### 6.4.5.6.3 Measurement of the volume flow rate of the circulating pumps $q_{VPC}$

See 6.4.5.2.

#### 6.4.5.7 Measurement of the make-up water volume flow rate $m_m$

The measurements shall be made as stated in 6.4.5.3.

### 6.4.6 Analysis of the circulating water

The concentrations of suspended or dissolved matter, of oils, tars and fatty substances in the circulating water shall be measured in accordance with EN 872.

### 6.4.7 Cooling tower pumping head

The tower pumping head shall be evaluated according to equation:

$$H_p = \frac{(p - p_a)}{\rho g} + \frac{v^2}{2g} + H$$

$p$ is the measured static pressure (in Pa)

$H$ is the height above the basin curb (in m)

It should be corrected by the dynamic pressure losses between measuring point and inlet duct at the height of the upper edge of the basin. Dynamic pressure losses in this sense are for example due to wall friction, bends and abrupt changes of section.

### 6.4.8 Fan power consumption

Only the electrical power used by the fan motors shall be measured.

Power input shall be determined by measurement of the voltage, current, and power factor or by measurement of the power input. When it is necessary to measure fan motor power input at some point distant from the motor, provision shall be made to account for line losses between the point of measurement and the motor.

If the performance guarantee is based on driver output, efficiencies stated by the manufacturer of the driver may be used.

The power measuring instrument shall be calibrated by a recognized, independent laboratory to an accuracy of at least ± 1,5 % prior to test (see Table 3).

**Table 3 — Typical tolerances for different power measurements**

| Fan power measurement | Typical tolerance range as % of fan power |
|---|---|
| Watt-meter | 1 % - 5 % |
| Volt/Amp-meter | 3 % - 8 % |

### 6.4.9 Drift losses performance tests

#### 6.4.9.1 Drift losses conditions

The volume flow rate of water entrained by drift losses $m_P$ shall remain below the threshold specified at the time of ordering.

#### 6.4.9.2 Measurement method

The volume flow rate of water entrained by the air shall be measured at 16 points, the latter being spread out in such a manner that each one monitors approximately 1/16 of the air flow rate:

- counterflow cooling tower: the measurement shall be conducted at a height of 1,5 m above the drift eliminators,
- crossflow cooling tower: the measurement shall be conducted at a distance of 3 m downstream from the drift eliminators or at the fan exhaust.

The volume flow rate of entrained water shall be measured using an isokinetic sensor where the volume of water gathered is deduced from the quantity of salts collected, or by any other equivalent method.

### 6.4.10 Extra-plume verification

#### 6.4.10.1 General

For cooling towers designed for plume abatement the plume invisibility has been proofed if the measured outlet air state and the predicted outlet air state are in a specified range of tolerance e.g. in the Mollier diagram.

#### 6.4.10.2 Measurements

The outlet air state is measured at a fictitious plane at 1 m above the outlet of the same diameter as the outlet structure. The measurements are taken along the main axis of the air outlet.

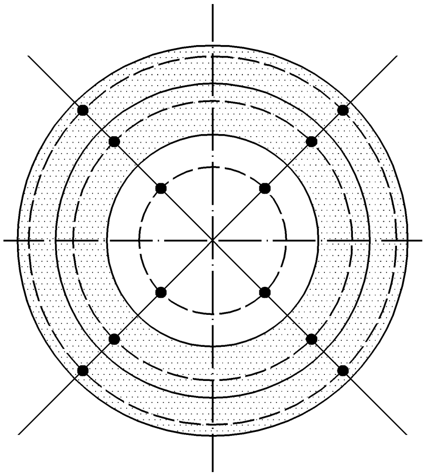


Figure 2 — Example of sectioning of the measuring area (circular area)

The outlet area is sub-divided in adequate sections which are equal in area.

On the lines of gravity of these sections as well as the central point, one psychrometer each is installed. The dry bulb temperature $t_{s2}$ and the wet bulb temperature $t_{w2}$ are the data measured for the appropriate segment.

All further outlet air data, and in particular the relative humidity $\varphi_2$ can be calculated on the basis of the dry bulb and wet bulb temperatures.

## 6.5 Arrangement of measuring devices

The supplier shall elaborate by contract in accordance with the customer or his representative the necessary measuring plan for conducting the acceptance by selection in the complete arrangement those which are deemed important (see Annex B).

Subsequent modifications of this plan shall be subject of agreement between the parties.

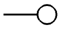
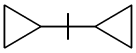
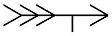
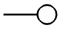
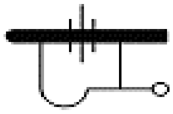
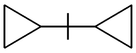
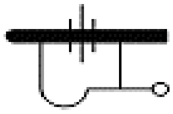
For the determination of the minimum number of measuring points, Table 4 shall be used. The number of measuring points shall be determined taking into account eventually additional local considerations.

The parameters to be measured and their symbols shall comply with Table 5.

**Table 4 — Minimum number and arrangement of measuring points**

| N° | Parameter | Minimum number | Remark |
|---|---|---|---|
| 1 | Water volume flow | 1 for each pipe | In the pipe. |
| 2 | Hot water temperature | 0,5 $\frac{A}{m^2}$<br>A = surface of the pipe section at measuring point. | In the middle of the flow. |
| 3 | Cold water temperature | 2,5 $(\frac{m}{k.s^{-1}}\ 10^{-3})^{0,5}$ | Measure at the basin outlet. Determination at the key point by splitting the flow into M sections of equal surface. For depth over 1,5 m two measuring lines one over the other. |
| 4 | Inlet dry and wet bulbs temperature | $n_c = \left\lvert L_{ai}^{0,3} + 0,5 \right\rvert_{\text{int}}$<br>in the horizontal direction<br>$n_v = \left\lvert \frac{h_{ai}}{6} + 1 \right\rvert_{\text{int}}$<br>in a vertical direction<br>$L_{ai}$ length of air inlet (m)<br>$h_{ai}$ height of air inlet (m) | |
| 5 | Surrounding air inlet relative humidity | $n_c = \left\lvert L_{ai}^{0,3} + 0,5 \right\rvert_{\text{int}}$<br>in the horizontal direction<br>$n_v \geq 1$ in a vertical direction | If the air inlet wet bulbs are not measured. |
| 6 | Air pressure | 1 | |
| 7 | Wind speed | 1 | See 6.4.1. |
| 8 | Fan power | 1 | At power inlet or at electrical cabinet in case of multiple power inlet. |
| 9 | Pumping head | 1 | See 6.4.7. |

Table 5 — Parameter to be measured and symbols

| N° | Parameters to be measured | Symbols |
|---|---|---|
| 1 | Inlet air temperature |  |
| 2 | Inlet wet bulb temperature or relative humidity | |
| 3 | Atmospheric pressure, 10 m above ground |  |
| 4 | Wind speed, 10 m above ground |  |
| 5 | Wind direction, 10 m above ground |  |
| 6 | Ambient temperature, 10 m above ground |  |
| 7 | Ambient wet bulb, 10 m above ground | |
| 8 | Atmospheric pressure |  |
| 11 | Hot water mass flow rate |  |
| 12 | Hot water temperature |  |
| 13 | Cold water temperature | |
| 14 | Cold water flow velocity, if necessary |  |
| 15 | Pumping head | |
| 21 | Plume temperature |  |
| 22 | Plume velocity |  |
| 23 | For large towers |  |
| 31 | Fan power | |
| 41 | Make-up water temperature |  |
| 42 | Make-up water flow rate |  |
| 43 | Blow down water flow rate | |

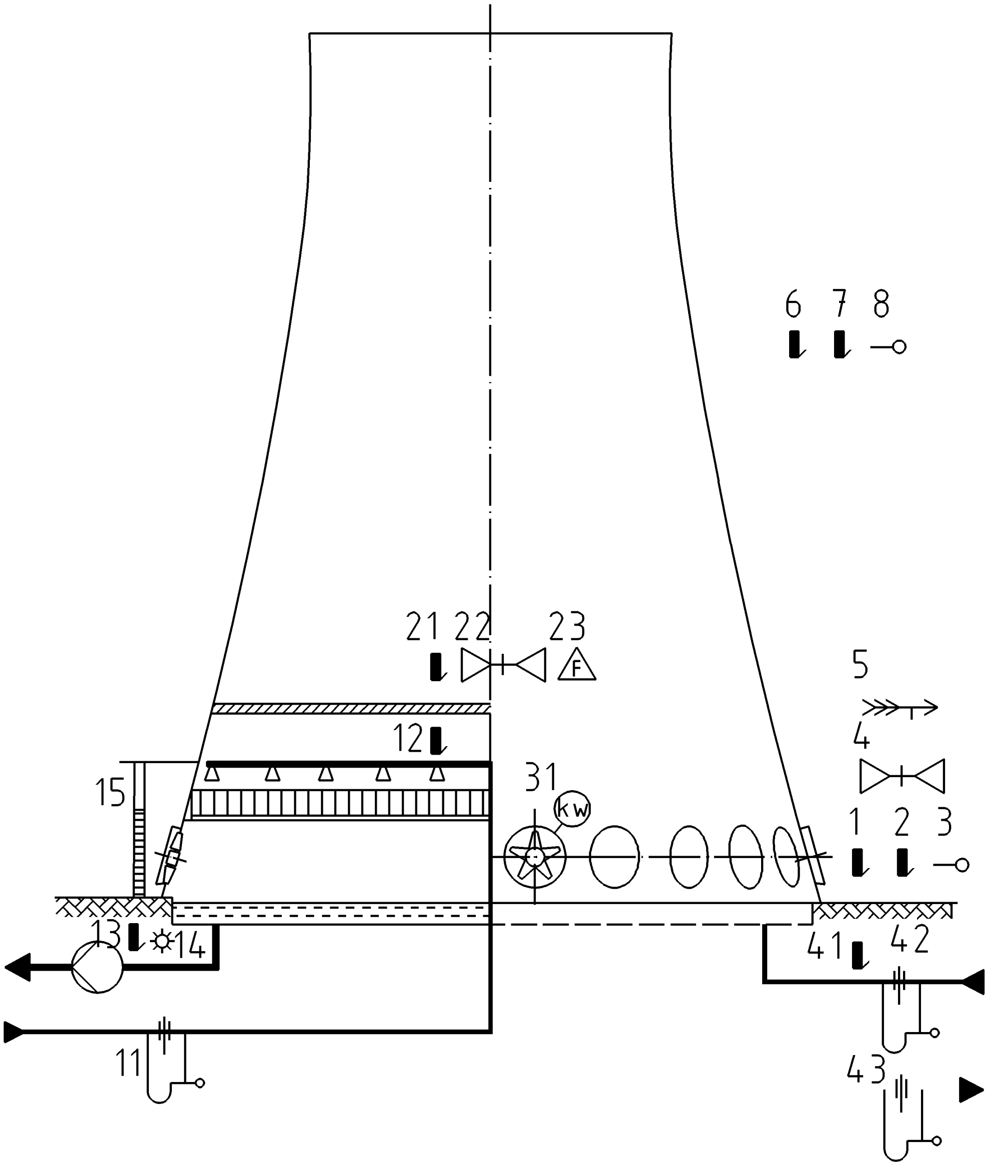


Figure 3 — Measuring arrangement for fan assisted natural draught cooling tower

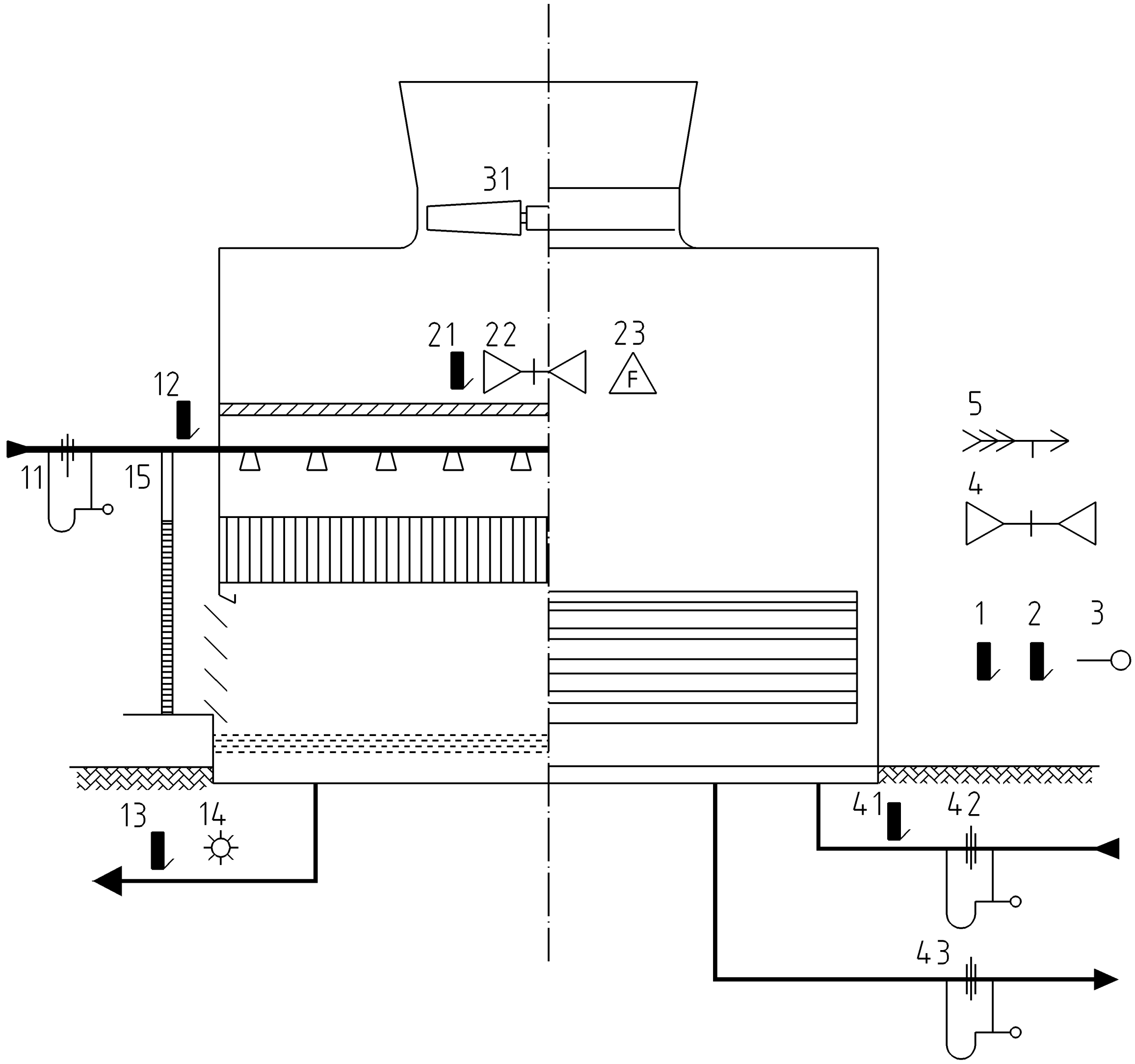


Figure 4 — Measuring arrangement for mechanical draught cooling towers

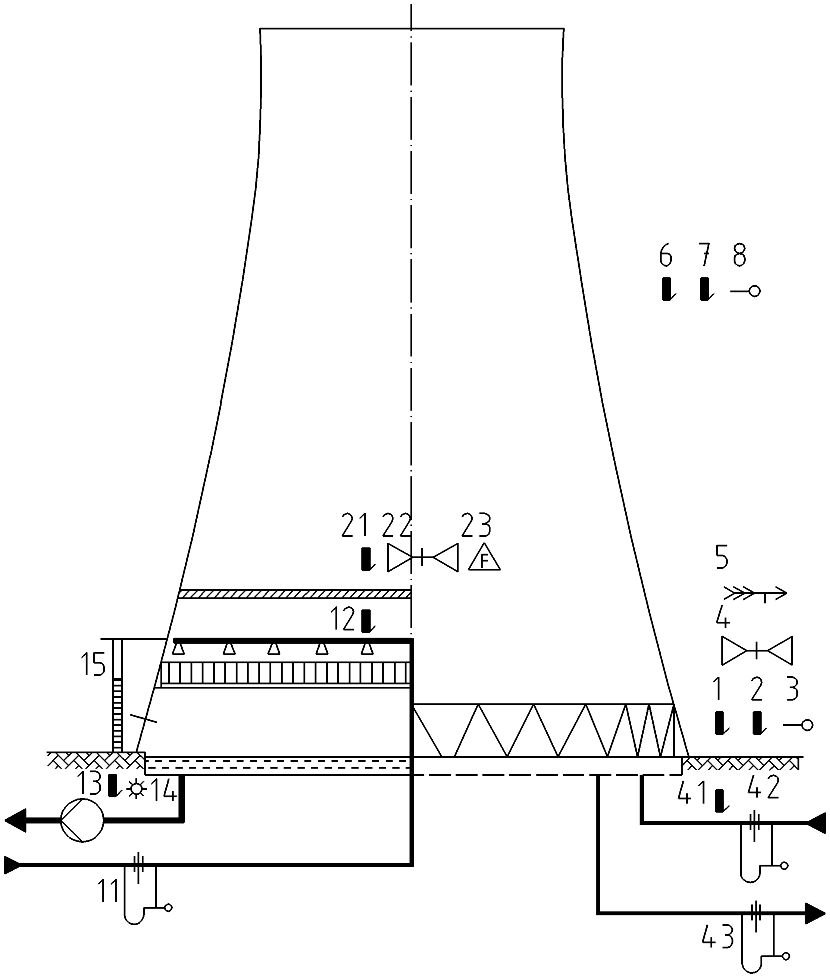


Figure 5 — Measuring arrangement for natural draught wet cooling tower

## 6.6 Measuring apparatus

### 6.6.1 Data acquisition method

The measurement shall be conducted using a data acquisition device which allows to record in a few seconds the indications given by all of the measuring devices involved.

### 6.6.2 Sensors

The characteristics of the sensors which allow to measure the parameters relating to the hydraulic and thermal performance tests (as defined in this standard) are presented in Annex B.

### 6.6.3 Inspections to be carried out prior to testing

A certain number of inspections shall be carried out prior to conducting the actual tests:

- checking of the good condition of the equipment;
- calibration of the sensors being used;

- previous calibration of the measuring devices in the case of the use of an indirect method for determining a flow rate.

# 7 Conducting the performance tests

## 7.1 Definition of a test

### 7.1.1 Basic test

A total basic test shall consist of:

. periods with a time duration of one hour each. The acquired data of every measured quantity have to be averaged over each period;

. each period consists of intervals lasting a maximum of 10 min. All measuring points have to be acquired at least once within each interval. The acquired data of each interval have to be averaged for each measured quantity.

### 7.1.2 Extended test

Where an extended test is agreed upon, a total test shall consist of:

. periods with a time duration of 10 min each. The acquired data of every measured quantity have to be averaged over each period;

. each period consists of intervals lasting a maximum of 2 min. All measuring points have to be acquired at least once within each period.

Moreover to evaluate properly wind effect on performances additional validity conditions shall be fulfilled:

. during the hour preceding the end of the period the difference between the maximum and minimum values of the temperature of the recooled water shall not exceed 1 K;

. wind velocity condition (see 5.3.4.2);

$\sigma \langle$ 0,5 + 0,2 $V_{10}$ averaged

. during the period the variation in the recooled water temperature shall not exceed 0,2 K.

### 7.1.3 Principle

The principle of this test is to compare:

- the measured recooled water temperature to the recooled water temperature as guaranteed by the cooling tower manufacturer for the cooling tower test conditions and corrected eventually for the measured wind speed.

- the measurement results obtained in a period shall only be taken into account in the test if the requirements mentioned in 5.3 are met. All the valid periods recorded shall be taken into consideration in the test.

This method of test can only be applied if:

- the running conditions are inside the range covered by the manufacturer performance charts;

- the wind velocity is inside the range covered by the manufacturer wind influence curve (if provided).

## 7.2 Duration of the test

### 7.2.1 Duration of the acceptance test – Number of periods

#### 7.2.1.1 Basic test

Acceptance measurement duration shall be chosen according to change with time of the air temperature in order to reach an accurate and satisfactory mean value and shall represent a complete day.

If the change in the dry air temperature is greater than ± 1 K/h during the performance test, then equivalent measuring windows with rising and falling branches of the dry air temperature, shall be used for the assessment. Each individual measuring period shall last one hour.

For larger cooling tower, a basic test shall consist of ten periods.

A smaller number of test periods shall be acceptable, if tests conditions are particularly steady.

For small cooling tower, a minimum of two periods shall be satisfactory.

#### 7.2.1.2 Extended test

In order to reach an accurate out satisfactory mean value according to wind effect the thermal acceptance inspection requires at least 300 periods.

If the period of the acceptance test includes large changes of parameters, the measuring time shall be considered long enough if a total of at least 300 periods can be assessed.

Acceptance measurement shall be representative of a complete day. Periods occurring with air temperature increasing and air temperature decreasing shall have equal weighting.

### 7.2.2 Frequency of readings (see 7.1)

#### 7.2.2.1 General

An interval shall last 10 min (or 2 min for extended tests maximum). It begins at the time $T$ and stops at the time $T$ + 10 (or 2) (counted in minutes). The characteristic values of an interval shall be deduced from the means of the measurements conducted during these said minutes.

For extended test, subject to the conditions mentioned in 7.1.2 being fulfilled, the first interval of a series can therefore only be considered as being completed after one hour of readings.

If they comply with these same conditions, the following intervals shall be consecutive.

#### 7.2.2.2 Data acquisition

Each interval, of a duration of 10 min (or 2 min for extended tests) shall be organized in the following manner:

- scanning of the instantaneous values of all the parameters at the minimum at the times $T$ and $T$ + 10 (or 2), counted in minutes;
- scanning, at a minimum of five times per minute, of the wind velocities and of the wind direction.

Wind speed should be measured continuously this allowing gust of wind to be registered.

### 7.2.2.3 Calculation of the means at each measuring point

#### 7.2.2.3.1 Reference wind velocity and direction

Their means during the interval are equal to the arithmetical means of the few dozen measurements conducted during the interval.

#### 7.2.2.3.2 Other measurements

##### 7.2.2.3.2.1 General

Their means during the interval are equal to the arithmetical means of the measurements conducted between the times $T$ and $T + 10$ (or 2) (limits included).

The conditions under which the calculations of the test-related quantities are made from these mean values are described here under.

##### 7.2.2.3.2.2 Calculation of the mean temperature of the cold water $t_a$

**Measurements conducted directly in the water discharge structure**

In this case, two possibilities are to be considered for each outflow:

- If the maximum difference between the temperatures measured is inferior to 1,0 K, the mean temperature of the circulating water leaving the basin is equal to the arithmetical mean of the temperatures measured.
- If the maximum difference between the temperatures measured is greater than 1,0 K, each temperature measurement $t_i$ is weighted by the velocity at the same point $v_i$. The mean temperature of the circulating water leaving the basin is equal to:

$$t_a = \frac{\sum v_i t_i}{\sum v_i}$$

(each measurement point relates to an equal surface).

##### 7.2.2.3.2.3 Calculation of the mean temperature of the recooled water $t_c$

The temperature of the recooled water $t_c$ is derived from the temperature of the cold water $t_e$ account being taken of:

- the thermal inertia of the basin,
- the atmospheric gradient,
- the auxiliary water flow rates which intervene at the level of the cold water basin or of the water outlet upstream from the cold water temperature measurement section.

EXAMPLE In the event of the blow-down and make-up intervening at the level of the cold water basin, the calculation of $t_c$ shall be conducted with the aid of the following equations:

- introduction of the auxiliary flow rates:

$$\theta = \frac{q_{Ve} t_e + q_{Veb} t_{eb} - q_{Vem} t_{em}}{q_{Ve} + q_{Veb} - q_{Vem}}$$

From this one derives the values of q at the times $T$ and $T$ + 10, calculated with the aid of the predetermined values $m$, $m_{\mathrm{m}}$, as defined in 6.4.5.6, 8.2.7 and $t_{\mathrm{e}}$, $t_{\mathrm{b}}$, $t_{\mathrm{tm}}$ measured at these times. In the case of the simplified tests $t_{\mathrm{b}} = t_{\mathrm{e}}$.

— introduction of the thermal inertia:

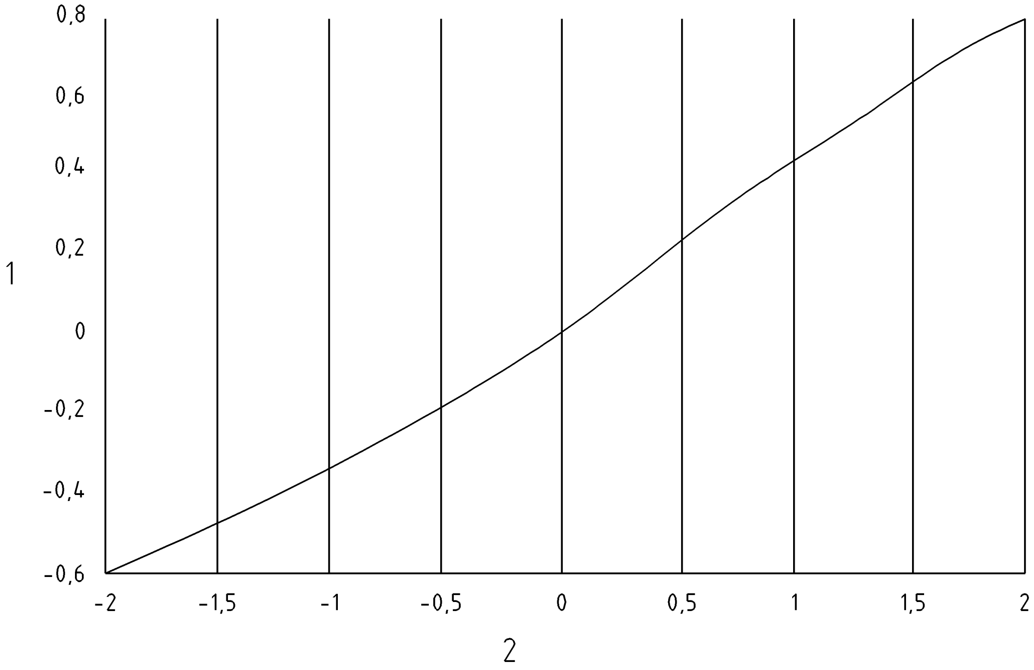
One shall use the following formula which supposes the make-up water temperature as being constant. However, the error made is quite negligible.

$$t_2 = \frac{1}{2}(\theta(T+10) + \theta(T)) + \frac{T_{\mathrm{V}}}{10}(\theta(T+10) - \theta(T))$$

where $T_{\mathrm{V}}$, basin renewal time, shall be determined from the volume of water in the basin and from the water volume flow rate $m$.

— introduction of atmospheric gradient.

An example of gradient effect on cold water temperature is shown in Figure 6:



**Key**

1 Effect on cold water (in kelvins)

2 Atmospheric gradient (in kelvins per 100 m)

Figure 6 — Gradient effect on cold water T

Average value of G is - 0,65 K/100 m (decrease) of height. Positive value means inversion.

#### 7.2.2.3.2.4 Determination of the evaporated water volume flow rate $m_{\mathrm{E}}$

The value of the evaporated water flow rate shall be determined either from manufacturer's data or any other equivalent method.

#### 7.2.2.3.2.5 Determination of the blow-down water volume flow rates $m_b$ and $m_{bm}$

The determination of these flow rates shall be conducted as indicated below:

a) Irrespective of the cooling tower type involved, the value of the blow-down water volume flow rate $m_b$ which enters into the calculation of the corrected cooled water temperature, shall be taken as being equal to the difference between the make-up water volume flow rate $m_m$ (see 6.4.5.3) and the evaporated water volume flow rate $m_E$ (see 7.2.2.3.2.4):

$m_b = m_m - m_E$

b) The value of the blow-down water volume flow rate $m_{bm}$, which enters into the calculation of the recuperation system leaking water volume flow rate $q_{VF}$ shall be measured as stated in 6.4.5.4.

#### 7.2.2.3.2.6 Determination of the recuperation system leaking water volume flow rate $q_{VF}$

In cooling towers, it is necessary to check that the leaking water volume flow rate of the recuperation system (see 6.4.5.5) is inferior to the contractual value.

The leakage flow rate value shall be determined from the measured or predetermined flow rates $m_{bm}$ and $m_m$, and from the calculated flow rates $m_b$ and $m_E$:

$q_{VF} = m_b - m_{bm}$ where $m_b = m_m - m_E$

#### 7.2.2.3.2.7 Calculation of the entrained water flow rate

The drift losses flow rate shall be calculated from the arithmetic mean of the results obtained at the different measuring points.

# 8 Calculation methods

## 8.1 General

See 8.2.7 for $\rho_e$ water density at hot water temperature in addition to formulas given, relative humidity as a function of dry and wet built temperature for air density (see 9.3.5.3).

## 8.2 Methods

### 8.2.1 General

See 7.2.2.3 for mean value calculation at each measuring point.

### 8.2.2 Calculation of means wind velocity and direction

The mean velocity of the wind $V_{10}$ is equal to the arithmetical mean of the two nearest velocity measurements, the latter having between them a size tolerance inferior to 0,2 $m \cdot s^{-1}$.

The mean direction of the wind $D_{10}$ is equal to the arithmetical mean of the two nearest direction measurements, the latter having between them a size tolerance inferior to an angle of 10°.

### 8.2.3 Calculation of mean absolute and relative humidity

The mean values of the absolute $x\varphi$ and relative $\varphi$ humidity of the ambient air are equal, in both cases, to the arithmetical mean of the two nearest values during an interval, the latter having between them a relative difference inferior to 10 %.

### 8.2.4 Calculation of the dry mean temperature of the ambient air

The dry mean temperature of the ambient air $t_a$ is equal to the arithmetical mean of the two nearest temperatures, the latter having between them a tolerance inferior to 0,2 K.

### 8.2.5 Calculation of the mean temperature

The mean temperature is equal to the average of the different measurements taken over the complete set of probes for a given interval.

$$t_s = \sum_{1}^{n_c \cdot n_v} \frac{t_i}{n_c \; n_v}$$

### 8.2.6 Calculation of the mechanical pressure loss

On the basis of the measured differential static pressure $\Delta p_s$, the mechanical pressure loss $\Delta p$, corresponding to the volume flow rate $m$, is obtained by carrying out the following corrections:

a) Variation in the kinetic energy of the water between the cross sections $S_1$ and $S_2$ perpendicular to the pressures taps:

$$\frac{1}{2} \rho_e \, (\mathrm{v}_2^1 - \mathrm{v}_2^2)$$

b) If the pressure taps are not situated at the limits of the structure, the mechanical load loss per unit of length in the pipe sections located between the measurement sections and the limits of the structure shall be calculated by Colebrook's formula using the following universal mechanical load loss coefficient for circulating water pipes of diameter $D$:

$$\lambda \, \rho_e \, \frac{v_i^2}{2D}$$

Uncommon pressure losses due to the elbows shall be calculated using the formula:

$$0{,}2 \times \frac{a}{90} \times \frac{\rho_e v_i^2}{2}$$

c) If the pressure loss measurement is carried out for a volume flow rate m different from the nominal flow rate $m_N$, the pressure at the nominal flow shall be deduced from measured pressure loss $\Delta p$:

$$\Delta p_N = p_0 + (\Delta p - p_0) \cdot \left( \frac{m_N}{m} \right)^2$$

with: $p_0 = \rho_e g x$

### 8.2.7 Calculation of the volume flow rate of circulating water entering the cooling tower $m$

This flow rate is composed of the flow rate of the circulating pumps (invariant), corrected for auxiliary flow rates (make-up, blow-down), if any, when the latter are injected or sampled between the outlet of the pumps and the cooling tower inlet.

The volume $m$ and mass $m_\mathrm{e}$ flow rates shall be defined at the cooling tower inlet.

$m$ result from measurement (see 6.4.5.6.3). Accuracy on $m$ measurement is essential for the evaluation of the thermal performances.

The calculation of the mass flow rate introduces the density of the water $\rho_\mathrm{e}$ at the hot water temperature. It is calculated by the following formula:

$$\rho_\mathrm{e} = 998{,}36 - 0{,}4116(t-20) - \frac{2{,}24(t-20)(t-70)}{625}$$

This formula is derived from the values recommended by the 6th International Conference on the properties of water and steam. Within the range from 10 °C to 50 °C, the relative error on $\rho_\mathrm{e}$ is inferior to $1 \times 10^{-4}$.

### 8.2.8 Determination of the transferred heat load ($P$)

The value of the transferred heat load results from the measurement of the output of the whole installation.

### 8.2.9 Verification of guarantee of plume invisibility

#### 8.2.9.1 General

The verification of plume invisibility is divided into two parts:

a) Verifying the mixing point to be reached according to the prediction as per thermal performance characteristic;

b) Verifying the mixing quality of the two air flows, i.e. homogeneous mixing above the air outlet.

#### 8.2.9.2 Guarantee verification of the mixing point

The outlet air states $t_{\mathrm{s2nominal}}$, $\varphi_{\mathrm{2nominal}}$, and $x_{\mathrm{2nominal}}$ which were predicted for the current operating state are determined using the thermal performance characteristic of the hybrid cooling tower. These outlet air states result in the theoretical mixing point $MP_{\mathrm{nominal}}$, (see Figure 7).

The mean value per spatial unit and time unit of the outlet air temperature $t_{\mathrm{s2actual}}$ and the outlet air humidity $\varphi_{\mathrm{2actual}}$ are calculated on the basis of the measured data.

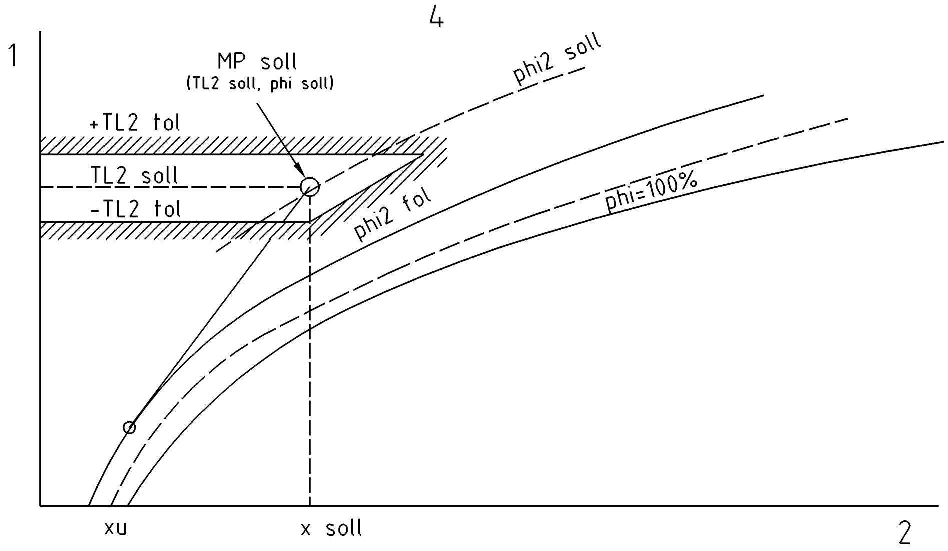
The mixing point $MP_{\mathrm{actual}}$ in the Mollier-h-x-diagram is determined with these data.

The guarantee is fulfilled if:

$$t_{\mathrm{s2}_{\mathrm{nominal}}} - t_{\mathrm{s2}_{\mathrm{actual}}} \leq \varepsilon_1$$

$$\varphi_{2_{\mathrm{nominal}}} - \varphi_{2_{\mathrm{actual}}} \geq \varepsilon_2$$

with $\varepsilon_1$ and $\varepsilon_2$ being the ranges of tolerance to be agree upon.



Key

1 Mass enthalpy of the air, *h*

2 Absolute humidity of the ambient air, *xφ*

3 Mollier -h-x-Diagram

**Figure 7 — Representation of the tolerance zone for the mixing point**

Expressed in other words: the actual value of mixing $MP_{\text{actual}}$ shall be above the limiting line $t_{2\text{tol}}$ and on the left side of the limiting curve (see Figure 7). The tolerance values result from the tolerance ranges $\varepsilon_1$ and $\varepsilon_2$:

$$t_{\text{s2}_{\text{tol}}} = t_{\text{s2 nom}} + \varepsilon 1$$

$$\varphi_{\text{R2}_{\text{tol}}} = \varphi_{\text{R2 nom}} + \varepsilon 2$$

### 8.2.9.3 Verification of mixing quality

Sufficient mixing quality is achieved if the standard deviation $\sigma_{\text{x}}$ of the absolute water content *x* which was determined on the basis of the dry bulb temperature $t_{\text{s2}}$ and the wet bulb temperature $t_{\text{w2}}$ of the outlet air flow is lower than the tolerance value $\varepsilon_3$:

$$\frac{\sigma_x}{x_n - x_u} \leq \varepsilon_3$$

where

$$\sigma_{\text{x}} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x}_i)^2}$$ Standard deviation

$x_{\text{n}}$ is the averaged water content of the outlet air after wet section

$x_{\text{u}}$ is the water content of the ambient air

$x_{\text{i}}$ is the water content of one individual measuring point

$\bar{x}_i$ is the water content averaged over all measuring points

# 9 Evaluation of thermal performances

## 9.1 General

The thermal performance of a cooling tower is its ability to produce guaranteed recooled water temperatures under specified operating conditions and inlet air conditions.

This can be achieved by a direct comparison between the test results and the manufacturer's performance curves or by reference of the test results to the design conditions.

The effect of measurement errors shall be taken into account when interpreting the results.

## 9.2 Basic thermal performance test evaluation

### 9.2.1 Assessment of the measured values

For each of the period test results, first the arithmetic mean of each parameter is calculated over a period and put into the assessment report. Then using these averages the guaranteed value for the recooled water temperature $t_{cg}$ is taken from the performance curve for each test period.

### 9.2.2 Comparison with the guaranteed values

The difference between the average of the recooled water temperatures measured $\bar{t}_{\text{cmk}}$ and the guaranteed mean recooled water temperature $\bar{t}_{\text{cgk}}$ is calculated for each measuring test result.

$$\Delta t_{\text{k}} = \bar{t}_{\text{cmk}} - \bar{t}_{\text{cgk}}$$

and from these the arithmetic mean is calculated for all the measuring results:

$$\Delta t = \frac{1}{\text{K}} \sum_{\text{j}=1}^{\text{K}} \Delta t_{\text{j}}$$

Unless otherwise specified in the contract:

The guarantee figures are deemed to be achieved if $\Delta t \leq 0$ .

Evidence that the guarantee figures were achieved can be produced by using the measurement uncertainty when:

$$0 < \Delta t_{\text{G}} \leq \delta t_{\text{c}} + \delta t_{\text{tol}}$$

The deviation $\Delta t_{\text{G}}$ that applies to the guarantee conditions shall be calculated as specified in 9.2.3 and the uncertainty $\delta t_{\text{c}}$ of the comparison between measured and guaranteed recooled water temperature as specified in 9.4. The base tolerance $\delta t_{\text{tol}}$ allows for influences in the operation of the cooling tower that were not measured (e.g. effects due to varying wind direction due to nearby buildings, effects of the wind profile, effects of additives in the cooling water, etc.) and is considered to be 0,2 K.

### 9.2.3 Correcting the guarantee conditions for the deviation

The guarantee value $t_{cgk}$ may be exceeded to a certain extent within the range of the performance curve in which the acceptance tests may be carried out. In order to make the assessment independent of the measuring points the difference $\Delta t_k$ is applied for each measuring result to the guarantee conditions ($t_a$, $\varphi_G$, $z_G$).

The correction shall be done as follows with the help of the performance curve:

With the measurement results for the $k^{th}$ measuring test result:

| | |
|---|---|
| — temperature of the ambient air | $t_{a,k}$ |
| — air density (for mechanical draught, fan assisted cooling towers) | $\rho_k$ |
| — relative humidity of the ambient air | $\varphi_k$ |
| — hot water temperature | $t_{hk}$ |
| — recooled water temperature | $t_{c,k}$ |

a fictious water mass flow rate $\rho_F$ can be determined from the performance curve, for which the guarantee recooled water temperature would have been achieved. With this fictious mass flow and the guarantee conditions ($t_{aG}$, $\varphi_G$, $z_G$) a fictious cold water temperature $t_{cGF}$ shall be determined from the performance curve. The difference:

$$\Delta t_{GK} = t_{cGF,k} - t_{cG,k}$$

corresponds to the deviation of the measured cold water temperature from the guarantee value at the guarantee conditions. Thus $t_{cGF,k}$ is this set value. It is obtained from the performance curve with the measured water mass flow rate $\rho_k$ and the guarantee conditions $t_{aG}$, $\varphi_G$, $z_G$. The deviation $\Delta t_G$ that applies to the guarantee conditions is obtained as the arithmetic mean over all the measuring result.

$$\Delta t_G = \frac{1}{K}\sum_{j=1}^{K} \Delta t_{Gk}$$

The correction method shown here can also be used to make an assessment, that is independent of the measuring points, of a shortfall of the guaranteed recooled water temperature if, for example, a bonus was agreed between the parties in the contract for this case.

### 9.2.4 Air density effect on fan power

The air density corresponding to guaranteed mechanical fan power $F_{pG}$ (electrical power divided by motor efficiency) is given by the manufacturer: $\rho_G$.

The air density during the test is $\rho_k$. The corrected value $F_{pc}$ corresponding to guaranteed value is:

$$F_{pc} = F_{pG} \times \rho_G / \rho_k$$

## 9.3 Extended thermal performance test evaluation

### 9.3.1 Method for examining the thermal performance tests

For each valid measuring point, one shall calculate the difference between the calculated cooled water temperature (calculated from the cold water temperature) and the recooled water temperature guaranteed under the test conditions. It is therefore necessary to determine the latter on the basis of the data supplied by the manufacturer. One then weights the mean difference obtained for each wind class by the weight of the class.

### 9.3.2 Characteristic equations of the cooling tower

The operating of the cooling tower is assumed to be governed by the following two equations:

- operating equation:

$$\frac{KAV}{q_{\mathrm{me}}} = C\left(\frac{q_{\mathrm{mas}}}{q_{\mathrm{me}}}\right)^{n}$$

in which the ratio $\frac{KAV}{q_{\mathrm{me}}}$ is the Merkel number.

- draft equation:

$$\rho_1 - \rho_2 = \frac{1}{2}\frac{\rho_1}{gH}C_{\mathrm{F}}v_{\mathrm{D}}^{2}$$

The performances of the apparatus are therefore characterised by the heat coefficient $C$, the exponent n of the transfer law, the apparent mechanical pressure loss coefficient $C_{\mathrm{F}}$, the exchange body frontal surface $S_{\mathrm{F}}$ and the draft height $H$ which are supplied by the manufacturer at the time of submitting the offer.

The heat coefficient $C$ and the mechanical pressure loss coefficient $C_{\mathrm{F}}$ are supplied by the manufacturer in the form of a function of the wind velocity at 10 m and of others parameters which interfere.

The manufacturer may also provide a table of values between which a linear interpolation is conducted.

These data shall be defined by mutual agreement between parties of the contract.

The flow rate velocity $V_{\mathrm{D}}$ is calculated by the following formula:

$$v_{\mathrm{D}} = \frac{q_{\mathrm{mas}}(1 + x\varphi)}{\rho_1 S_{\mathrm{F}}}$$

### 9.3.3 Simplifying assumptions

The hot air is assumed to be saturated.

The variation in the flow rate of water passing through the cooling tower is overlooked in the energy balance. The output transferred is therefore assumed to be equal to $q_{\mathrm{me}}\, c_{\mathrm{pe}}\, (t_{\mathrm{h}} - t_{\mathrm{c}})$.

The enthalpy of the hot air is then expressed by:

$$h_2 = h_1 + \frac{q_{\mathrm{me}}}{q_{\mathrm{mas}}} c_{\mathrm{pe}}(t_{\mathrm{h}} - t_{\mathrm{c}})$$

### 9.3.4 Calculation of the Merkel number

#### 9.3.4.1 General

Using the Merkel hypotheses, this number shall be calculated by the following equation, applied to the exchange body:

$$\frac{KAV}{q_{\mathrm{me}}} = c_{\mathrm{pe}} \frac{1}{\gamma} \int_{t_2}^{t_1} \frac{dt}{(h_{\mathrm{s}} - h)}$$

$\gamma$ is a correction factor, the value of which depends on the type of device:

- for counterflow devices, $\gamma = 1$;
- for crossflow devices, the value of $\gamma$ is given by Table 4 as a function of two coefficients $\mu$ and $\nu$ calculated from the initial condition and final condition of the two fluids.

#### 9.3.4.2 Calculation of absolute humidity

##### 9.3.4.2.1 Calculation of absolute humidity at saturation

Air absolute humidity $x_{\mathrm{s}}$ is calculated from water vapour pressure at saturation $p_{\mathrm{s}}$

$$p_{\mathrm{s}}(t) = c \times p \left( \frac{17{,}438\ t}{239{,}78 + t} + 6{,}4147 \right) \text{ for } t \geq 0\ °\mathrm{C}$$

$$x_{\mathrm{s}}\ (t, p) = \frac{p_{\mathrm{s}}\ (t) \times 0{,}622}{p - p_{\mathrm{s}}\ (t)}$$

##### 9.3.4.2.2 Calculation from psychometric data

Psychometers provide dry bulb temperature $t_{\mathrm{s}}$ and wet bulb temperature$t_{\mathrm{w}}$. Then

$$x\ (t, t_{\mathrm{h}}, p) = \frac{x_{\mathrm{s}}\ (t, p)\ \left[h_{\mathrm{v}}\ (t_{\mathrm{h}}) - h_{\mathrm{H20}}\ (t_{\mathrm{h}})\right] + h_{\mathrm{s}}\ (t_{\mathrm{h}}) - h_{\mathrm{A}}\ (t)}{h_{\mathrm{v}}\ (t) - h_{\mathrm{H20}}\ (t_{\mathrm{h}})}$$

where enthalpies $h_{\mathrm{i}}$ (t) of component i at temperature *t* are defined in 9.3.4.2.

##### 9.3.4.2.3 Calculation from hygrometric data

An hygrometer provides relative humidity $\varphi$

$$x(t\ p\ \varphi) = x(x_{\mathrm{s}}, \varphi) = \frac{0{,}622\ \varphi\ x_{\mathrm{s}}\ (t, p)}{x_{\mathrm{s}}\ (t\ p)(1 - \varphi) + 0{,}622}$$

#### 9.3.4.3 Enthalpies

Enthalpies for dry air, water vapour and ice are in J·kg$^{-1}$.

$$h_{\mathrm{A}}(t) = \int_0^t (1005{,}67 + 16{,}035 \times 10^{-3}\ \tau)\ d\tau$$

$$h_{\mathrm{V}}(t) = \int_0^t (1835 - 0{,}7342)\ d\tau + 2501{,}6 \times 10^{-3}$$

$$h_{\mathrm{E}}(t) = \int_0^t (4217{,}8 - 1{,}7245\ \tau + 33{,}98 \times 10^{-3}\ \tau^2 - 253{,}4 \times 10^{-6}\ \tau^3)\ d\tau$$

$$h_{\mathrm{G}}(t) = \int_0^t (2105{,}1 + 3{,}722\ \tau)\ d\tau - 333{,}5498 \times 10^3$$

$$h_{\mathrm{H20}}(t) = \begin{cases} h_{\mathrm{E}}(t)\ \mathit{if}\ \ t \geq 0\ °C \\ h_{\mathrm{G}}(t)\ \mathit{if}\ \ t \langle\ 0\ °C \end{cases}$$

Wet air enthalpy is:

$$h(tx) = h_{\mathrm{A}}(t) + x h_{\mathrm{v}}(t)$$

### 9.3.4.4 Density

Knowing the absolute humidity and the dry temperature of the moist air, the density is determined by the equation:

$$\rho(t, x, P\mathrm{a}) = 1{,}293 \frac{P\mathrm{a}}{101325} \frac{273{,}15}{273{,}15 + t} \frac{0{,}622(1 + x)}{0{,}622 + x}$$

with $\rho$ in kg·m$^{-3}$, $t$ in °C and $P\mathrm{a}$ in pascals.

### 9.3.4.5 Merkel number for counter flow

Following Merkel exchange equations (see Table 6):

**Table 6 — Exchange equation**

| **Counter flow** |
|---|
| $\frac{dh}{dZ} = \frac{\beta \times a}{Fa}(h_{\mathrm{s}} - h)$ |
| $\frac{dt}{dZ} = \frac{Fa}{Fe} \frac{1}{C\mathrm{pe}} \frac{dh}{dZ}$ |

The Merkel number is:

$$M_{\mathrm{e}} = \int_{t_2}^{t_1} \frac{C_{\mathrm{pe}}(t)\ dt}{h_{\mathrm{s}}(t) - h}$$

Where $h_s(t)$ is the saturation enthalpy of air at water temperature $t$ and $h$ is the air enthalpy which for counter flow is:

$$h = h_1 + \frac{q_{\mathrm{me}}}{q_{\mathrm{mas}}} \int_{t_2}^{t_1} C_{\mathrm{pe}}(t)\, dt$$

It is therefore a question of determining the numerical value of the integral in which the enthalpy of the air is expressed by heat balance as a function of the water temperature and of the conditions at the cooling tower inlet:

$$h = h_1 + \frac{q_{\mathrm{me}}}{q_{\mathrm{mas}}} c_{\mathrm{pe}}(t - t_{\mathrm{c}})$$

For this, one uses Simpson's rule. Indeed, although the function to be integrated f (t) = $\frac{1}{h_{\mathrm{s}} - h}$ cannot be explained simply as a variable function of $t$, one knows how to calculate the numerical value of f ($t$) for all values of t included between the integration limits, using calculation tables, diagrams or formulae.

The value of the integral is obtained using the following expression:

$$I = \int_{t_{\mathrm{c}}}^{t_{\mathrm{h}}} f(t)dt = \frac{p}{3}\left[f(t_{\mathrm{c}}) + 4f(t_{\mathrm{c}} + p) + 2f(t_{\mathrm{c}} + 2p) + \ldots + 2f(t_{\mathrm{c}} + (2k-2)p) + 4f(t_{\mathrm{c}} + (2k-1)p) + f(t_{\mathrm{h}})\right]$$

with $p = \frac{t_{\mathrm{h}} - t_{\mathrm{c}}}{2k}$

The higher the value chosen for 2 *k*, greater the accuracy of the calculation is. In practice, for the calculation of the integral $I$, the accuracy is satisfactory for 2 *k* = 8.

#### 9.3.4.6 Merkel number for cross flow

The Merkel exchange equations are given in Table 7:

**Table 7 — Exchange equation**

| Cross flow |
|---|
| $\frac{\partial h}{\partial X} = \frac{\beta \times a}{Fa}(h_{\mathrm{s}} - h)$ |
| $\frac{\partial t}{\partial Z} = \frac{Fa}{Fe}\frac{1}{C_{\mathrm{pe}}}\frac{\partial h}{\partial x}$ |

These equations shall be integrated in two directions (parallel and square to the airflow) e.g. by the Runge Kutta method from the intersection of air and water inlet.

To avoid calculation delays a table of equivalence between integration and counter flow calculation has been published in Revue Générale de Thermique using a $\gamma$ factor based on the Nusselt studies (see Table 8).

Therefore, the Merkel number is:

$$M_{\mathrm{e}} = \frac{1}{\gamma} \int_{t_2}^{t_1} \frac{C_{\mathrm{pe}}(t)\, dt}{h_{\mathrm{s}}(t) - h}$$

which follows Merkel exchange equation:

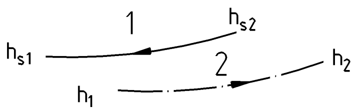
$$\frac{dh}{dZ} = \frac{B \times a}{Fa} (h_s - h)$$

$$\frac{dt}{dZ} = \frac{Fa}{Fe} \frac{1}{C_{pe}} \frac{dh}{dZ}$$

## Table 8 — Correction factor $\gamma$ for wet crossflow cooling towers

| $\nu$ | $\gamma$ | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **0,500** | **0,550** | **0,600** | **0,650** | **0,700** | **0,750** | **0,800** | **0,850** | **0,900** | **0,950** |
| **0,2** | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 1,000 | 0,970 | 0,930 | 0,875 | 0,750 |
| **0,3** | 0,990 | 0,985 | 0,985 | 0,975 | 0,955 | 0,930 | 0,895 | 0,855 | 0,790 | 0,650 |
| **0,4** | 0,968 | 0,966 | 0,952 | 0,940 | 0,917 | 0,875 | 0,840 | 0,786 | 0,720 | 0,590 |
| **0,5** | 0,942 | 0,937 | 0,919 | 0,890 | 0,55 | 0,820 | 0,776 | 0,729 | 0,665 | 0,540 |
| **0,6** | 0,915 | 0,900 | 0,878 | 0,855 | 0,825 | 0,780 | 0,732 | 0,680 | 0,620 | 0,500 |
| **0,7** | 0,875 | 0,860 | 0,834 | 0,805 | 0,775 | 0,735 | 0,691 | 0,636 | 0,580 | 0,470 |
| **0,8** | 0,838 | 0,816 | 0,790 | 0,764 | 0,728 | 0,690 | 0,655 | 0,600 | 0,550 | 0,440 |
| **0,9** | 0,795 | 0,773 | 0,748 | 0,726 | 0,690 | 0,655 | 0,621 | 0,569 | 0,520 | 0,420 |
| **1,0** | 0,750 | 0,733 | 0,712 | 0,688 | 0,658 | 0,625 | 0,591 | 0,541 | 0,490 | 0,390 |
| **1,2** | 0,682 | 0,663 | 0,645 | 0,624 | 0,595 | 0,570 | 0,536 | 0,493 | 0,450 | 0,360 |
| **1,4** | 0,620 | 0,610 | 0,590 | 0,568 | 0,540 | 0,510 | 0,489 | 0,451 | 0,420 | 0,330 |
| **1,6** | 0,555 | 0,544 | 0,535 | 0,519 | 0,496 | 0,473 | 0,450 | 0,418 | 0,380 | 0,300 |
| **1,8** | 0,505 | 0,500 | 0,490 | 0,480 | 0,465 | 0,440 | 0,420 | 0,385 | 0,360 | 0,285 |
| **2,0** | 0,450 | 0,445 | 0,440 | 0,436 | 0,425 | 0,410 | 0,390 | 0,360 | 0,334 | 0,270 |
| **2,5** | 0,380 | 0,375 | 0,370 | 0,360 | 0,355 | 0,345 | 0,330 | 0,310 | 0,174 | 0,230 |
| **3,0** | 0,325 | 0,320 | 0,315 | 0,310 | 0,305 | 0,300 | 0,290 | 0,270 | 0,260 | 0,210 |
| **4,0** | 0,245 | 0,245 | 0,245 | 0,245 | 0,245 | 0,235 | 0,230 | 0,220 | 0,210 | 0,175 |
| **5,0** | 0,196 | 0,196 | 0,196 | 0,194 | 0,194 | 0,194 | 0191 | 0,182 | 0,175 | 0,150 |
| **7,0** | 0,145 | 0,145 | 0,145 | 0,145 | 0,145 | 0,145 | 0,140 | 0,135 | 0,130 | 0,120 |
| **10,0** | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 0,090 |

NOTE The table gives $\mu$ as a function of $\gamma$ and $\nu$. The values of the parameters $\mu$ and $\nu$ are respectively:



**Key**

1 Water

2 Air

$$\mu = \frac{h_2 - h_1}{h_{s1} - h_1} \quad \text{and} \quad \nu = \frac{h_{s1} - h_{s2}}{h_2 - h_1}$$

The air is assumed to be saturated.

### 9.3.5 Processing of the tests

### 9.3.5.1 Calculation of the guarantee deviation for each test

The algebraic difference $\Delta t_k$ between the recooled water temperature $t_{ck}$ obtained from the measurements conducted on the cooling tower and the guaranteed temperature $t_{cGk}$ obtained by curves or equations (B) and (C) is then determined by the following equation:

$$\Delta t_{\mathrm{k}} = t_{\mathrm{cK}} - t_{\mathrm{cGk}}$$

### 9.3.5.2 Classification and number of tests

The tests shall then be grouped together into n classes, as a function of the reference wind velocity at 10 m during the test such as:

- $m^0 = 1 \quad 0 \leq V_{10} < \mathrm{x}\ \mathrm{m \cdot s^{-1}}$
- $m^0 = 2 \quad x \leq V_{10} < \mathrm{y}\ \mathrm{m \cdot s^{-1}}$
- etc.

The number of classes to be considered shall be mentioned in the contract as well as the limits of each class.

It is suggested that the spread of a class does not exceed 2 $\mathrm{m \cdot s^{-1}}$. For each wind class the valid tests shall be divided into two groups provided that the number of tests in both groups exceed 30 % of the total number of tests in the wind class (if not, all the tests of a wind class shall be considered as one group): air inlet wet bulb temperature increasing during the period and air inlet wet bulb temperature decreasing during the period.

The weighting coefficients $\alpha_{\mathrm{m}}^0$ supplied by the manufacturer, at the time of the consultation, are then introduced:

$$\left( \sum_{m^0=1}^{m^0=n} \alpha_m^0 = 1 \right)$$

A class including less than four valid period shall be considered as not filled.

Only the classes which are filled shall be taken into consideration. The weighting coefficients shall be corrected so that their sum reaches 100 % by respecting the relative initial weight of each filled class.

Furthermore, all the valid periods, recorded up until the obtaining of these conditions, shall be taken into account in the examination.

### 9.3.5.3 Calculation of the weighted mean deviation

In both groups of each class calculate the mean algebraic value $t_k$ of the $\Delta t_h$ with $n^{bm1}$ being the number of tests of the first group of tests in one class.

$$\Delta t_{\mathrm{m1}} = \frac{1}{n^{bm1}} \sum_{k=1}^{k=n^{bm1}} (t_{\mathrm{ck}} - t_{\mathrm{cG}})$$

$$\Delta t_{\mathrm{m2}} = \frac{1}{n^{bm2}} \sum_{k=1}^{k=n^{bm2}} (t_{\mathrm{ck}} - t_{\mathrm{cG}})$$

with $n^{bm2}$ being the number of tests of the second group of tests in the same class.

For each class, the mean algebric value $\Delta t_m$ is :

$$\Delta t_{\mathrm{m}} = \frac{1}{2}\left(\Delta t_{\mathrm{m1}} + \Delta t_{\mathrm{m2}}\right)$$

If the test of a class cannot be divided into two groups (condition of 9.3.5.2) calculate directly as follows:

$$\Delta t_{\mathrm{m}} = \frac{1}{n^{bm}} \sum_{k=1}^{k=n^{bm}} (t_{\mathrm{ck}} - t_{\mathrm{cG}})$$

with $n^{bm}$ being the number of tests in this class.

The weighted mean deviation of the cooling tower in relation to its guarantee is the algebraic sum of the mean deviations in each class together with their coefficient:

$$\Delta t = \sum_{m^0=1}^{m^0=n} \alpha_{\mathrm{m}}^{0} \, \Delta t_{\mathrm{m}}$$

#### 9.3.5.4 Guarantee

The weighted mean deviation on the recooled water temperature $\Delta t$ shall remain below the threshold specified in the contract.

This threshold depends upon the overall accuracy of the results.

NOTE As an indication, if a minimum number of 300 periods are available, and for standard operating conditions, the achievable overall accuracy is around 0,4 K.

## 10 Test tolerance

### 10.1 General

The uncertainty $\delta t_c$ of the comparison between measured and guaranteed recooled water temperature is calculated from two components.

$$\delta t_{\mathrm{m}} = \sqrt{\delta t_{\mathrm{s}}^{2} + \delta t_{\mathrm{r}}^{2}}$$

The first component represents the uncertainty of the comparison because of the unmeasurable systematic deviations of the measured figures, the second represents the uncertainty due to random deviations of the measured figures and variations of the parameters with time.

### 10.2 Error created by non-measurable systematic deviations of operating parameters

#### 10.2.1 General

The measurement errors of the individual parameters have influence on the determination of the cold water temperature. An example demonstrates how these influences can be determined. An example of performance curves used for this purpose is shown in Annex A.

### 10.2.2 Influence of wet bulb measurement uncertainties, $\Phi_w$

The influence factor $\Phi_w$ indicates the change in cold water temperature $\Delta t_c$ for a given variation of the wet bulb temperature $\Delta t_w$, providing all other influencing parameters, water flow rate, fan power and range are according to guaranteed conditions.

The variation of $\Delta t_w$ shall be selected so, that a relation between $t_w$ and $t_c$ is close to linear (see Annex A for example).

### 10.2.3 Influence of cooling range measurement uncertainties, $\Phi_z$

The influence factor $\Phi_z$ indicates the change of cold water temperature $\Delta t_c$ for a given variation of the range $\Delta z$, providing the water flow rate and fan power are at guaranteed conditions and the wet bulb temperature is the average measured value. The deviation of $\Delta z$ shall be ± 1 K (see Annex A for example).

### 10.2.4 Influence of fan power measurement uncertainties, $\Phi_F$

The influence factor $\Phi_F$ indicates the change of cold water temperature $\Delta t_c$ for a given variation of the fan power $\Delta F_p$ (in %), providing the water flow rate and range are at guaranteed conditions and the wet bulb temperature is the average measured value. Variations of $\Delta F_p$ shall be ± 10 %.

If the curves do not give the influence of fan power, the influence on the water outlet temperature shall be calculated using a corrected flow (see Annex A for example).

### 10.2.5 Influence of water flow rate measurement uncertainties, $\Phi_m$

The influence factor $\Phi_m$ indicates the change of cold water temperature $\Delta t_C$ for a given variation of the water volume flow rate $\Delta m$ (in %), providing fan power and range are at guaranteed conditions and the wet bulb temperature is at the average measured value. Variations of $\Delta m$ shall be ± 10 % (see Annex A for example).

### 10.2.6 Determination of measuring equipment tolerances

The measuring tolerances for different instruments are indicated in Annex B. The values actually to be used shall be defined by the contractual parties prior to the measurement and shall not exceed the values shown in Table 9.

**Table 9 - Measuring equipment tolerances acceptable for the test**

| Quantity | Acceptable tolerance of instrumentation | |
|---|---|---|
| Wet bulb temperature | $\varepsilon\ t_w = 0{,}1$ K | |
| Water temperature | $\varepsilon t = 0{,}1$ K | |
| Water mass flow rate | $\varepsilon_m$ 5 % up to 1 000 kg·s$^{-1}$ | $\varepsilon_m =$3 % over 1 000 kg·s$^{-1}$ |
| Fan power<br>up to 25 kW<br>25 kW < $F_p \leq$ 200 kW<br>more than 200 kW | <br>$\varepsilon_{F_p}$ = 5 %<br>$\varepsilon_{F_p}$ = 2,5 %<br>$\varepsilon_{F_p}$ = 1,0 % | |

For the individual instruments the systematic deviations $\varepsilon_x$ shall be determined from the operation guidelines for the instruments used or shall be taken from Table 9.

The applicable tolerances ($\varepsilon_x$) are combined with the influence factors $\Phi$ found in 10.2 and allow the calculation of the error caused by non-measurable systematic deviations of the operating parameters.

### 10.2.7 Error caused by non-measurable systematic deviations of operating parameters

The error $\delta t_s$ of the comparison due to systematic non-measurable influences can be calculated as follows:

$$\delta t_{\mathrm{s}} = \sqrt{(\Phi_{\mathrm{W}} \times \varepsilon t_{\mathrm{W}})^2 + (\Phi_{\mathrm{z}} \times 2\varepsilon_t)^2 + (\Phi_{\mathrm{m}} \times \varepsilon_{\mathrm{m}})^2 + (\Phi F_{\mathrm{p}} \times \varepsilon F_{\mathrm{p}})^2 + (\varepsilon t_{\mathrm{c}})^2}$$

The tolerance of the measurement of the cold water temperature $\varepsilon t_C$ is naturally applied directly to the result.

### 10.2.8 Determination of errors caused by random deviation of test results and temporary oscillation of the operating parameters

Random events cause that the differences $\Delta t_k$ between measured and guaranteed cold water temperature, calculated according to 7.2, fluctuate around the average $\Delta t$ calculated from all measuring periods.

A measure of this fluctuation is given by the empirical standard deviation

$$S\Delta_{tk} = \sqrt{\frac{1}{k-1}\sum_{k=1}^{k}(\Delta t_{\mathrm{a}} - \Delta t_{\mathrm{k}})^2}$$

The measuring tolerance $\delta t_r$ caused by random deviation of measuring results and temporary oscillations of the measured quantities with the level of confidence for a probability of 95 % shall be found using the equation below. Values of the $S_t$ distribution according to Student are given in Table 10.

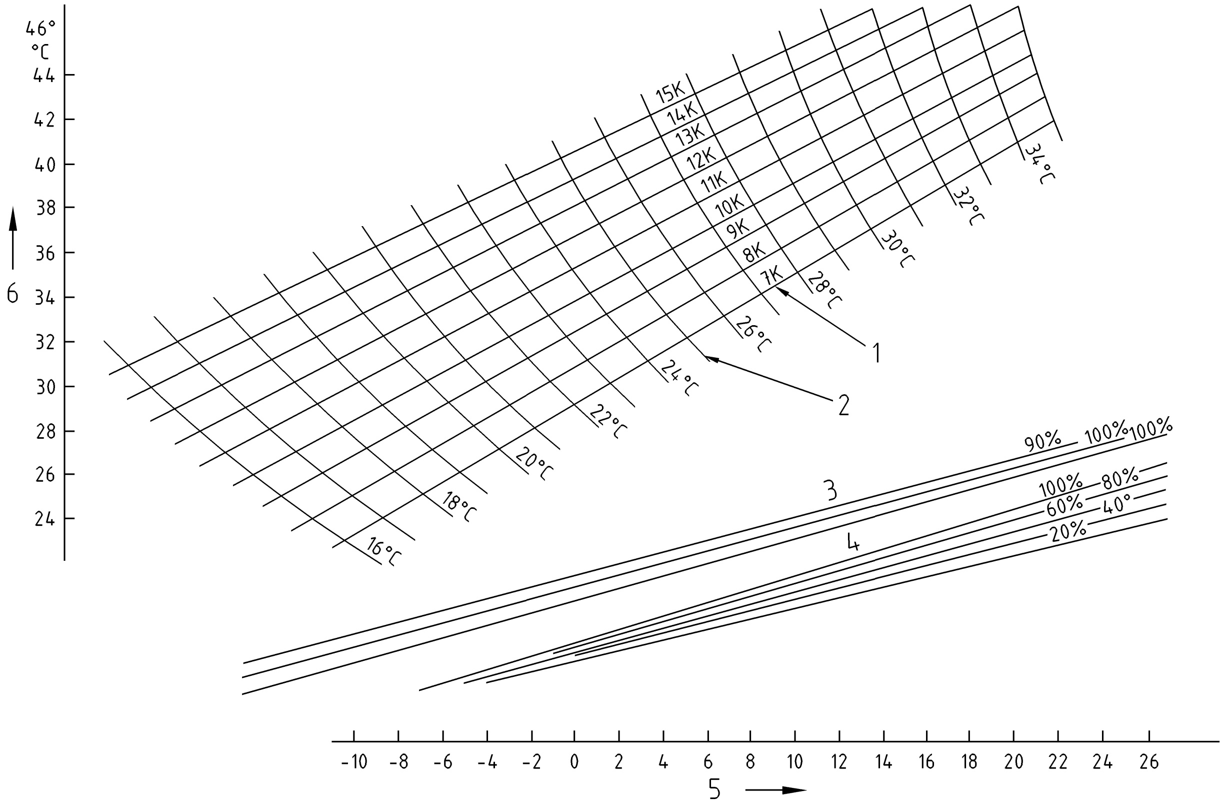
$$\delta t_{\mathrm{r}} = \frac{S_{\mathrm{t}}(k)}{\sqrt{k}} S\Delta t_{\mathrm{k}}$$

**Table 10 — Distribution according to Student for a level of confidence of 95 %**

| k | $S_t$ (k) | k | $S_t$ (k) |
|---|---|---|---|
| 2 | 12,710 | 16 | 2,131 |
| 3 | 4,303 | 17 | 2,120 |
| 4 | 3,182 | 18 | 2,110 |
| 5 | 2,776 | 19 | 2,101 |
| 6 | 2,571 | 20 | 2,093 |
| 7 | 2,447 | 21 | 2,086 |
| 8 | 2,345 | 22 | 2,080 |
| 9 | 2,306 | 23 | 2,074 |
| 10 | 2,262 | 24 | 2,069 |
| 11 | 2,228 | 25 | 2,064 |
| 12 | 2,201 | 26 | 2,060 |
| 13 | 2,179 | 27 | 2,056 |
| 14 | 2,160 | 28 | 2,052 |
| 15 | 2,145 | 29 | 2,048 |

# Annex A
(informative)

## Performance curves



**Key**

1 Cooling range
2 Recooled water temperature $t_c$
3 Ratio of hot water massflow rate m/mg
4 Relative humidity of ambient air $\varphi_R$
5 Dry temperature of ambient air $t_z$
6 Hot water temperature $t_n$

**Figure A.1 — Natural draught performance curves**

Performance curve with example to find the change of the cold water temperature $t_c$ due to changes of the influencing factor "wet bulb temperature" $t_w$.

With: $t_w = 15,5 \pm 0,5$ °C; and $z = 6$ K; $F$p = 100 %; $m$ = 100 % constant, the result is:

$$\Delta t_W \frac{\delta t_c}{\delta t_w} = \frac{0{,}8K}{1°C} \rightarrow \Phi_W = 0{,}8\frac{K}{°C}$$

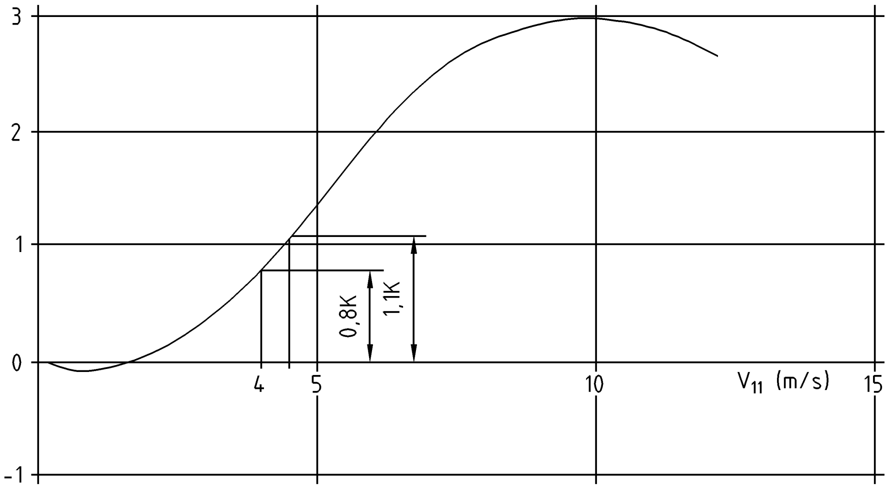
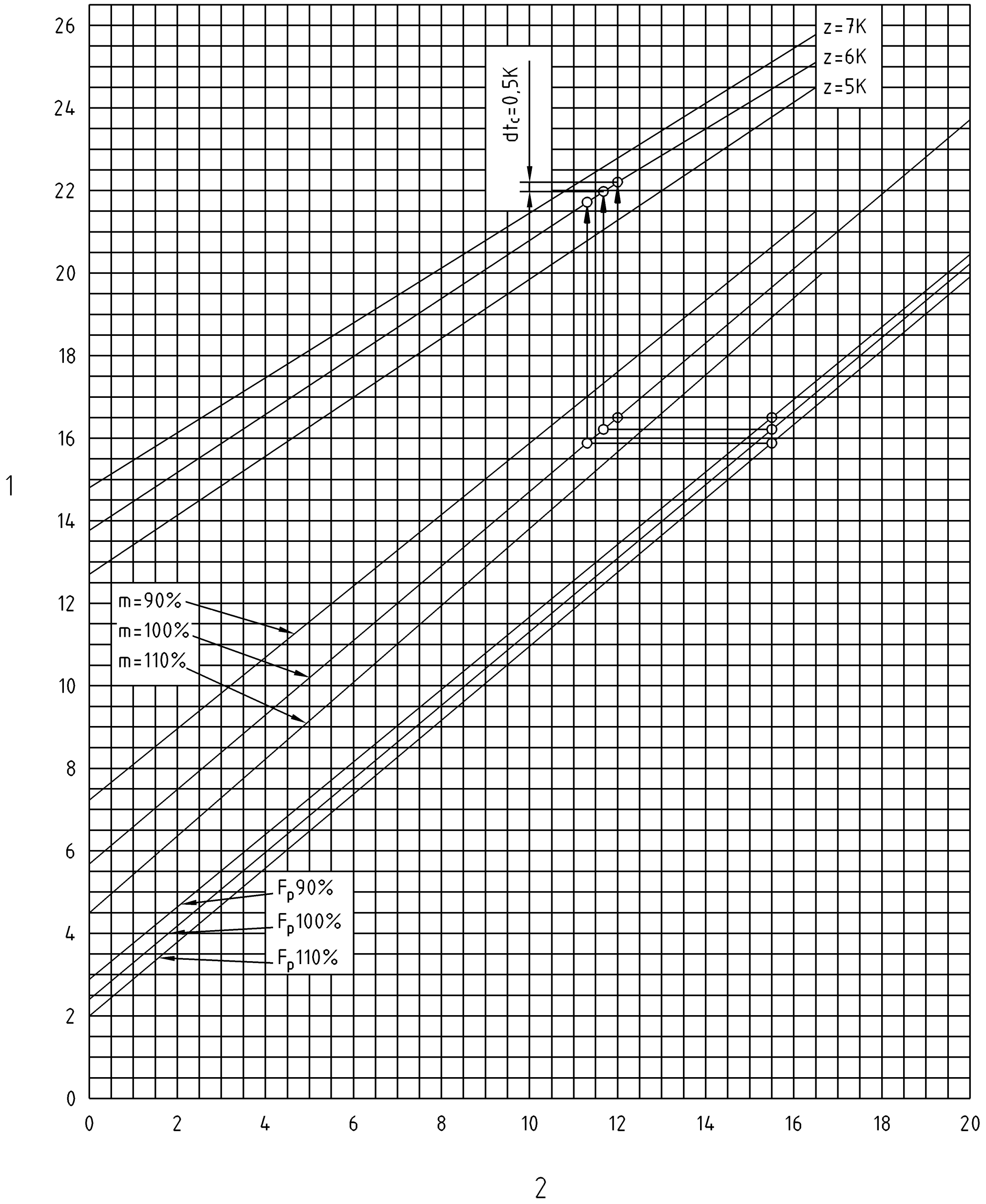


Figure A.2 — Rain counterflow cooling towers with natural draft example of wind effect



**Key**

1 Cold water temperature $t_c$ (°C)

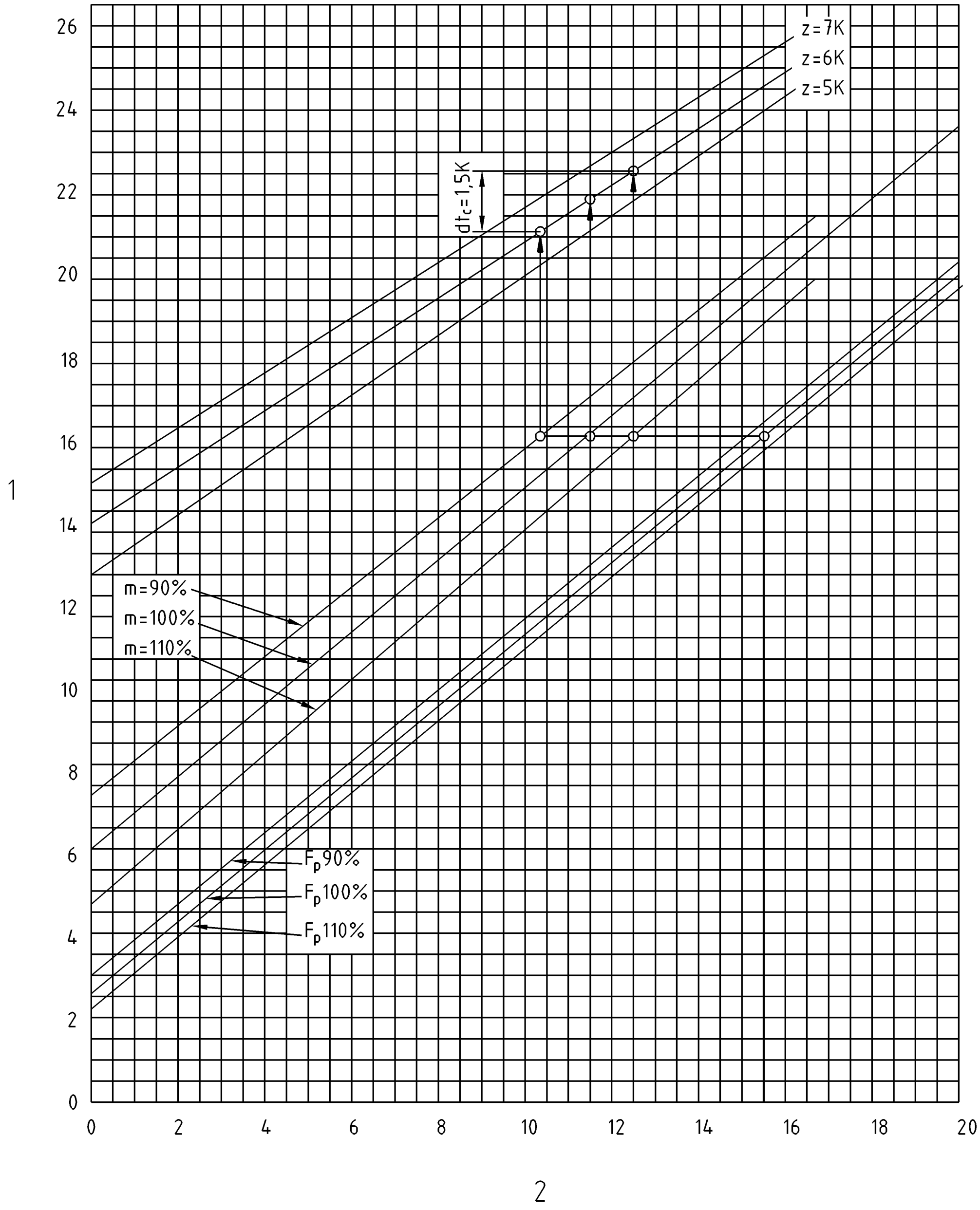
2 Wet bulb temperature $t_w$ (°C)

**Figure A.3 — Mechanical draught wet cooling tower**

Performance curve with example to find the change of the cold water temperature $t_c$ due to changes of the influencing factor "fan power $F_p$.

With: $F_p$ = 100 % ± 10 %; and $t_w$ = 15,5 °C; z = 6 K, $m$ = 100 %, the result is:

$$\Delta F_p \frac{\delta t_c}{\delta F_p} = \frac{0,5K}{20\%} \rightarrow \Phi_W = 0,025\frac{K}{\%}$$



**Key**

1 Cold water temperature $t_c$ (°C)

2 Wet bulb temperature $t_w$ (°C)

Figure A.4 — Mechanical draught wet cooling tower

Performance curve with example to find the change of the cold water temperature $t_c$ due to changes of the influencing factor "water volume flow $m$".

With: $m$ = 100 % ± 10 %; and $t_w$ = 15,5 °C; $z$ = 6K, $F_p$ = 100 % constant, the result is:

$$\Delta m \frac{\delta t_c}{\delta m} = \frac{1{,}5\mathrm{K}}{20\%} \rightarrow \Phi_W = 0{,}075 \frac{K}{\%}$$

# Annex B
(normative)

# Requirements concerning the measuring apparatus used for the tests

**Table B.1 — Requirements concerning the measuring apparatus used for the tests**

| Type of measurement | Type of equipment | Sensing element | Measuring range | Accuracy | Time constant | Comments |
|---|---|---|---|---|---|---|
| Measurement of the air or water temperatures | Platinum PT 100 resistance probe | Platinum resistance 100 Ω at 0°C Class A EN 60751 | - 40 °C to + 80 °C | ± 0,1 °C | air: 30 s<br>water: 0,5 s | |
| | Liquid thermometer | | ≤ 100 °C | ± 0,2 °C | | |
| | Thermo couplings | | ≤ 100 °C | ± 0,2 °C | | |
| | Quarz sensor | | -40 °C to 100 °C | ± 0,1 °C | | |
| Measurement of the humidity of the air | Capacitance hygrometer | Capacitance element | 30 % RH to 95 % RH | ± 1,5 % RH | 10 s | |
| Measurement of the air velocities at the R.A. inlet | Propeller-type anemometer | Propeller coupled to a generator voltage proportional to the velocity | 0 $m \cdot s^{-1}$ to 22 $m \cdot s^{-1}$ | ± 0,1 $m \cdot s^{-1}$ | Starting threshold 0,2 $m \cdot s^{-1}$ | |
| Measurement of the wind velocities | Cup-type anemometer | 3 cups on an axis<br>Frequency proportional to the velocity | 0,3 $m \cdot s^{-1}$ to 40 $m \cdot s^{-1}$ | ± 0,2 $m \cdot s^{-1}$ | Starting threshold | Built-in heating avoids frost in winter |
| Measurement of the wind directions | Sensitive weather vane | Weather vane coupled to a potentiometer<br>Resistance proportional to the angle<br>North = 0° = 0 | 0°-360°= 0-400 | ± 2,5 ° | idem | |
| Measurement of pluviometry | Bucket-type pluviometer | Tipping buckets or PTC resistance | - | - | - | idem |
| Measurement of atmospheric pressure or manometric head | Absolute or relative pressure sensor | Sensor variable capacity cell | 900 mbar to 1200 mbar (0 to 2,5 bar) | ± 0,2 % | - | - |
| Measurement of fan power consumption | Wattmeter | | | 1 % to 2 % | | |

**Table B.2 — Guideline values for some water mass flow measuring instrument accuracy**

| Measurement with | $\varepsilon_m$ |
|---|---|
| a) Meters, with a measuring period<br>t ≥ 50 s and when using<br>- a volume measurement meter in the permitted range<br>- a propellor meter in the permitted range | 2,0 %<br>1,5 % |
| b) Throttle measuring instrument | 1 % to 1,5 % |
| c) Hydrometric propellors in pipelines<br>with D ≥ 1 500 mm<br>800 ≤ D < 1 500 mm<br>in open ducts with rectangular section | 1,2 %<br>1,5 %<br>2,0 % |
| d) Pitot tubes in pipe lines with D ≥ 800 mm with variations of the static pressure<br>- by less than 1 % of the value read<br>- with wider variations of the pressure head | 1,5 %<br>2,0 % |
| e) Measuring weir with calibrated weir when using a weir formula<br>- for rectangular weirs without reduction of area at the sides<br>- for rectangular weirs with reduction of area at the sides | 2,0 % - 1,5 %<br>2,5 % |
| f) Electromagnetic device<br>velocity 0,8 $m{\cdot}s^{-1}$ to 1,5 $m{\cdot}s^{-1}$<br>velocity greater than 1,5$m{\cdot}s^{-1}$ | 2,0%<br>1,5 % |
| g) Ultrasonic devices | 3 % to 5 % |

# Annex C
(normative)

# Calculation of the evaporated water flow rate

## C.1 General

If blowdown volume flow rate cannot be measured or no charts or curves from the supplier are available calculation is possible following this annex.

## C.2 Introduction

It is necessary to know the volume flow rate of evaporated water $m_E$ for the calculation of the volume flow rate of blow-down water $m_p$. A precise assessment of this flow rate implies the use of Poppe's formula for calculating the thermal performances.

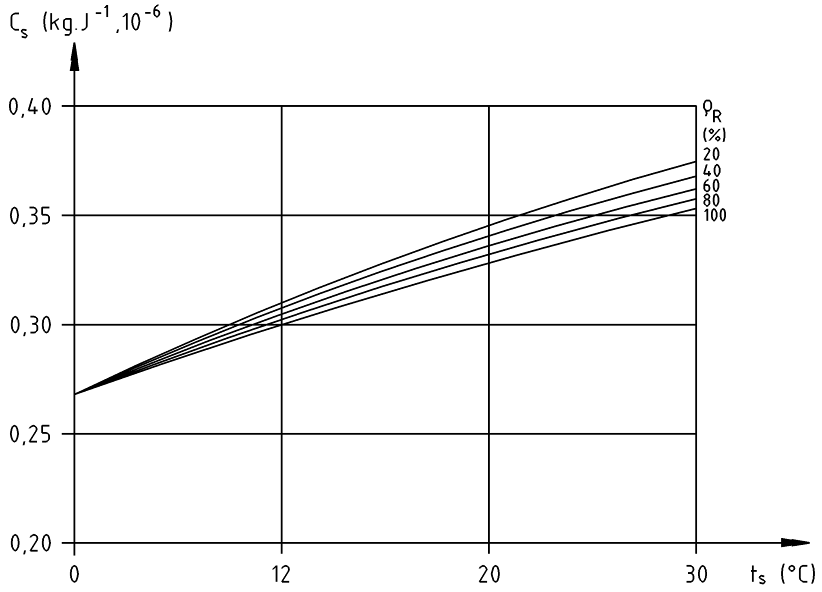
## C.3 Specific water consumption $C_S$

The use of Poppe's formula has enabled one to plot nomograms which determine the specific water consumption $C_S$.

From the analysis of the results, it is apparent that one can overlook the influence of the approach, *ap*, and that of the ratio of the air and water mass flow rates $\frac{q_{mas}}{q_{me}}$.

Furthermore, the influence of the cooling range ($Z$) is only perceptible for variations greater than 20 %.

Consequently, if one is only interested in the evaporation water flow rate corresponding to the nominal output (case of acceptance tests), one can consider the specific consumption, $C_S$, as being independent of the choice of the cooling tower. One shall then use a single nomogram (see Figure C.1), which gives the specific consumption as a function of the atmospheric conditions $t_s$ and $\varphi_R$.



**Key**

$t_s$ Mean dry temperature in the air inlet in degree Celsius

$\varphi_R$ Relative humidity of the ambient air in percentage

$C_s$ Specific water consumption in (kg·J$^{-1}$.10$^{-6}$)

**Figure C.1 — Specific water consumption**

This figure has been drawn up by numerical integration of the Poppe equations for a cooling range $Z$ of 12,6 K which is the nominal value of the standardized series 1 300 MWe and an approach, *ap*, of 12,5 K. It can be used without correction for cooling towers with different characteristics.

## C.4 Evaporated water volume flow rate $m_E$

Knowing the dry temperature $t_S$ and the relative humidity $\varphi$ of the air at the cooling tower inlet, one reads the specific consumption $C_S$ and from it one derives the evaporated water flow rate by the equation:

$$m_E = m c_{pe} Z C_s$$

where: $Z = t_h - t_c$

Table C.1 provides the numerical values of $C_S$ for different ambient temperature and relative humidity conditions. It can be introduced into a programme which calculates $C_S$ by interpolation between two values.

**Table C.1 — Specific water consumption $C_S$ as a function of the climatic conditions**

| $\varphi$ in % | $t_s$ in °C | | | |
|---|---|---|---|---|
| | 0 | 10 | 20 | 30 |
| 20 | 0,269 | 0,308 | 0,345 | 0,378 |
| 40 | 0,269 | 0,305 | 0,339 | 0371 |
| 60 | 0,269 | 0,302 | 0,335 | 0364 |
| 80 | 0,269 | 0,302 | 0,331 | 0357 |
| 100 | 0,271 | 0,303 | 0,331 | 0354 |
| NOTE $C_S$ is expressed in kg; $J^{-1}$; $10^{-6}$ | | | | |

## C.5 Variation susceptibility of $C_S$ to the operating parameters

The variations of $C_S$ due to modifications in the mass flow rate of dry air passing through the exchange body $q_{mas}$, in the approach *ap* or in the cooling range $Z$ in relation to the above case have been calculated. Table C.2 gives the results obtained for the mean climatic conditions ($t_s$ = 11 °C, $\varphi$ = 78%). One remarks that the specific consumption is practically independent of these parameters.

In conclusion, Table C.1 can therefore apply to all types of wet cooling towers within a fairly wide approach and cooling range.

**Table C.2 — Variation susceptibility of $C_S$ to the operating parameters**

| Nature of the modification | Relative variation of $C_S$ |
|---|---|
| + 20 % on $q_{mas}$ | - 0,6 % |
| + 20% on $Z$ | - 1,4 % |
| + 2 °C on *ap* | + 0,8 % |

# Annex D
(normative)

# Reminders on error calculations

## D.1 Mean (Arithmetical mean)

Let us suppose that one has recorded a series of individual, independent $n^{\mathrm{b}}$ values, free of their systematic errors, $x_1$ ....... $x_{\mathrm{i}}$ (for example for the degree of moisture or the mass of a part); one then takes as the result the arithmetical mean of these said individual $n^{\mathrm{b}}$ values which is called the mean $\bar{x}$.

$$\bar{x} = \frac{1}{n^{\mathrm{b}}} \sum_{\mathrm{i}=1}^{n^{\mathrm{b}}} x_{\mathrm{i}}$$

## D.2 Standard deviation of the recorded individual values in relation to the mean

The totality of the random dispersions of the individual values in relation to their mean is characterized by the standard deviation s:

$$s = \sqrt{\frac{1}{n^{b} - 1} \sum_{i=1}^{n^{b}} (x_i - \bar{x})^2}$$

## D.3 The confidence limit and confidence interval of the mean value

The mean $\bar{x}$ according to D.1 is not identical to the true value recorded, but it is possible to indicate two limits between which the true value is situated together with the selected statistical probability *P* and subject to a "normal distribution". It is a question of the confidence limits of the mean. The interval between these limits is called the confidence interval of the mean.

The confidence limits of the mean are calculated according to the formula:

$$\bar{x} \pm \frac{\tau}{\sqrt{n^{\mathrm{b}}}} s$$

The factor $\tau$ then depends on the selected statistical probability and also on the number of individual values.

Unless otherwise agreed, the confidence limits shall always be indicated for a statistical probability of 95 %.

Values for $\tau$ and $\frac{\tau}{\sqrt{n^{\mathrm{b}}}}$ for a statistical probability of 95 %.

**Table D.1**

| $n^b$ | $\tau$ | $\frac{\tau}{\sqrt{n^b}}$ |
|---|---|---|
| 3 | 4,3 | 2,5 |
| 4 | 3,2 | 1,6 |
| 5 | 2,8 | 1,24 |
| 6 | 2,6 | 1,05 |
| 8 | 2,4 | 0,84 |
| 10 | 2,3 | 0,72 |
| 20 | 2,1 | 0,47 |
| 30 | 2,05 | 0,37 |
| 50 | 2,0 | 0,28 |
| 100 | 2,0 | 0,20 |
| 200 | 1,97 | 0,14 |
| > 200 | 1,96 | 0 |

# Annex E
(normative)

## Cold water temperature correction for heat added by pump

When cold water temperature is measured at a throttle valve on the discharge side of a pump heat, is added to the water by the combined effects of the throttling pump from a high to low pressure and the inefficiency of the pump.

Expansion through a throttle valve is an adiabatic process so:

$$\Delta h = 0 = \Delta U + \Delta \frac{b}{\rho_e}$$

As the throttle valve inlet is at the atmospheric pressure:

$$\Delta U = \frac{p_1}{\rho e_1} \text{ J/kg}$$

i.e. for water with $\rho_e$= 980,67 kg/m$^3$

and $\xi$ being the pump efficiency

$p_1$ being the pump discharge pressure in pascals,

$$\Delta T = \frac{p_1}{\xi} 2{,}39 \times 10^{-7} \text{ K}$$

# Bibliography

[1] EN 13741, *Thermal performance acceptance testing of mechanical draught series wet cooling towers*

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