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Water-cooling towers — Testing and rating of thermal performance

Tours de refroidissement de l'eau — Essais et détermination des caractéristiques de performance

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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The committee responsible for this document is ISO/TC 86, *Refrigeration and air-conditioning*, Subcommittee SC 6, *Testing and rating of air-conditioners and heat pumps*.

Water-cooling towers — Testing and rating of thermal performance

1 Scope

This International Standard covers the measurement of the thermal performance and pumping head of open- and closed-circuit, mechanical draft, wet and wet/dry cooling towers and natural draft and fan-assisted natural draft, wet and wet/dry cooling towers. The standard rating boundaries for series mechanical draft, open- and closed-circuit cooling towers are specified.

This International Standard does not apply to the testing and rating of closed-circuit towers where the process fluid undergoes a change in phase as it passes through the heat exchanger or where the thermophysical properties of the process fluid are not available.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply. The symbols used to identify the terms contained in this International Standard are listed and defined in Clause 3.

2.1
airflow rate
total amount of dry air and associated vapour water moving through the cooling tower

2.2
ambient air conditions
atmosphere adjacent to, but not affected by, the cooling tower

2.3
approach
difference between cold (re-cooled) water temperature and the inlet-air wet-bulb temperature

2.4
approach deviation
deviation between the guaranteed and adjusted test approach

2.5
atmospheric gradient (lapse rate)
average rate of change of dry-bulb temperature with change in altitude from cold water basin curb, or sill, level to around twice the height of the cooling tower

Note 1 to entry: The convention for use with this International Standard will be to use a negative value for decrease in temperature as height increases.

2.6
average wind direction
predominant direction of the wind over the duration of the test period

2.7
average wind speed
arithmetical average of wind speed measurements taken over the duration of the test period

2.8
barometric pressure
atmospheric pressure taken over the duration of each test period

2.9
basin
open structure located beneath the cooling tower for collecting the circulating water and directing it to the sump or suction line of the circulating pump

2.10
basin curb
top elevation of the tower basin

Note 1 to entry: Usually the datum from tower elevations is measured.

2.11
blowdown
water discharged from the system to control the concentration of salts or other impurities in the circulating water

2.12
capability
measured thermal capacity of a cooling tower, expressed as a percentage of the design water flow rate

2.13
cell
smallest subdivision of the tower, bounded by exterior walls and partition walls, which can function as an independent unit

Note 1 to entry: Each cell can have one or more fans or stacks and one or more distribution systems.

2.14
cell dimensions
dimensions that describe the size of a cooling tower cell

Note 1 to entry: The dimensions include

a) dimension perpendicular to the tower longitudinal axis and usually at right angles to the air inlet faces,

b) length: dimension parallel to the longitudinal axis and the plane where air inlets are usually located, and

c) height: on induced draft towers, the distance from the basin curb to the top of the fan deck, but not including the fan stack.

Note 2 to entry: On forced and natural draft towers, the distance from the basin curb to the discharge plane of the tower.

2.15
closed-circuit cooling tower
cooling tower comprised of a water flow loop re-circulating over the outside of a closed-circuit heat exchanger containing the process fluid loop

Note 1 to entry: Air is drawn through the water passing over the outside of the closed-circuit heat exchanger, enabling cooling by evaporation. No direct contact occurs between the process fluid loop and the open evaporative cooling loop.

2.16
cold (re-cooled water temperature) water
in an open cooling tower, the average temperature of the water entering the tower basin

Note 1 to entry: The convention from here on will be to use the term “cold water” in ISO 16245.

Note 2 to entry: In the case where the measurement is downstream of the basin or the pump, corrections are needed for the effects of the pump and any other makeup water, blowdown, or heat sources entering the basin.

2.17
cooling range
difference between the hot and cold water or process fluid temperatures

Note 1 to entry: The term 'range' is also applied to this definition, but is regarded as a non-preferred term.

2.18
cooling tower
apparatus in which process fluid is cooled by evaporative heat exchange with ambient air

2.19
counter-flow
situation in which air and water flow in opposite direction within the cooling tower

2.20
cross-flow
situation in which air flows perpendicularly to the water flow within the cooling tower

2.21
discharge plume
discharge air stream of the cooling tower when made visible (wholly or in part) by the condensation of water vapour as the moist air stream is cooled to ambient temperature

2.22
distribution system
system for receiving the water entering the cooling tower and distributing it over the area where it contacts the atmospheric air

2.23
drift eliminator
assemblies downstream of the heat transfer media which serve to reduce the drift loss

2.24
drift loss
portion of the water flow rate lost from the tower in the form of fine droplets mechanically entrained in the discharge air stream, commonly expressed as mass per unit time or a percentage of the circulating water flow rate

Note 1 to entry: It is independent of water lost by evaporation.

2.25
dry-bulb temperature
temperature of an air-vapour mixture indicated by a thermometer with a clean, dry sensing element that is shielded from radiation effects

Note 1 to entry: Dry-bulb temperature can be further categorised as either

a) ambient dry-bulb temperature: the dry-bulb temperature of air measured windward of the tower and free from the influence of the tower or

b) entering dry-bulb temperature: the dry-bulb temperature of the air entering the tower, including the effect of any re-circulation and/or interference.

2.26
entering air conditions
average characteristics of the airflow entering the cooling tower

2.27
fan power
power consumed by the fan driver, which might or might not include the efficiency of the driver, depending on the contract

2.28
fill (pack)
devices placed in the cooling tower within the heat exchange section for the purpose of enhancing the surface area and/or the rate of heat transfer from the water stream to the air stream

2.29
final test result
average of the results from the minimum number of valid test periods

2.30
flow rate
quantity of hot process fluid to be cooled by the tower

2.31
fluid type
type of process fluid to be cooled by the tower

2.32
fouling factors
expression of reduction of heat transfer capability caused by internal and/or external contamination of the heat exchanger

2.33
heat exchanger pressure drop
pressure drop of the process fluid across the contractual inlet and outlet locations of the heat exchanger(s) of a closed-circuit or wet/dry cooling tower, adjusted for elevation and velocity

2.34
heat load
rate of heat removal from the process fluid within the tower

2.35
hot process fluid temperature
average temperature of the process fluid entering the heat exchanger in a closed-circuit tower

2.36
hot water temperature
average temperature of the inlet water in an open-circuit cooling tower

2.37
interference
thermal contamination of air entering the cooling tower by a source extraneous to the tower, generally another cooling tower

2.38
L/G
ratio of total mass flow rates of liquid (water) over gas (dry air) in an open-circuit cooling tower

2.39
makeup
water added to the system to replace the water lost by evaporation, drift, blowdown, and leakage

2.40
mechanical draft cooling tower
cooling tower where the air circulation is produced by a fan

Note 1 to entry: Mechanical draft cooling towers can be further categorised as either

a) forced draft: the fan is located in the entering air stream or

b) induced draft: the fan is located in the discharge air stream.

2.41
natural draft cooling tower
cooling tower wherein the air circulation is produced by a difference in density between the cooler air outside the cooling tower and the warmer, more humid air inside

Note 1 to entry: Natural draft towers can be fan assisted.

2.42
non-series type
design, generally site constructed, for which the performance is project dependent

2.43
open-circuit (wet) cooling tower
cooling tower wherein the process fluid is warm water which is cooled by the transfer of mass and heat through direct contact with atmospheric air

2.44
partition wall
vertical interior wall, either transverse, longitudinal, or radial, that subdivides a cooling tower into cells

2.45
process fluid
working fluid used to transport heat from heat source to the cooling tower

Note 1 to entry: It can be water or any chemical element, compound or mixture, liquid or gas, in single phase flow.

2.46
pump head
in an open-circuit tower, the sum of static head and dynamic head from the contractual inlet interface to the discharge of the distribution system to atmosphere

2.47
re-circulation
portion of the outlet air that re-enters the tower

2.48
relative humidity
ratio of the mole fraction of water vapour in a given air sample to the mole fraction of water vapour in a sample of saturated air at the same temperature and pressure, usually expressed as a percentage

2.49
series type
design which is fixed and described in the manufacturer's catalogue, generally factory assembled, and for which the performance data are pre-determined

2.50
spray water flow
quantity of water flowing over the outside of the heat exchanger in a closed-circuit tower

2.51
test agent
person or entity responsible for conducting the testing

2.52
test period
time duration where readings or recordings of every measurement have to be averaged and test period results can be calculated

2.53
test readings
individual sets of data recorded at regular intervals for each instrument or measurement point required

2.54
thermal lag
time interval before the temperature of the water leaving the influence of the cooling air is detected at the point of cold water temperature measurement

2.55
tolerance
numerical value defined in contract documents or by a certification program expressed in percentage points or degrees Celsius which can be applied to the test results when determining compliance with the pass/fail criteria

Note 1 to entry: Typically, a tolerance is agreed for taking test variability into account.

2.56
top of shell wind speed
for natural draft or fan-assisted natural draft towers, the wind speed at the elevation of the plane through the top of shell and within the defined distance from the tower

2.57
total dissolved solids
weight of inorganic and organic matter in true solution per unit volume of water

Note 1 to entry: Typically, over 90 % of all solids dissolved in water are present as six different ions. Calcium, magnesium, sodium, chlorides, sulphates, and carbonates are usually expressed as mg/l.

2.58
total suspended solids
weight of particulates, both organic and inorganic, suspended, but not dissolved, per unit of water

Note 1 to entry: Total suspended solids are usually expressed as mg/l.

2.59
uncertainty, random
estimate characterizing the range of values within which it is asserted with a given degree of confidence that the true value of the measure can be expected to lie

2.60
valid test period
test period where constancy and values of measured parameters are within the limits of this code

2.61
water flow rate
quantity of hot water flowing into an open cooling tower

2.62
water loading
water flow rate expressed as quantity per unit of fill plan area of the tower

2.63
wet-bulb temperature
temperature of air indicated by a thermometer, shielded from radiation, with the sensing element covered by a thoroughly wetted and adequately ventilated wick

Note 1 to entry: Properly measured, it closely approximates the temperature of an adiabatic saturation and can be further categorised as either

a) ambient wet-bulb temperature: the wet-bulb temperature of air measured windward of the tower and free from the influence of the tower or

b) entering wet-bulb temperature: the wet-bulb temperature of the air entering the tower, including the effect of any re-circulation and/or interference.

2.64
wet/dry cooling tower
cooling tower incorporating two concurrent modes of heat transfer: wet or evaporative and dry or sensible

Note 1 to entry: Wet/dry towers can be of open or closed type and are most often used to control or limit the discharge plume, but can also be used to reduce water consumption.

2.65
design
set of parameters defined by specification or contract as the basis against which the cooling tower performance is analyzed

3 Symbols and abbreviations

A_C	total internal area of hot water conduit at tower inlet, expressed in square metres, m^2
A_{FILL}	gross face area of fill, perpendicular to direction of airflow, expressed in square metres, m^2
a	area of transfer surface per unit of fill volume, expressed in square metres per cubic metres, m^2/m^3
C	heat transfer coefficient
C_{CAP}	tower capability, expressed as a percentage (%) of design flow
C_F	pressure loss coefficient, expressed as a dimensionless unit
c_p	specific heat of a fluid at constant pressure, expressed in kJ/kg °C
	NOTE Assumed to be 4,186 kJ/kg °C for water.
D	diameter of pipe, expressed in metres, m
d	diameter of wet bulb and covering, expressed in millimetres, mm
ΔE	difference in elevation between the inlet and outlet nozzles of the heat exchanger of a closed-circuit tower, expressed in metres, m
G	mass flow rate of dry air through the cooling tower, expressed in kilograms of dry air per second, kg dry air/s
g_c	acceleration due to gravity, expressed in metres per square second, m/s^2
H	elevation difference between top of the shell of a natural draft tower and the midpoint of fill height, expressed in metres, m
H_P	tower pumping head of flowing fluid, expressed in metres, m
h	enthalpy, expressed in kiloJoules per kilogram dry air, kJ/kg dry air
h	enthalpy difference, expressed in kiloJoules per kilogram of dry air, kJ/kg dry air
h_A	enthalpy of air, expressed in kiloJoules per kilogram dry air, kJ/kg dry air
h_{HA}	enthalpy of air-water vapour mixture at bulb air temperature, expressed in kiloJoules per kilogram dry air, kJ/kg dry air
h_M	enthalpy of saturated air-water vapour mixture at bulb water temperature, expressed in kiloJoules per kilogram of dry air, kJ/kg dry air
I_{CAP}	tolerance for instance for tests uncertainty on tower capability, expressed as a percentage, %

I_{TEMP} tolerance for instance for tests uncertainty on tower approach deviation, expressed in degrees Celsius, °C

K overall heat and mass transfer coefficient, expressed in kilograms per second, kg/s°m^2

KaV/L tower characteristic, expressed in dimensionless units

kW_{FM} input power to an electric fan motor, expressed in kilowatts, kW

kW_{PM} input power to an electric pump motor, expressed in kilowatts, kW

K_0:K_1: constants in formulae, derived by combining known values of K_2

L mass flow rate of water entering the cooling tower, expressed in kilograms per second, kg/s

L/G ratio of mass flow rate of water to that of air, expressed in dimensionless units

n an integer number, typically the nth term in a series

P_B barometric pressure, expressed in pascals, Pa

P_{HE} pressure loss across the heat exchanger of a closed-circuit or wet/dry cooling tower, expressed in kilopascals, kPa

P_I static pressure of the process fluid at the inlet nozzle to the heat exchanger of a closed-circuit tower, expressed in pascals, Pa

P_O static pressure of the process fluid at the outlet nozzle to the heat exchanger of a closed-circuit tower, expressed in pascals, Pa

P_T total pressure referred to atmospheric, expressed in pascals, Pa

P_{ST} static pressure at the centreline of the tower hot water inlet conduit, expressed in metres of flowing fluid, m

P_V velocity pressure (computed from $v^2/2g_c$) at the centreline of tower hot water inlet conduit, expressed in metres of flowing fluid, m

P_1 static pressure of water or process fluid at suction of main circulating pump, expressed in kilopascals, kPa

P_2 static pressure of water or process fluid at discharge of main circulating pump, expressed in kilopascals, kPa

Q_A volumetric flow rate of air, expressed in cubic metres per second, m^3/s

Q_{BD} volumetric flow rate of blowdown water, expressed in mass flow rate of water per second, L/s

Q_{MU} volumetric flow rate of makeup water, expressed in mass flow rate of water per second, L/s

Q_{PF} volumetric flow rate of process fluid, expressed in mass flow rate of water per second, L/s

Q_{RW} volumetric flow rate of water re-circulating over the external surface of the heat exchanger of a closed-circuit cooling tower, expressed in mass flow rate of water per second, L/s

Q_W volumetric flow rate of circulating water in an open cooling tower, expressed in mass flow rate of water per second, L/s

q heat transfer rate from water/process fluid to the ambient air, expressed in kiloJoules per second, kJ/s

q_{DRY} dry heat transfer rate for wet/dry cooling tower, expressed in kiloJoules per second, kJ/s

q_{WET} wet heat transfer rate for wet/dry cooling tower, expressed in kiloJoules per second, kJ/s

q_{TOT}	total heat transfer rate for wet/dry cooling tower, expressed in kiloJoules per second, kJ/s
R	cooling range, expressed in degrees Celsius, °C
RH	relative humidity, expressed as a percentage, %
S	thermal lag, expressed in seconds, s
T_{App}	approach deviation, expressed in degrees Celsius, °C
T_{BD}	temperature, blowdown water, expressed in degrees Celsius, °C
T_{CW}	temperature, cold water leaving the tower, expressed in degrees Celsius, °C
T_{CPF}	temperature, cold process fluid leaving the tower, expressed in degrees Celsius, °C
T_{DB}	temperature, air dry-bulb, expressed in degrees Celsius, °C
T_{HW}	temperature, hot water entering the cooling tower, expressed in degrees Celsius, °C
T_{HPF}	temperature, hot process fluid entering the tower, expressed in degrees Celsius, °C
T_{MU}	temperature, makeup water, expressed in degrees Celsius, °C
T_{RW}	temperature, re-circulating water of a closed-circuit cooling tower measured at the pump discharge, expressed in degrees Celsius, °C
T_{WB}	temperature, air wet-bulb, expressed in degrees Celsius, °C
T_{am}	ambient dry-bulb temperature, expressed in °C
T_{ent}	average entering dry-bulb temperature, expressed in °C
tex	linear mass density of fibres, expressed as mass in grams per 1 000 metres (1 tex = 10^{-6} kg/m)
V	effective cooling tower fill volume, expressed in cubic metres, m^3
V_A	velocity of air, expressed in metres per second, m/s
Vavg	average wind velocity
VFD	variable frequency drive
V_L	velocity of liquid, expressed in metres per second, m/s
V_W	velocity of wind, expressed in metres per second, m/s
v_A	specific volume of air, expressed in cubic metres of mixture per kilogram of dry air, m^3 mixture/kg dry air
W_{FM}	fan motor power output, expressed in kilowatts, kW
$X_{x,\,adj}$	designates the value has been adjusted, e.g. for fan power, makeup water temperature, etc.
$X_{x,\,amb}$	designates the value pertains to the ambient air surrounding the tower
$X_{x,\,1}$	designates value pertains to air entering the tower inlet
$X_{x,\,2}$	designates value pertains to air leaving the tower (discharge)
$X_{x,\,d}$	designates the value pertains to the design condition
$X_{x,\,dry}$	indicates the value pertains to the dry section of a wet/dry cooling tower

$X_{x, i}$ indicates the value is obtained from the intercept of two curves

$X_{x, (n)}$ number counter, e.g. the n^th^ term

$X_{x, PF}$ designates the value pertains to the process fluid circulating through the heat exchanger of a closed-circuit cooling tower

$X_{x,pred}$ designates a predicted value determined from the manufacturer's performance data

$X_{x, t}$ designates the value pertains to a measured test condition

$X_{x, w}$ designates the value pertains to the water circulating through an open cooling tower

$X_{x, wet}$ indicates the value pertains to the wet portion of a wet/dry

x exponent applied to L/G ratio in the cooling tower operating formula, expressed in dimensionless units

NOTE Typically on the order of −0,6.

y exponent applied to ratio of design to test fan motor power to adjust dry capacity of wet/dry towers expressed in dimensionless units

Z_i vertical distance from basin curb to centreline of tower piping inlet, expressed in metres, m

z exponent applied to ratio of design to test fan motor power to adjust capacity of closed-circuit towers, expressed in dimensionless units

NOTE Typically on the order of 0,2.

γ weighting coefficient, expressed in dimensionless units

ρ_W density of water, expressed in kilograms per cubic metre, kg/m^3

Υ correction factor for crossflow towers, from Annex E, expressed in dimensionless units

η_{FM} efficiency of fan motor, expressed as a percentage, %

η_P efficiency of main circulating pump (not motor), expressed as a percentage, %

ρ specific mass or density, expressed in kilograms per cubic metre, kg/m^3

ρ_A density of air, expressed in kilograms per cubic metre, kg/m^3

ρ_{PF} density of process fluid, expressed in kilograms per cubic metre, kg/m^3

τ_1 time at the start of the test period, expressed in hours and minutes, hr-min

τ_2 time at the end of the test period, expressed in hours and minutes, hr-min

φ_A absolute humidity of air, expressed in kilograms of mixtures per kilograms of air, kg mixture/kg air

4 Performance tests — General

4.1 Application of standard

The performance test forming the subject of this International Standard can be carried out as a contractual acceptance test or as a qualification or re-verification test, as part of a certification programme. This International Standard can also be used as a guideline to monitor the performance of equipment during its operation. The method described in this International Standard for the verification of performance applies to all cooling towers described in the Scope.

4.2 Test schedule

Acceptance tests should be carried out within a period of one year after start up, preferably after commissioning. To achieve full thermal performance of open cooling towers with film fill, the cooling tower shall operate under heat load for a sufficient period to condition the fill. For this reason, a mutual agreement about the anticipated test schedule between owner/purchaser, testing agency, and manufacturer shall be reached.

For closed-circuit cooling towers, it is preferred to conduct the test as shortly as possible after the start up to avoid the influence of heat exchanger surface contamination. This can also apply to certain wet/dry configurations, where water is sprayed on the heat exchanger surface.

4.3 Pretest agreements

4.3.1 General

If the test is being performed to establish compliance with contractual obligations, it is recommended the parties to the contract agree to several aspects of the test, prior to the test.

4.3.2 Test tolerance and uncertainty

When testing is run according to this code, the results represent without correction for uncertainty the best available assessment of the actual performance of the equipment. The parties to a test should agree before starting a test and ideally before signing a contact on any tolerances that can be applied to measured final test results. Agreement should also be reached prior to testing as to whether, how, and by whom an uncertainty calculation shall be made to assess the quality of the testing conducted, including any criteria for rejection of testing based on uncertainty.

4.3.3 Fouling factors

On closed-circuit cooling towers where a fouling factor is included in the performance guarantee, the purchaser and the manufacturer should agree upon the degree of fouling assumed to be present at the time of the test and the method for adjusting the test results to the fouling allowance specified.

4.3.4 Additional or rescheduled tests

The parties to the test should agree to the allocation of additional expenses incurred if for some reason the test shall be halted and rescheduled at another time or if one or more parties request additional tests.

4.3.5 Scope of test and evaluation method

The parties of the test should agree on the scope of the test, i.e. the use of single or multiple valid test periods, engineering or survey grade, extended test method, and the test evaluation method, either by determination of the tower capability or by approach deviation. For wet/dry closed-circuit cooling towers, it needs to be determined whether the test shall also include verification of performance in the dry operating mode.

4.3.6 Documentation

Prior to the testing contract and preferably with the original tower proposal, the manufacturer shall submit performance documents setting out the guaranteed properties as function of the allowable influence parameters (see 5.3).

4.4 Flexibility

It is recognized that the data limitations specified throughout this test procedure represent desired conditions which might not exist at the time the test is performed. In such cases, existing conditions can be used for performance test, if mutually agreed upon by authorized representatives of the manufacturer, the purchaser, and the agency conducting the test (if applicable). In such cases, the accuracy of the test is compromised (see 10.4) and full compliance to this code can no longer be claimed.

5 Objective of tests

5.1 General

The objective of the testing is to verify the guaranteed thermal and hydraulic properties of the cooling tower supplied, including verifying the following items:

a) determination of the tower capability or approach deviation at measured conditions;

b) pump head, flow rates, and pressure losses.

5.2 Basis of guarantee

The cold water (process fluid) temperature is as a function of:

a) water (process fluid) flow rate;

b) wet-bulb temperature or relative humidity and dry bulb;

c) cooling range, or hot water temperature, and where applicable, as a function of other parameters such as

- — dry-bulb temperature,
- — fan driver power consumption (as driver input or output as contractually agreed),
- — atmospheric pressure,
- — atmospheric vertical temperature gradient,
- — wind speed, and
- — wind direction;

d) cooling tower pump head or the heat exchanger pressure drop applicable parameters, which are defined by tower type in Table 1;

e) other parameters can be guaranteed subject to the contract.

5.3 Form of the guarantee documents

5.3.1 General

The guarantee documents shall take the form of performance curves or characteristic curves and associated tabular data, or spread sheets, curves, formulas, computer programs, etc. A block of data shall be included on the curves containing the guaranteed parameters for the appropriate products as defined in Table 1. If supplied as spread sheets, formulas, computer programs, etc., the information shall be equivalent in scope and detail to the requirements for curves in 5.3.2 through 5.3.6 and characteristic equations in 5.3.7.

5.3.2 Performance curves — Mechanical draft

The tower manufacturer shall submit tower performance data in the form of a family of performance curves consisting of a minimum of three sets of three curves each. One set shall apply to 90 %, one set to 100 %, and the other to 110 % of the design process fluid flow rate. Each set shall be presented as a plot of wet-bulb temperature as the abscissa versus cold water temperature as the ordinate, with cooling range as a parameter. Curves shall be based on constant fan speed and pitch.

a) In addition to the design cooling range curve, at least two bracketing curves at approximately 80 % and 120 % of the design cooling range shall be included as a minimum. The design point shall be clearly indicated on the appropriate curve.

b) The curves shall fully cover (but not necessarily be limited to) allowable variations from design specified in 8.2.4.2.

c) On closed-circuit towers, including wet/dry, where the process fluid is a mixture (e.g. an aqueous glycol solution), the performance curves shall be expanded to encompass solution concentration as a parameter with curves for at least three concentrations: design, five percentage points above design, and five percentage points below design (e.g. for a design concentration of 25 %, performance curves shall be submitted for 20 %, 25 %, and 30 % concentrations). These curves shall be interpolated to the measured concentration at the time of the test evaluation.

d) For wet/dry closed-circuit cooling towers, the manufacturer shall specify the operating conditions and control settings of the tower required to yield full capacity in the wet/dry operating mode. If verification of performance in the dry operating mode is required, the manufacturer shall specify operating conditions and control settings in this mode and submit performance curves as specified above but with the dry-bulb temperature as abscissa.

5.3.3 Performance curves — Wet/dry and fan-assisted natural draft towers

The tower manufacturer shall submit a family of curves which relate the pertinent performance variables, including as a minimum, one set of curves for each of three process fluid flow rates, one at 90 % of design, one at 100 % of design, and one at 110 % of design. Each set shall consist of three or more cooling range curves and at least four relative humidity curves, arranged to show the effects of wet-bulb temperature, relative humidity, and cooling range on the cold process fluid temperature. Curves shall be based on constant fan speed and pitch.

NOTE In special cases where performance guarantees are limited for winds from specific directions, measurement of the wind direction would become mandatory.

Table 1 — Measured parameters for guarantee by tower types

	Series			Non-series			Natural drift	Natural drift fan assisted
	Open	Closed and Closed Wet/Dry	Open Wet/Dry	Open	Closed and Closed Wet/Dry	Open Wet/Dry		
Flow rate	M	M	M	M	M	M	M	M
Fluid type	M	M	M	M	M	M	M	M
Fan power	M	M[c]	M	M	M	M	—	M
Cold temp., or range and approach	M	M	M	M	M	M	M	M
Entering WBT or RH and DBT	M	M	M	M	M	M	M	M
Entering DBT	M	M	M	M	M	M	M	M
Hot temp., or range and approach	M	M	M	M	M	M	M	M
Barometric pressure	M	M	M	M	M	M	M	M
Average wind speed	M	M	M	M	M	M	M	M
Average wind direction	S[d]	S[d]	S[d]	S[d]	S[d]	S[d]	S[d]	S[d]
Top of shell wind speed	—	—	—	—	—	—	M[b]	M[b]
Ambient dry bulb	—	—	—	—	—	—	M	M
Atmospheric gradients	—	—	—	—	—	—	M	M
Liquid gas ratio (*L*/*G*)	O	O	O	O	O	O	—	O
Pump head	S	S	S	M	M	M	M	M
Heat exchange pressure drop	—	M	S[a]	—	M	S[a]	—	—
Spray pump power	—	M	—	—	M	—	—	—
Dissolved and suspended solids	M	M	M	M	M	M	M	M
Fouling factors	—	S	S	—	S	S	—	—
Fluid properties	—	M	—	—	M	—	—	—

NOTE 1 Parameters indicated with M are mandatory.

NOTE 2 Parameters indicated with O are required for induced draft towers, as it is needed for possible corrections of the fan power.

NOTE 3 Parameters indicated with S are not mandatory, but only suggested for information purposes.

a Required for wet/dry cooling towers with dry heat exchangers on separate heat sources.

b Mandatory but not practical to measure in most cases. This parameter should be evaluated through a visual criteria in the case of daytime basic tests, and is not relevant in the case of extended tests.

c For wet/dry closed-circuit towers, the fan power requirement in dry operating mode should be indicated if verification of dry performance is included in the test.

d In special cases where performance guarantees are limited for winds from specific directions, measurement of the wind direction would become mandatory.

In addition to the design cooling range curve, at least two bracketing curves at approximately 80 % and 120 % of the design cooling range shall be included as a minimum. The design point shall be clearly indicated on the appropriate curve.

The relative humidity curves shall be presented in approximately equally spaced curves and shall cover the extent of expected conditions (e.g. 20 %, 40 %, 60 %, and 100 % relative humidity or 60 %, 70 %, 80 %, and 100 % relative humidity). Each curve shall include the dry-bulb temperature expressed as a function of the wet-bulb temperature and relative humidity on which the curve is based.

The curves shall fully cover (but not necessarily be limited to) the allowable variations from design specified in 8.2.4.2.

In the case where multiple modes of air and/or water flow control are guaranteed, additional sets of curves shall be submitted.

5.3.4 Performance curves — Natural draft towers

The manufacturer shall submit a family of curves which relate the pertinent performance variables, including as a minimum, one set of curves for each of three process fluid flow rates, one at 90 % of design, one at 100 % of design, and one at 110 % of design. Each set shall consist of three or more cooling range curves and four or more relative humidity curves, arranged to show the effects of wet-bulb temperature, relative humidity, and cooling range on the cold process fluid temperature.

a) In addition to the design cooling range curve, at least two bracketing curves at approximately 80 % and 120 % of the design cooing range shall be included as a minimum. The design point shall be clearly indicated on the appropriate curve.

b) The relative humidity curves shall be presented in approximately equally spaced curves and shall cover the extent of expected conditions (e.g. 20 %, 40 %, 60 %, and 100 % relative humidity or 60 %, 70 %, 80 %, and 100 % relative humidity). Each curve shall include the dry-bulb temperature expressed as a function of the wet-bulb temperature and relative humidity on which the curve is based.

c) The curves shall fully cover (but not necessarily be limited to) the allowable variations from design specified in 8.2.4.2.

5.3.5 Performance curves — Scale

Temperature scales comprising the ordinate and abscissa shall be based on increments no greater than 0,2 °C at a spacing no closer than 0,1 °C/mm, to enable reading precision.

5.3.6 Characteristic curves (mechanical draft for basic tests)

When the performance of an open-circuit cooling tower is to be evaluated by the characteristic curve method, the manufacturer shall submit tower performance data in the form of a curve or family of curves relating tower characteristic (KaV/L) to the water/air ratio (L/G), clearly indicating the design L/G to be used for the test evaluation. This relationship can be presented as a formula, with all constants listed, or as a curve or properly identified family of curves, expressing the effects of variables (such as hot water temperature and airflow rate) that can have a significant effect on the result. The data submitted shall cover a range of L/G values extending from 80 % or less of the design L/G to 120 % or more.

5.3.7 Characteristic curves — Scale

If the relationship is presented as a curve, the graphical scaling shall permit the determination of KaV/L to a minimum precision of three significant figures.

5.3.8 Characteristic equations (natural draft towers for extended tests)

When extended tests are conducted, performance curves are not practical for test evaluation. Instead, the performance of the tower is assumed to be described by Formula (1) (operating equation) and

Formula (2) (draft equation) and the manufacturer shall submit polynomials or values for the coefficients involved in these characteristic equations.

$$\frac{KaV}{L} = C\left(\frac{L}{G}\right)^{X} \tag{1}$$

$$\rho_{A,1} - \rho_{A,2} = (0{,}5)\,\frac{\rho_{A,1}}{g_C H} C_F\, v_A{}^2 \tag{2}$$

The heat transfer coefficient, C, and the pressure loss coefficient, C_F, are supplied by the manufacturer in the form of a function of the wind velocity at 10 m and of other parameters which affect the tower performance such as the average velocity of the air, V_A. The factors C, C_F, and h shall apply between 90 % and 110 % of the water flow rate, and between 80 % and 120 % of the design cooling range. The values of draft height, H, and gross fill plan area, A_{FILL}, are also supplied by the manufacturer. The average velocity of air through the fill, $\overline{V_A}$, is calculated by Formula (3).

$$\overline{V_A} = G\,\frac{(1 + \varphi_A)}{\rho_{A,1}\, A_{FILL}} \tag{3}$$

NOTE The tower thermal capacity obtained in solving the characteristic equations is an approximation of the actual thermal capacity, which performance curves show when drawn according to an exact method. However, this approximation is generally acceptable and is validated by this International Standard as long as the hot water temperature does not exceed 50 °C.

5.3.9 Tabular data

A table shall be included on or accompany the performance or characteristic curves listing the design point conditions of

a) the type of process fluid and, if other than water, the composition,

b) the process fluid flow rate,

c) the temperature of the hot process fluid entering the tower,

d) the temperature of the cold process fluid leaving the tower,

e) the entering wet-bulb and dry-bulb temperatures,

f) the design liquid-over-gas ratio (L/G),

g) the design wind conditions and atmospheric gradient, if applicable, and

h) the design barometric pressure or altitude.

And, additionally for mechanical draft towers:

a) the design fan driver power (input or output as contractually agreed);

b) the efficiency of the fan driver (if applicable);

c) the density of the air entering the fan(s) at the design operating point;

d) the exponent (EXP) to be used to determine the adjusted test flow rate on closed-circuit towers or, alternatively, a performance curve relating % capability to % design fan driver power encompassing, as a minimum, the range of 90 % to 110 % design fan power. In the case when no value is given for the exponent in the contract, 1/3 could be used, subject to mutual agreement;

e) for induced, mechanical draft towers, the volumetric airflow rate entering the fan(s) at the design operating condition;

f) for closed-circuit towers including wet/dry, the output power and motor efficiency of the external circuit re-circulating pump when the pump and piping are supplied by the manufacturer. Alternatively, when the pump and/or the piping is supplied by others, the manufacturer shall specify the flow rate of the re-circulating water and the static pressure required at the re-circulating water inlet connection(s) (or the static head of a gravitational system) to produce the design flow rate;

g) in the specific case of separate fans serving dry and wet portions of a tower or separate towers, the manufacturer shall submit dry surface pressure drop and heat transfer exponents as required for use in evaluating the fan driver output power exponent (γ) in Formula (66);

h) for wet/dry closed-circuit cooling towers, the manufacturer shall provide the fan power requirement in dry operating mode, if dry performance verification is included in the test.

6 Test preparation

6.1 Purpose

The purpose of this Clause is to set forth

a) the responsibilities of the owner or site contractor and the testing agency in preparing a cooling tower for a field performance or acceptance test and

b) the conditions that shall be present at the time of the test to ensure the test results accurately reflect the capability of the tower.

6.2 Test scheduling and site preparation

Proper preparation of the cooling tower and scheduling of the test will expedite the actual test, control test costs, and ensure the measured data accurately reflect the true capability of the cooling tower.

6.2.1 Responsibilities

The cooling tower owner or his representative is responsible for helping to arrange the test date with the parties to the test, for preparing the tower for test, and for providing free and safe access to the tower and all the instrument and control locations during the test. Execution of the test is contractually defined and preferably should be conducted by a suitable, independent third party test agency mutually agreeable to owner and manufacturer. The parties to an acceptance test are the owner's representative, the manufacturer's representative, and the test agent, if an independent third party agency.

6.2.2 Scheduling

The actual date for the test should be set only after ensuring:

a) the tower is in good operating order;

b) the necessary provisions for measuring all required test parameters have been installed (see 6.4);

c) the operating personnel have been advised of the test and the tower is expected to be operating within the deviations from design conditions allowed by the test code (see 8.2.4 and 8.3.5);

d) the closer the tower is to operating at design conditions during the actual test, the more likely the test results will reflect the actual capability of the tower. For this reason, the test codes require the tower be operating within specific, maximum allowable deviations from design. In towers comprised of multiple, identical cells, if agreeable to the parties to the test, the number of cells in operation can be adjusted prior to the test in order to bring the cells being tested within the allowable limits;

e) all parties to the test, including the owner, purchaser, and manufacturer and test agent, shall have been notified of a proposed test date and can be present on site if they so desire;

f) final confirmation of the test date should be made only after considering the local weather forecasts. For basic tests, conditions that should be avoided include winds above 4,5 m/s (unless otherwise contractually specified), continuous rain, thunderstorm activity, dry-bulb temperature below 5 °C, and high likelihood of a warm or cold front moving through the area.

In cases where it is not practical to measure the wind speed at the top of the shell, an indicator of the wind conditions at the top of the shell shall be the appearance of plume at the exit. For an acceptable test, visual observations of the plume shall indicate that the plume completely fills the shell outlet and rises vertically for a minimum distance of approximately one-half of the outlet diameter.

6.3 Tower physical condition

6.3.1 General

For the cooling tower to produce the rated capacity, all of the individual components shall be operating properly and be clear of any obstructions or blockages. The manufacturer shall be given an opportunity to conduct a detailed, pre-test inspection of the tower, prior to the scheduled test date.

6.3.2 Heat transfer media

The heat transfer media should be in a suitable operating condition.

6.3.2.1 Film-filled open-circuit towers

The fill surface shall be properly conditioned by operation for at least 500 h (for PVC) with hot water temperature of at least 32 °C. Other materials can require longer conditioning periods.

6.3.2.2 All open-circuit fill media

The fill shall be operating in an unobstructed manner, free of visible silt, algae, slime, or other accumulations which cause flow to channel. Such channeling sometimes leaves visible high and low water flow areas at the discharge of the fill, indicating a heavy fouling. In any case, the most effective way to detect an accumulation of any kind is to inspect an inside layer, if fill is layered, by removing the upper one.

6.3.2.3 Closed-circuit towers (including wet/dry)

The heat exchangers shall be operating without excessive internal fouling that would restrict heat transfer beyond the specified value. The external surfaces of the heat exchangers shall be operating, free of silt, algae, slime, scale, and other accumulations which impede heat transfer or retard or channel the normal flow of air and water.

6.3.3 Water distribution system

Design flow and unobstructed water distribution shall be provided over the heat transfer media (fill) if the tower is to produce rated capacity. Therefore, the following shall be verified before conducting a thermal performance or acceptance test.

a) Distribution system is in good operating condition, free of algae, slime, or other obstructions to flow.

b) All nozzles/orifices are properly installed, clean, and in good operating condition.

c) Circulating water is essentially free of oil or other foreign materials.

d) The flow rate to the tower (or cells to be tested) is within ±10 % of design.

e) The flow to all hot water basins/cells is balanced.

NOTE If balancing is necessary, open all balancing valves and check the water level in each hot water basin (crossflow towers) or the spray pressure at each inlet connection (counterflow towers). Then, at the basin/connection with the highest level/pressure, slowly reduce the flow until all levels/pressures are essentially equal. Serious imbalances can require more than one adjustment.

f) All bypass valves are operating properly with no leakage across the valve when in the closed position. At the time of test, all bypass valves shall be locked in the closed position with no leakage.

6.3.4 Mechanical equipment

The mechanical equipment on each cell should be checked to verify

a) the fans and drivers are in good working order, turning freely with no binding or interference,

b) the fans rotate in the proper direction, and

c) when operating within the deviations from design conditions allowed by the test code, the fan drivers shall be loaded to within ±10 % of the design power consumption of the fan.

6.3.5 Drift eliminators

All drift eliminators shall be properly installed and in good operating condition, free of algae, slime, or other obstructions to airflow.

6.3.6 Air inlets

The air inlets to the tower shall be free of all obstructions or blockages which were not considered or accounted for in the tower selection and design. Louvers, if any, are all installed and in their proper position.

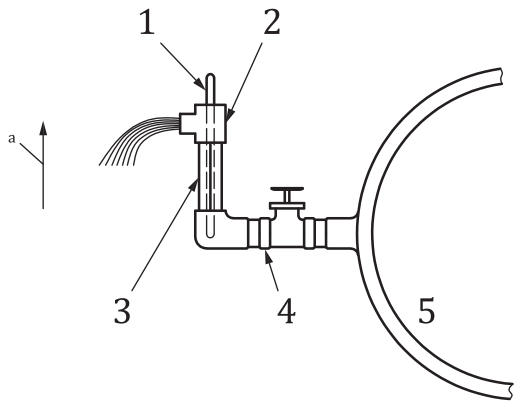
6.4 Provisions for instrumentation

6.4.1 Description

Unless otherwise specified in the contract documents or through prior agreement, the agency conducting the test will provide all the instrumentation required to properly conduct the test. However, it is typically the responsibility of the tower owner and/or site contractor to provide the temperature taps, thermowells, Pitot taps, power for instrumentation, other utilities, etc. necessary for the test, as detailed in Clause 7.

6.4.2 Temperature measurements

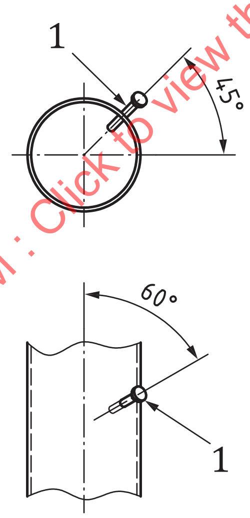
In closed conduits, temperature measurements can be made using a flowing tap in the line (see Figure 1) or with a temperature well (see Figure 2) filled with a heat conducting paste or fluid. The stations should be located at a point where the water is well mixed and, if taps are used, at a positive pressure.



Key

1 Thermometer
2 tee (optional)
3 nipple, 12,5 mm × 150 mm
4 gate valve, 12,5 mm
5 pipe
a Vertical.

Figure 1 — Temperature tap



Key

1 temperature well

Figure 2 — Temperature well

NOTE Taps should not be used if the continuous bleeding of water from the tap over the duration of the test would present a system or environmental problem. In open channels, a grid structure can be required to support and locate temperature sensors. To power the psychrometers, furnish AC power to the tower site with sufficient extension cords to reach all inlet faces of the tower. Check with the testing agency for the preferred supply voltage.

6.4.3 Flow measurement

6.4.3.1 General

Accurate measurement of the cooling tower flow rate is essential to an accurate determination of the cooling tower capability and appropriate care shall be taken in selecting both the instrument(s) to be used and the point at which the measurement is made.

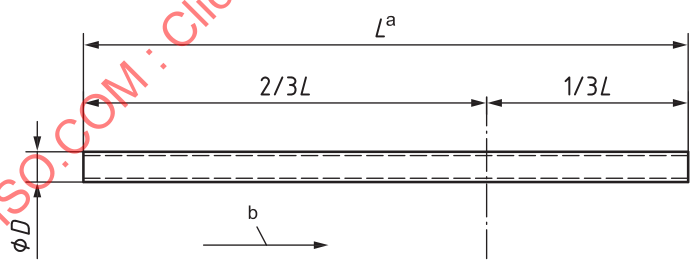
6.4.3.2 Measurement site

When the flow rate of the circulating water or process fluid is to be measured in a closed conduit, the measurement station can be situated in virtually any easily accessible line with a positive pressure, typically in the main hot water header or in the individual risers to each cell. If a main header is selected, make certain the flow being measured is only for the tower(s) under test and no other flow streams are added or removed between the measurement station and the tower inlet connection(s). Flow measurements at each individual riser require more time, but they ensure only the flow to the tower(s) being tested is measured and, where more than one riser is being used, they provide information on the balance of flow between cells.

6.4.3.3 Location

Most of the commonly used flow measurement devices require a fully developed velocity profile at the point of measurement. To ensure accurate measurement, the flow measurement station shall be situated in a section of straight pipe, free of any valves or fitting, extending 20 pipe diameters in length. The measurement station should be located with 2/3 the length of straight pipe upstream and 1/3 the length downstream (see Figure 3). Compromises in these criteria will adversely affect the accuracy of the flow measurement and the test result.

In addition to the considerations for accuracy, it is also imperative that the measurement site be safely accessible to test personnel during the test. The tower owner and/or site contractor shall provide the necessary ladders, scaffolding, and safety harnesses.



Key

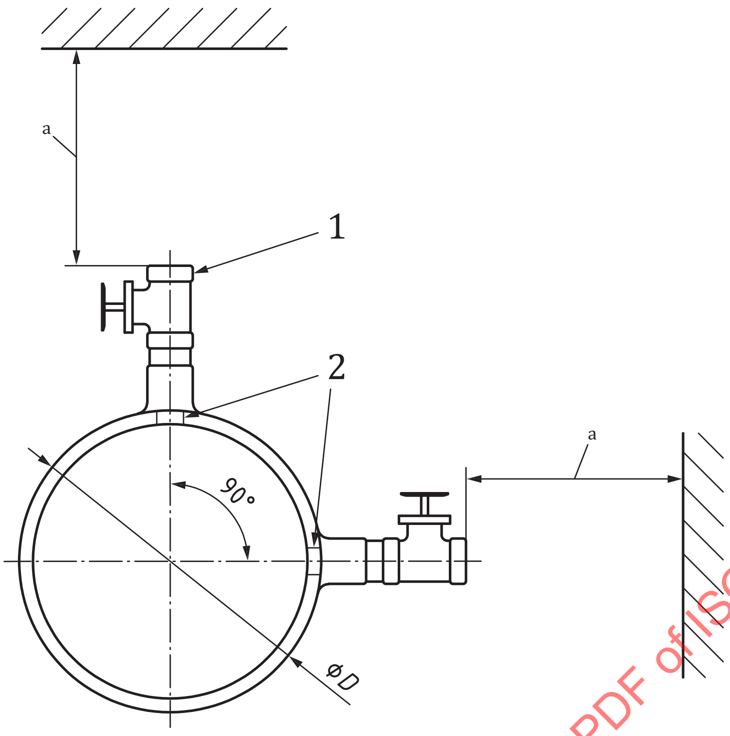
a ideally 20*D*, minimum 10*D*

b flow

Figure 3 — Flow measurement site

6.4.3.4 Measurement by Pitot tube traverse

When the flow rate to the tower is to be measured by Pitot tube traverse of the conduit, install two taps at the point of measurement in the same transverse plane through the pipe, separated by 90°, and fit them with 30 mm or 40 mm, full ported gate valves as illustrated in Figure 4. On large diameter pipes, a reinforced Pitot tube can be required and the size of the taps and valves increased accordingly. If there is any doubt to the size, coordinate with the testing agency. Additionally, ensure adequate clearance is available beyond each valve to accommodate the full length of the Pitot tube for insertion and withdrawal. As noted in Figure 4, for conduits 600 mm or less in diameter, provide at least 1,3 m clearance. For conduits larger than 600 mm, provide a clearance equal to three times the conduit diameter.



Key

1 2 each of 30 mm or 40 mm full ported gate valves

2 2 each of 30-mm-diameter clean drilled holes, free of burrs

a Minimum clearance: for $D \leq 600$ mm, use 1,3 m; for $D \geq 760$ mm, use $3D$

Figure 4 — Pitot tube taps and required clearance

6.4.3.5 Flow measurements by other methods

Instruments other than a Pitot tube can be used for flow measurement, some of which are not intrusive. In such cases, the tower owner and/or site contractor shall work with the test agent to ensure the proper provisions, as described in the appropriate International Standard, are made for the flow measurement, prior to the scheduled test date.

6.4.3.6 Makeup flow

Unless the makeup flow can be shut off for several hours for the duration of the test, a volume type meter or other suitable flow measuring device should be installed in the makeup line leading to the tower.

6.5 Fan driver input power

For electric motors, provide access at the disconnect switch or the starter for each fan motor to measure the power input with a portable, clamp-on power meter. If the fan motor voltage is over 600 v, the fan motor is equipped with a variable frequency drive (VFD), or if the fans are not driven by electric motors, the tower owner and/or site contractor shall work with the test agent to make such provisions as are necessary to correctly measure the power input to the fan(s).

6.6 Site conditions

6.6.1 General

Typically, cooling tower tests are tentatively scheduled by the test purchaser well in advance of the actual test date. This tentative date should be selected such that the likelihood is high that the required tower operating conditions and the weather conditions will comply with the test code requirements.

6.6.2 Tower operating conditions

The closer the tower is to operating at design conditions during the actual test, the more likely the test results will reflect the actual capability of the tower. For this reason, the test codes require the tower be operating within specific, maximum allowable deviations from design.

These allowable deviations are set forth in 8.2.4 and 8.3.5 of this International Standard and every effort should be made to comply with them at the time of the test.

NOTE In towers comprised of multiple, identical cells, if agreeable to the parties to the test, the number of cells in operation can be adjusted prior to the test in order to bring the cells being tested within the allowable limits.

6.6.3 Weather conditions

For basic test, final confirmation of the test date should be made only after considering the local weather forecasts. Conditions that should be avoided include

a) winds above 4,5 m/s unless otherwise contractually specified,

b) continuous rain,

c) thunderstorm activity,

d) dry-bulb temperature below 5 °C, and

e) high likelihood of a warm or cold front moving through the area.

6.7 Miscellaneous

There are also several other aspects of preparing for a test which are not covered in this International Standard, but shall be addressed to ensure the test proceeds smoothly, on the appointed day. These include, but are not limited to:

a) When power input measurements shall be made on electric fans or pump motors, arrange for an electrician to be on site on the day of the test to assist with these measurements.

b) Similarly, have operators available on the day of the test should the need arise to adjust valves or make minor adjustments to the system or tower to facilitate the test.

c) Arrange for security clearances and vehicle passes for test personnel and observers as well as any necessary plant safety orientations, special training, certificates of insurance, etc.

d) Install all ladders, lifts, scaffolding, railings, and safety equipment necessary to ensure safe access to the tower and all measurement stations, particularly the flow measurement station, during the test.

e) See checklist, Annex M.

7 Instrumentation and test setup

7.1 Calibration

All instrumentation employed during the course of the test shall be calibrated prior to the test. Calibration shall be traceable to primary or secondary standards calibrated by a recognized authority, such as a national standards authority, or derived from accepted values of natural physical constants. Instruments shall be recalibrated on a regular schedule appropriate for the respective instrument and full calibration records shall be maintained. The minimum calibration frequencies shall be as shown in A.1.1. An instrument shall also be calibrated whenever it is damaged or its accuracy is called into question for any other reason. Additionally, at the request and expense of the test purchaser, any and all instrumentation used on a test can be calibrated before and/or after a test.

7.2 Flow measurements

7.2.1 General

All tests require measurement of the main circulating water or process fluid flow rate. Measurement of the makeup water flow rate and the blowdown water flow rate might be necessary, depending upon the tower operating mode during the test.

The flow rates shall be measured using any of the methods specified in A.2.2. The method employed, the location, and the number of measurements taken will depend upon the nature of the installation, the importance of the measurement, and the type of test.

7.2.2 Flow rate measurements

The flow rate of the water or process fluid shall be measured at a point where a well-developed velocity profile exists, preferably in the piping leading to the tower. The measurement location should be 20 diameters downstream and 10 diameters upstream of any obstructions or transitions in the piping. Measurement stations with insufficient upstream and downstream distances will have significant, adverse impact on the velocity profile and the accuracy of the measurement and should be resolutely avoided.

7.2.3 Inspections of measurement devices

Flow measurement devices, whether temporarily or permanently installed, shall be inspected prior to the test for dimensional conformity and functionality.

7.3 Temperature measurements

7.3.1 General

Temperature shall be measured using any of the methods specified in Annex A. The temperature-sensitive elements shall be carefully located to ensure the measurement is representative of the true bulb temperature of the fluid at the point of measurement.

The indicator or recorder shall be graduated in increments of not more than 0,1 °C and be readable to ±0,05 °C. The temperature-sensitive element shall be accurate to ±0,05 °C.

7.3.2 On-site comparison

Prior to the test, an on-site comparison of all temperature sensors shall be conducted. In the case of electronic data acquisition systems, this shall be performed after all wiring connections are made. If in doubt, a temperature sensor will be compared to another similar sensor and replaced if it is questionable.

7.3.3 Water/process fluid temperatures

7.3.3.1 General

The temperatures of the water/process fluid shall be measured at full flowing bleeds, directly in the process stream or in thermometer wells installed at the point of measurement. Thermometer wells shall be filled with a thermal conducting liquid or paste to ensure the temperature-sensing device is exposed to a representative temperature.

7.3.3.2 Hot water or process fluid temperatures

The temperature of the hot water or process fluid entering the tower shall be measured in the tower riser(s) or at the discharge of the inlet riser(s) into the distribution system or, for a multi-cell tower, in the supply header just upstream of the first riser. For closed-circuit towers, including wet/dry, the temperature of the hot process fluid entering the tower shall be measured at the inlet to the heat exchanger or, for towers with multiple heat exchangers or cells, in the supply header just upstream of the inlet connection to the first heat exchanger. For either type of tower, if the source is a mixture of two or more streams at different temperatures, complete mixing shall be ensured at the point of measurement or sufficient flow rate and temperature measurements of the individual streams shall be made to ensure an accurate weighted average fluid temperature.

7.3.3.3 Cold water or process fluid temperatures

Although other locations can be used, the temperature of the cold water leaving the tower should preferably be measured at the circulating pump discharge for best mixing, and the average measured value corrected for heat added by the pump in accordance with 9.2.4. For closed-circuit towers, including wet/dry, the temperature of the cold process fluid leaving the tower shall be measured at the outlet of the heat exchanger or, for a tower with multiple heat exchangers or cells, in the header just downstream of the last outlet connection. For either type of tower, if the best available measurement is made at a location such as a water discharge flume where temperatures and velocities are not uniform over the stream cross section, sufficient flow rate measurements should and temperature measurements shall be made to ensure an accurate, weighted average fluid temperature.

7.3.3.4 Makeup water temperature

If the makeup system is running during the test, the temperature of the makeup water shall be measured at the point the makeup water enters the system.

7.3.3.5 Blowdown temperature

If the blowdown system is operative during the test, the temperature of the blowdown water shall be measured at the point the blowdown leaves the system.

7.3.4 Entering air temperatures

7.3.4.1 Required entering air temperature

Entering air wet-bulb temperature is required for all cooling-tower tests. Entering air dry-bulb temperature is required for forced draft and natural draft towers to determine the thermodynamic properties of the air entering or around the tower and for induced draft configurations to facilitate the determination of the psychometric properties of the air entering the fan(s) and/or when estimating the evaporation rate.

7.3.4.2 Measurement stations

Air temperature measurement stations shall be located 1,5 m from the cooling tower air intake(s). A sufficient number of measurement stations shall be employed to ensure the average of the test readings yields an accurate representation of the true inlet wet-bulb temperature. Requirement for the minimum number and location of measurement stations is given in Annex C.

7.3.4.3 Dry-bulb temperature

When the entering air dry-bulb temperature measurement is for the sole purpose of determining the physical properties of the entering air on a mechanical draft tower, this can be achieved, in most cases, by means of a single measurement station, or at most two stations.

7.3.5 Ambient air temperature

Ambient air dry-bulb temperature, T_{am}, is required for natural draft cooling towers. This measurement shall be placed at a fixed meteorological mast of 10 m height, located at least 300 m from the tower, and in an open and unobstructed location.

7.3.6 Atmospheric gradient for natural draft

The inlet dry-bulb temperature gradient is a critical measurement on natural draft towers since it is used to determine the inlet-air density which, in turn, is part of the driving force that makes the cooling tower perform. The following are the dry-bulb temperature measurement requirements for natural draft towers.

a) For the direct measurement of natural draft cooling tower vertical ambient dry-bulb temperature gradient, the plan location of the instruments shall be neither downwind of nor within the influence of the cooling tower or any other site sources of turbulence or thermal gradients which might substantially affect the measured data. The vertical elevations shall be as specified in Annex A. Instrumentation locations and techniques will be site-specific and shall be based upon mutual agreement prior to testing.

b) As an indicator of the vertical dry-bulb temperature gradient on natural draft towers, two dry-bulb instruments shall be located at the same circumferential near or above the top of the air inlet. The instrument placed near or above the top of the air inlet can be located on a stairway at or above the elevation of the top of the air inlet if the location otherwise satisfies the criteria herein. The instruments shall not be place downwind of the cooling tower. Every effort shall be made to place the instruments in locations not subject to radiation or to convective air heating effects due to solar heating of the shell. The placement of the gradient indicator instruments shall be mutually agreed upon by the parties to the test.

c) As another indicator, we shall compare the ambient dry-bulb temperature, T_{am} (as defined in 7.3.5), with the average entering dry-bulb temperature, T_{ent}, and only consider test periods such as:

$$-1 < T_{ent} - T_{am} < 0$$

7.4 Pressure measurements

7.4.1 General

Pressures shall be measured using any of the devices specified in Annex A as appropriate for the magnitude of the pressure to be measured.

7.4.2 Pressure taps

Tappings into conduits for pressure measurements shall be 3 mm or less and be free of burrs and other irregularities.

7.4.3 Heat exchanger pressure drop

Measurements for determining the pressure drop of the process fluid across the heat exchanger of a closed-circuit or wet/dry tower shall be made in accordance with A.4. The stations shall be located as closely as possible to the contractual inlet and outlet locations of the heat exchanger(s). Corrections shall be made for fitting losses, changes in pipe size, etc. that produce pressure differences between the measuring stations and the contractual locations.

7.5 Fan/pump driver power

7.5.1 General

The power consumed by the fan/pump driver shall be measured. If the tower performance is based on driver output, the measured power input shall be adjusted for the efficiency of the driver using the efficiency provided by the driver manufacturer.

7.5.2 Electric motors

In the case of electric motors, power input shall be determined by direct measurement of the kilowatt input at a location such that the instrumentation can accurately measure the total power input to the device. A line loss correction shall be made, unless otherwise agreed by all parties.

7.5.3 Variable frequency drives

If the electric motor is equipped with a variable frequency drive (VFD) or other power altering device, appropriate actions (such as bypassing the device) shall be taken to ensure an accurate measurement and that no speed changes are made to the fan over the duration of the test.

7.6 Wind velocity (speed and direction)

7.6.1 General

Wind velocity shall be measured with any of the devices specified in Annex A, preferably remote reading and recording. The number of measurement stations and their location is dependent upon the type of tower under test and the test type.

7.6.2 Mechanical draft towers

For mechanical draft towers, the wind velocity measurement shall be made in an open and unobstructed location, upwind of the tower and beyond the influence of the inlet-air approach velocity. Care shall be taken to ensure the recorded wind speed and direction are representative of wind conditions affecting the tower. Placement of the wind measurement device shall be subject to mutual agreement by all parties to the test. Wind direction shall be recorded in compass degrees with the reference north clearly indicated.

7.6.2.1 Tower heights less than or equal to 6 m

For cooling towers with an overall height of 6 m or less between the basin curb and discharge elevations, the wind velocity shall be measured 1,5 m above the elevation of the basin curb, at a point within 15 m to 30 m of the tower, if practical.

7.6.2.2 Tower heights greater than 6 m

Where the distance between basin curb and the discharge elevation exceeds 6 m, the wind velocity shall be measured at a height above the curb elevation that is approximately one-half the difference between the curb and discharge elevations and at a distance of at least 30 m from the tower, if practical.

7.6.3 Natural draft towers

7.6.3.1 Inlet

For natural draft towers, the wind velocity shall be measured at a height equal to one-half the inlet height and a distance from the cooling tower that is at least twice the air inlet height and no less than a quarter of the base diameter of the tower. When conducting extended tests, a fixed meteorological tower/mast, typically 10 m height, can be used if located at least 300 m from the tower and in an open and unobstructed location.

7.6.3.2 Discharge

For natural draft towers, the wind velocity shall be measured in a horizontal plane extending through the discharge opening at the top of the shell at a point within 45 m to 450 m from the edge of the shell, if practical. Situations where there is a strong wind at the discharge and little or no wind at the air inlet should be avoided.

An indicator of the wind conditions at the top of the shell shall be the appearance of plume at the exit. For an acceptable test, visual observations of the plume shall indicate that the plume completely fills the shell outlet and rises vertically for a minimum distance of approximately one-half of the outlet diameter.

In the case of extended tests, top of shell wind speed parameter is not relevant.

7.7 Tower pump head

Two measurements are required for determining tower pumping head:

a) the gauge static pressure at the centreline of the water inlet connection;

b) the measured, vertical distance between the top of the basin curb and the centreline of the hot water inlet connection.

7.8 Water or process fluid analysis

A sample of the circulating water and, where applicable, the process fluid shall be taken during the test if any parties to the test question water quality. The sample shall be analysed by a reputable testing laboratory to determine the composition of the fluid.

8 Execution of test

8.1 Requirements for testing type

Execution of two types of tests, basic and extended, is described in this Clause. The decision to run one type of test rather than the other depends on the type of tower (extended tests typically only apply on natural draft cooling towers) and on the contract (guarantee parameters involved). Basic tests take place over a short duration. Extended tests require longer duration and an unattended data acquisition is required.

8.2 Basic tests

Basic tests are appropriate for all types of cooling towers.

8.2.1 Duration of the test period

A test period (see definition in Clause 3) lasts 1 h plus any thermal lag time, if applicable.

A valid test period fulfils all requirements listed in 8.2.4.

Only valid test periods will be considered in an acceptable test.

8.2.2 Required number of valid test periods

The minimum number of valid test periods required for mechanical draft is one and for natural draft is six collected over 2 d. Test periods shall not overlap. The results of all valid test periods shall be taken into account in the acceptance test.

8.2.3 Test measurements

Tests can be categorised as either engineering grade or survey grade depending upon the method and frequency of acquiring the test readings.

8.2.3.1 Engineering grade

Engineering grade is the more rigorous and preferred method of acquiring test data. An automated, electronic data acquisition shall be employed to scan all measuring instruments at regular intervals no greater than 15 s in duration. Test readings shall be comprised of no less than four scans of each required instrument averaged over a 1 min period (see Table 2). Engineer grade tests are recommended for acceptance and certification testing.

8.2.3.2 Survey grade

In survey grade tests, readings shall be taken and recorded manually at regular intervals over the test period, as specified in Table 2.

8.2.4 Validity conditions for basic acceptance tests

A test period shall be valid only if the requirements below are met.

8.2.4.1 Climatic condition requirements during the test period

a) No rain, snow, or hail.

b) No fog; the difference between dry-bulb and wet-bulb temperature shall be greater than 0,5 °C.

c) The wet-bulb temperature of the ambient air shall be greater than or equal to 2 °C.

d) If no other limits are specified in the contract, the average wind speed (see 7.6) shall not exceed 3 m/s for natural draft and 4,5 m/s for mechanical draft. Gusts of more than 5 m/s for natural draft and 7 m/s for mechanical draft shall not occur more than 10 times within an hour.

e) When testing natural draft towers, it is recommended that the following climatic conditions are also achieved during the hour preceding the start of any valid test period: the average vertical ambient dry-bulb temperature gradient G shall be within 0 °C/100 m of height and 1 °C decrease/100 m of height. Refer to 7.3.6.

f) If the indicator defined in 7.3.6 c) is used, the validity condition shall be: $-1 < T_{ent} - T_{am} < 0$.

8.2.4.2 Variations from design

The test shall be conducted within the following limitations.

The following variations from design conditions shall not be exceeded:

a) wet-bulb temperature: ±8,5 °C;

b) dry-bulb temperature (if applicable): ±14,0 °C;

c) range: ±20 %;

d) circulating water flow: ±10 %;

e) barometric pressure: ±3,5 kPa;

f) fan driver power: ±10 %.

g) water/process fluid quality: The quality of the water/process fluid, or in the case of closed-circuit cooling towers, the re-circulating spray water, shall be as follows.

  1) Dissolved solids or suspended solids shall not exceed 5,000 mg/l, or where specified in the contract documents, 1,1 times the specified value.

  2) Content of oil, tar, or fatty substances, as determined by a recognized national standard, shall not exceed 10 mg/L for splash fills and 1 mg/L for film fills.

  3) For wet/dry towers, the limits for variation of design conditions during dry operation and for foreign substances in the circulating water shall be by prior mutual agreement between the purchaser and the manufacturer.

Table 2 — Basic test — Frequency of readings and units of measure

Measurement	Readings per hour, min.		Units	Record to nearest unit
	Engineering grade	Survey grade		
Entering wet-bulb temperature[a]	60	12	°C	0,05
Entering dry-bulb temperature	60	12	°C	0,05
Cold water temperature	60	12	°C	0,05
Hot water temperature	60	12	°C	0,05
Water flow rate[b]	1	1	m^3/h	0,5 %
Tower pumping head	1	1	M	0,01
Fan driver power input[c]	1	1	kW	0,5 %
Wind velocity	60	cont.	m/s	0,5
Makeup temperature	60	2	°C	0,05
Makeup flow[d]	2	2	m^3/h	0,5 %
Blowdown temperature	60	2	°C	0,05
Blowdown flow[d]	2	2	m^3/hr	0,5 %
Barometric pressure	60	1	kPa	0,01
Atmospheric gradient[e]	1	1	°C/100 m	0,05
Wind speed at tower exit[e]	1	1	m/s	0,5
Spray water temperature[f]	60	12	°C	0,05
Heat exchanger pressure drop	3	3	kPa	0,01

[a] Or relative humidity and dry bulb.

[b] Three centre point readings per hour for comparison with full traverse reading (when measurement is made by Pitot tube traverse) to confirm variations in flow have not exceeded the allowable limit.

[c] If applicable or required. For wet/dry closed-circuit cooling towers during dry operation, the same requirements as indicated in this table apply.

[d] If makeup and/or blowdown can't be turned off during the test.

[e] For natural draft or fan-assisted natural draft.

[f] For closed circuit.

NOTE Depending on the fluid type, the chemical composition can be analysed. In case of glycol solutions with known glycol properties, it is sufficient to measure the glycol concentration.

Table 2 *(continued)*

Measurement	Readings per hour, min.		Units	Record to nearest unit
	Engineering grade	Survey grade		
Spray pump power	1	1	W	0,5 %
Fluid type	1	1	X	x

a Or relative humidity and dry bulb.

b Three centre point readings per hour for comparison with full traverse reading (when measurement is made by Pitot tube traverse) to confirm variations in flow have not exceeded the allowable limit.

c If applicable or required. For wet/dry closed-circuit cooling towers during dry operation, the same requirements as indicated in this table apply.

d If makeup and/or blowdown can't be turned off during the test.

e For natural draft or fan-assisted natural draft.

f For closed circuit.

NOTE Depending on the fluid type, the chemical composition can be analysed. In case of glycol solutions with known glycol properties, it is sufficient to measure the glycol concentration.

8.2.4.3 Constancy of test conditions

Scatter is the maximum permissible variation of any observation. It represents the greatest permissible difference between the maximum and minimum instrument readings during the period.

When expressed as a percentage, the maximum allowable variation is the specified percentage of the arithmetical mean of the observations. For a valid period, variations shall not exceed the following limits.

a) Circulating water flow rate shall not vary by more than ±1,5 % from the average period value.

b) Heat load shall not vary by more than ±2,5 % from the average period value.

c) Range shall not vary by more than ±2,5 % from the average period value.

d) Further, an individual reading of the entering air temperature (e.g. the average of all the psychrometer readings at one time interval) shall not deviate from the overall average for the duration of the period by more than the following:

   1) wet-bulb temperature: ±1,5 °C;

   2) dry-bulb temperature: ±4,5 °C (if applicable, e.g. testing wet/dry tower in the dry mode);

   3) trends: The temperature of the entering air, as measured at individual psychrometers or determined at dry-bulb sensors and hygrometers, can fluctuate during the period, but the linear least squares trend in the reading average (average for all stations) for the test period shall not exceed the following:

      i. Wet-bulb temperature: 1 °C per hour.

      ii. Dry-bulb temperature: 3 °C per hour (if applicable, e.g. testing wet/dry tower in the dry mode).

      iii. Cooling range: 1 °C per hour, or 10 % of the test range, whichever is less.

      iv. It is important to limit the magnitude of these trends for the following reasons. A sufficiently large, gradual, downward trend in wet-bulb or dry-bulb (wet/dry, opened or closed, natural draft and fan-assisted natural draft) will tend to make the tower result look worse than the tower result would be at steady wet-bulb. Likewise, a sufficiently large, gradual, upward trend will tend to make the tower look better than at a steady wet-bulb temperature. Similarly, a sufficiently large, gradual, downward trend in cooling range will tend to make the tower result look worse than at a steady cooling range. Conversely, a sufficiently large, gradual, upward trend in cooling range will tend to make the tower result look better than at a steady cooling range.

8.2.5 Data recording

Valid test periods can be consecutive, but not overlapping, as long as validity requirements are fulfilled.

When a measurement requires several probes, the data from each probe shall be recorded independently and the value of the parameter equals to the arithmetic average of all the readings. Then, the value of each parameter for the test period is an arithmetic average of the successive readings within the test period (see Clause 9).

8.3 Extended tests

8.3.1 General

Extended tests enable an actual verification of wind effect on tower performance. They are appropriate when the contract requires that the supplier guarantees the average cold water temperature (or approach) as a function of all main parameters, including wind speed.

8.3.2 Duration of the test period

A test period (see definition Clause 3) lasts 10 min.

8.3.3 Required number of valid test periods

A minimum of 300 valid test periods are required for an acceptance test. All valid test periods recorded shall be taken into account in the acceptance test.

8.3.4 Frequency of measurements in an extended test

Measurements shall be taken and recorded at regular intervals over a period (see Table 3). Recordings are required, due to the fact that extended tests take place over several weeks.

8.3.5 Validity conditions for extended tests

A test period shall be valid only if the requirements below are met.

8.3.5.1 Climatic condition requirements during the period

a) No rain, snow, or hail.

b) No fog; the difference between dry-bulb and wet-bulb temperature shall be greater than 0,5 °C.

c) The wet-bulb temperature of the ambient air shall be greater than or equal to 2 °C.

d) In the event of high obstacles (other cooling tower, turbine building) being in the vicinity of the cooling tower, only those test periods for which the wind does not come from the direction of these obstacles are taken into account.

e) The standard deviation, s, of the average wind velocity (V_{avg}) in the period shall be less than a limit value: $s < (0{,}5\ V_{avg} + 0{,}2\ V_{avg})$.

f) The average vertical ambient dry-bulb temperature gradient G shall lie within 0 °C/100 m of height and 1 °C decrease/100 m of height (see 7.3.6); if the indicator defined in 7.3.6 b) is used, the average dry-bulb temperature near the top of the air inlet shall not be higher than the average dry-bulb measured on the same circumferential 1,5 m above grade level.

g) Maintain constant basin level with makeup flow rate.

8.3.5.2 Variations from design

The following variations from design conditions shall not be exceeded in a test period:

a) wet-bulb temperature: ±8,5 °C;

b) dry-bulb temperature: ±14 °C;

c) circulating water flow rate: ±10 %;

d) range: ±20 %;

e) barometric pressure: ±3,5 kPa;

f) water/process fluid quality: The quality of the water/process fluid, or in the case of closed-circuit cooling towers, the re-circulating spray water, shall be as follows.

1) Dissolved solids or suspended solids shall not exceed 5,000 mg/l, or where specified in the contract documents, 1,1 times the specified value.

2) Content of oil, tar, or fatty substances, as determined by a recognized national standard, shall not exceed 10 mg/L for splash fills and 1 mg/L for film fills.

3) For wet/dry towers, the limits for foreign substances in the circulating water shall be by prior mutual agreement between the purchaser and the manufacturer.

Table 3 — Extended test — Minimum frequency of recordings and units of measure

Measurement	Minimum readings/ test period per station	Units	Record to nearest
Entering wet-bulb temperature	10	°C	0,05
Entering dry-bulb temperature	10	°C	0,05
Ambient dry-bulb temperature	10	°C	0,05
Cold water temperature	10	°C	0,05
Hot water temperature	10	°C	0,05
Water flow rate[b]	1	m^3/hr	0,5 %
Tower pumping head	once/test	m	0,01
Wind velocity	60	m/s	0,5
Makeup temperature	10	°C	0,05
Makeup flow[b]	1	m^3/hr	0,5 %
Blowdown temperature	10	°C	0,05
Blowdown flow[b]	1	m^3/hr	0,5 %
Barometric pressure	10	kPa	0,01
Atmospheric gradient[c]	1	°C/100 m	0,05
Wind speed at tower exit[c]	1	m/s	0,5

[a] Relative humidity and dry bulb.

[b] In case of constant water flow rate (flow produced by pumps, without adjusting mechanism on the circuit). This flow rate should be measured only once for the whole acceptance test, preferably at the beginning of the test.

[c] Direct measurement (if practical) or through indicator (see A.6.2).

8.3.5.3 Constancy of test conditions

During the hour preceding the end of the test period:

a) The difference between the maximum and minimum values of the cooling range on the tower shall not exceed 5 % of the average value.

b) The difference between the maximum and minimum values of the temperature of the cold water shall not exceed 1 °C.

c) During the test period, the variation from the maximum to the minimum in the average cold water temperature readings shall not exceed 0,2 °C.

8.3.6 Conducting an extended performance test

A test period shall last 10 min. Valid test periods can be consecutive, but not overlapping, as long as validity requirements are fulfilled.

When a measurement requires several probes, the value of the parameter equals the arithmetic average of all the readings. Then, the value of each parameter for the test period is an arithmetic average of the successive readings within the test period. See Clause 9.

9 Evaluation of tests

9.1 General

The thermal performance of a cooling tower is its ability to produce guaranteed cold water temperatures under specified operating conditions and inlet-air conditions. This can be verified 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 using characteristic curve analysis. When extended tests are carried out, the guaranteed temperature is calculated as a function of the different measured parameters for each test period.

9.2 Computation of test period values from test reading values

9.2.1 Determination of measured test values

The individual, consecutive test readings for each parameter shall be arithmetically averaged over the duration of the test period to obtain the measured test value for that parameter. Test readings shall be corrected for instrument calibration.

9.2.2 Thermal lag

If the test duration extending from τ_1 to τ_2 includes an extension (S) for thermal lag, in accordance with 4.4, the following readings shall be averaged over the first time period extending from τ_1 to (τ_2 – S):

a) hot water (process fluid) temperature (T_{HW});

b) dry-bulb temperature (T_{DB});

c) wet-bulb temperature (T_{WB}) or relative humidity (RH) and dry-bulb temperature (T_{DB});

d) flow rate of circulating water (process fluid) (Q_W);

e) flow rate and temperature of any water other than the circulating water entering the tower basin [e.g. makeup (Q_{MU} and T_{MU})];

f) fan driver power (W_{FM}).

The remaining measurements shall be averaged over the latter period extending from (τ_1 + S) to τ_2:

a) temperature of cold water (process fluid) leaving the tower (T_{CW});

b) flow rate and temperature of any flow stream leaving the tower basin [e.g. blowdown (Q_{BD} and T_{BD})].

9.2.3 Hot water (process fluid) temperature

The test hot water (process fluid) temperature (T_{HW}) used to evaluate the tower performance shall be the measured temperature readings of the entering flow stream, averaged over the duration of the test period. In the case of multiple streams, the mass flow weighted average temperature shall be used.

9.2.4 Cold water (process fluid) temperature

The test cold water (process fluid) temperature (T_{CW}) used to evaluate the tower performance shall be the measured temperature readings of the leaving flow stream, averaged over the duration of the test period. In the case of multiple streams, the mass flow weighted average temperature shall be used. Final results shall be corrected as necessary for the effects of the makeup, blowdown, and any other heat added or removed between the tower and the point of measurement.

a) If the test cold water temperature was measured at a point between the outlet connection on the tower and the suction of the re-circulating pump, no adjustment to the measured temperature for pump energy is necessary.

b) If the test cold water temperature was measured on the discharge side of the re-circulating pump using a flowing bleed stream open to the atmosphere, the measured temperature shall be adjusted for throttling process using Formula (4).

$$T_{CW,\,adj} = \left(T_{CW,t}\right) - 0{,}002\,39 \left(\frac{P_2}{\eta_P}\right) \tag{4}$$

c) If the test cold water temperature was measured on the discharge side of the re-circulating pump using a closed well, the measured temperature shall be adjusted for the heat added due to the inefficiency of the pump using Formula (5).

$$T_{CW,\,adj} = \left(T_{CW,t}\right) - 0{,}002\,39 \left(P_2 - P_1\right) \left(\frac{1-\eta_P}{\eta_P}\right) \tag{5}$$

9.2.5 Makeup and blowdown adjustments

For open-circuit cooling towers, if the makeup is injected and/or the blowdown is removed upstream the cold water measurement section, then the test cold water temperature shall be adjusted for the effect of makeup and/or blowdown, using Formula (6).

$$T_{CW} = \left[\frac{(Q_W)(T_{CW,adj}) + (Q_{BD})(T_{BD}) - (Q_{MU})(T_{MU})}{(Q_W) + (Q_{BD}) - (Q_{MU})} \right] \quad (6)$$

For closed-circuit cooling towers, the evaluation procedure calls for the flow rate of the process fluid to be adjusted to account for the effect of makeup and/or blowdown, using Formula (7).

$$Q_{PF,T,adj,1} = (Q_{PF,t}) - \left[\frac{(T_{RW} - T_{MU})(\rho_W)(c_{P,W})}{(T_{HPF} - T_{CPF})(\rho_{PF})(c_{P,PF})} \right] (Q_{MU}) \quad (7)$$

9.2.6 Entering air temperatures

The test values for the entering air wet-bulb temperature (T_{WB}) and, when required, the dry-bulb temperature (T_{DB}) shall be the arithmetic average of their respective readings taken over the duration of test to comply with the requirements of 8.2.4.3.

$$\left| T_{WB(n)} - \bar{T}_{WB} \right| \leq 1{,}5° \quad (8)$$

and

$$\left| T_{DB(n)} - \bar{T}_{DB} \right| \leq 4{,}5° \quad (9)$$

and the slope $\Delta T/\Delta t$ of a least square fit to the measured temperatures over the duration of the test period shall not exceed:

a) ±1 °C per hour for wet-bulb temperatures;

b) ±3 °C per hour for dry-bulb temperatures.

NOTE These conditions are not applicable for extended tests (see 9.3).

9.2.7 Ambient air temperature

The test values for the ambient air wet-bulb and wet-bulb temperatures shall be the arithmetic average of the readings taken over the test period.

9.2.8 Fan driver output power

If applicable, the fan driver output power shall be computed using Formula (10):

$$W_{FM,t} = (kW_{FM,t})(\eta_{FM}) \quad (10)$$

9.2.9 Validity of test

$$\left|\frac{q_{t,(n)}}{q_t} - 1\right| \leq 0{,}025 \tag{11}$$

$$\left|\frac{R_{t,\,(n)}}{\overline{R}_t} - 1\right| \leq 0{,}025 \tag{12}$$

$$\left|\frac{W_{FM,t}}{W_{FM,d}} - 1\right| \leq 0{,}1\, W_{FM,d} \tag{13}$$

9.2.10 Wind velocity

9.2.10.1 The recorded values for wind speed and direction shall be reviewed for conformance to 8.2.4 or 8.3.4, as applicable.

9.2.10.2 The vertical dry-bulb temperature gradient, either by the actual or the indicator, shall be calculated as 100 times the higher elevation temperature (°C) minus the lower elevation temperature divided by the higher elevation (m) measured minus the lower elevation, expressed in metres. The result is expressed as °C/100 m.

9.2.11 Tower pumping head

When pressure readings are taken at multiple inlets, the measured test values shall be corrected to the centreline of the inlet connection, if necessary, and combined by averaging the readings arithmetically to a single value.

$$\overline{P_{ST}} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} P_{ST(n)} \tag{14}$$

Then determine the test value of the velocity at the tower inlet connection(s) based on the measured test flow rate and the total area of the inlet connections.

$$v_{L,t} = \frac{1\,000 \times Q_{W,t}}{A_C} \tag{15}$$

Next, determine the velocity pressure of the re-circulating water at the inlet to the tower

$$P_{V,t} = \left(\frac{\rho_W \times v_{L,t}^2}{2\, g_C}\right) \tag{16}$$

and determine the total measured tower pumping head at test flow as

$$H_{P,t} = P_{V,t} + P_{ST,t} + \gamma Z_i \tag{17}$$

The pumping head corrected to design flow is

$$H_{P,d} = \left[\left(P_{V,1} + P_{ST,1}\right)\left(\frac{Q_{W,d}}{Q_{W,t}}\right)^2\right] + \gamma Z_i \tag{18}$$

9.2.12 Closed-circuit tower heat exchanger pressure drop

The static pressure at the inlet and outlet nozzles of the heat exchangers shall be measured in accordance with the provisions of A.4.

$$\Delta P_{HE,adj} = \Delta P_{HE,t}\left(\frac{Q_{PF,d}}{Q_{PF,t}}\right)^{1,8} \tag{19}$$

9.3 Basic thermal performance test evaluation (for all tower types)

The performance of a cooling tower can be evaluated from the measured test data using either the performance curve method (preferred) or the characteristic curve method, as agreed by the parties to the test, prior to the test.

9.3.1 Methodologies, a discussion

The characteristic curve analysis typically includes some simplifying assumptions which increase the inaccuracy of the result as the deviations between the measured test conditions and the design conditions increase. Additional inaccuracies are introduced when attempting to use this essentially counterflow methodology to evaluate crossflow cooling towers, although these can be partially mitigated through the use of adjustment factors. Therefore, the characteristic analysis is presented in this test code for open-circuit, mechanical draft cooling towers primarily as a means to evaluate the performance of an existing cooling tower for which the manufacturer's performance data are not available. It should not be used for acceptance or certification testing.

9.3.2 Psychrometrics

A single set of official psychrometric formulae has been adopted and is included in the code both in tabular form for ease of use and with source code for computer application. The purpose of including these data is not to endorse any one set of psychrometric formulae, but to adopt an easily available and computer friendly basis so that all persons calculating test results from this code will obtain the same answer from the same input data. This psychrometric information is included in Annex D.

9.3.3 Open-circuit, mechanical draft towers — Performance curve method

The formats for the performance curves and data submitted by the manufacturer are described in 5.3.2, 5.3.5, and 5.3.9.

9.3.3.1 Evaluation by flow rate capability

The cooling tower performance can be evaluated in terms of flow capability where the measured performance is expressed as a percentage of the flow rate predicted by the manufacturer's data for the measured test conditions. An example of this methodology is given in Annex F.

9.3.3.1.1 Determination of the predicted flow rate

The predicted flow rate for the measured test conditions shall be determined by crossplotting the manufacturer's performance curves. A suitable procedure consists of first entering the manufacturer's curves at the measured test wet-bulb temperature and determining the associated cold water temperature for each combination of range and flow rate. Using these data, prepare a crossplot relating cooling range to cold water temperature with the three water circulation rates as parameters. Enter this crossplot at the measured test range and determine the cold water temperature associated with each flow rate. Using these data, develop a second crossplot relating cold water temperature to water circulation rate. Enter this final curve at the corrected test cold water temperature and from the intersection with the curve, determine the predicted flow rate for the measured test conditions.

9.3.3.1.2 Determination of psychrometric properties of air at fans

Forced draft and induced draft tower configurations require different procedures for determining the properties of the air entering the fans.

9.3.3.1.2.1 Forced draft units

For forced draft towers, the fan inlet-air conditions are the same as the tower inlet-air conditions. Therefore the test density ($\rho_{A1,t}$) and the test specific volume ($v_{A1,t}$) are computed directly from the measured test wet-bulb temperature, dry-bulb temperature, and barometric pressure. The design conditions at the tower's air inlet shall be supplied by the manufacturer.

9.3.3.1.2.2 Induced draft units

For an induced draft tower, the condition of air at the inlet to the fan(s) is the tower discharge condition and both the design and test discharge air properties shall be determined by a heat balance calculation.

The heat balance formula states that the heat gain of the air as it moves through the cooling tower equals the heat loss of the water such that:

$$L \times \left(c_{P,W}\right) \times \left(T_{HW} - T_{OW}\right) = G \times \left(h_{A,2} - h_{A,1}\right) \tag{20}$$

Rearranging terms to isolate the value for exit air enthalpy, the heat balance formula becomes:

$$h_{A,2} = \left(\frac{L}{G}\right) \times \left(c_{P,W}\right) \times \left(T_{HW} - T_{OW}\right) + h_{A,1} \tag{21}$$

which can be solved directly for the enthalpy of the leaving air at design conditions, by submitting the data supplied by the manufacturer. The air leaving the tower and entering the fan(s) is assumed to be saturated at this enthalpy, and the remaining properties can be found using the thermodynamic properties for moist air from Annex D.

The test discharge air properties are calculated by substituting all known values into Formula (21) and reducing terms to express the test $(L/G)_t$ as a function of discharge air density and specific volume. This expression of $(L/G)_t$ is then substituted into the heat balance Formula (20) along with the known values for specific heat, temperatures, and enthalpy of the entering air and combining terms to express the enthalpy of the leaving air as a function of the density ($\rho_{A2,t}$) and specific volume ($v_{A2,t}$) of the leaving air:

$$h_{A2,t} = \left(K_1\right) \times \left(v_{A2,t}\right) + K_2 \tag{22}$$

where K_1 and K_2 are constants derived by combining the known numerical values.

At this point, a leaving air temperature is assumed and the values of density ($\rho_{A2,t}$) and specific volume ($v_{A2,t}$) for saturated air at that temperature are used to solve the formula for enthalpy. The calculated value for enthalpy is then compared to the actual enthalpy of saturated air at the assumed temperature and the process repeated with a new assumed air temperature until the calculated value closely matches the actual value. Then, the psychrometric properties of saturated air at that temperature are used for the density and specific volume of the air entering the fan(s). A detailed example is given in Annex F.

9.3.3.1.3 Determination of the adjusted test flow rate

The adjusted test flow rate is determined from Formula (23) below, using the procedure described above in 9.3.3.1.2 to determine the density of the air entering the fan(s).

$$Q_{W,t,adj} = Q_{W,t}\left(\frac{W_{FM,d}}{W_{FM,t}}\right)^{1/3}\left(\frac{\rho_{A,t}}{\rho_{A,d}}\right)^{1/3} \tag{23}$$

9.3.3.1.4 Determination of the tower capability

The capability, C_{CAP}, expressed in percent of design circulating flow, is then computed using Formula (24).

$$C_{CAP} = 100\left(\frac{Q_{W,t,adj}}{Q_{W,pred}}\right) \tag{24}$$

9.3.3.1.5 Multiple valid test periods

Where there are multiple valid test period results to be averaged, Formula (25) shall apply.

$$\bar{C}_{\mathrm{CAP}} = \left(\frac{1}{\mathrm{n}}\right)\sum_{\mathrm{i}=1}^{\mathrm{n}} C_{\mathrm{CAP(n)}} \tag{25}$$

9.3.3.1.6 Compliance

The tower shall have achieved the guaranteed condition if

$$C_{\mathrm{CAP}} + I_{\mathrm{CAP}} \geq 100\,\% \tag{26}$$

where $I_{\mathrm{CAP}} = 0$, unless specified differently in the contract.

9.3.3.2 Evaluation by approach deviation

Alternatively, the cooling tower performance can be evaluated in terms of approach deviation, the difference between the corrected cold water temperature and the cold water temperature predicted by the manufacturer's data. This comparison can be done at the measured test conditions or at the design conditions. However, when a penalty is contractually specified as a function of degrees deviation, the evaluation shall be made at design conditions per 9.3.3.2.2 below.

9.3.3.2.1 Predicted cold water temperature at measured test conditions

Using the final crossplot developed in 9.3.3.1.1 relating cold water temperature to water circulation rate, enter the plot at the adjusted test flow, as determined in 9.3.3.1.3, and project a line vertically to intersect the curve. Read the value for the predicted cold flow temperature ($T_{\mathrm{CW,\,pred}}$) at the point of intersection.

9.3.3.2.1.1 Comparison with measured cold water temperature

Compare the corrected test value for cold water temperature ($T_{\mathrm{CW,\,t}}$) to the predicted cold water temperature ($T_{\mathrm{CW,\,pred}}$) determined above such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{\mathrm{App}} = \left(T_{\mathrm{OW,\,corr}}\right) - \left(T_{\mathrm{ow,\,pred}}\right) \tag{27}$$

9.3.3.2.2 Approach deviation at design conditions

To determine the approach deviation at design conditions, first determine the tower capability as described in 9.3.3.1. Then, using the manufacturer's performance curves, develop a plot of leaving water temperature as a function of tower capability for the design range and wet-bulb temperature. A suitable procedure consists of first entering the manufacturer's curves at the design wet-bulb temperature and determining the cold water temperature at design range for each flow rate. Using these data, prepare a crossplot relating cold water temperature to the reciprocal of the percentage water circulation rate, expressed as a decimal (e.g. 90 % flow equates to 111,11 % capability, 110 % flow equates to 90,91 % capability). Enter this crossplot at the tower capability as determined in 9.3.3.1.4 and project a line vertically to intersect the curve. At the intersection, read the predicted cold water temperature ($T_{\mathrm{CW,\,pred}}$) for the tower at the test capability.

9.3.3.2.2.1 Comparison with design cold water temperature

Compare the predicted cold water temperature ($T_{CW, pred}$) determined above to the design value for cold water temperature ($T_{CW, d}$) such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = \left(T_{CW, pred}\right) - \left(T_{CW, d}\right) \tag{28}$$

9.3.3.2.2.2 Multiple valid test periods

When the data from multiple valid test periods are being used to evaluate the tower performance, the approach deviations for the individual tests should be averaged using Formula (29).

$$\overline{\Delta T}_{App} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \Delta T_{App(n)} \tag{29}$$

It is recommended, however, if there is any significant deviation between the operating conditions for each valid test period (such as might be the case if the valid tests were performed on different days), that the individual approach deviations should be evaluated at the design, not the measured test conditions.

9.3.3.2.2.3 Compliance

The guaranteed condition has been achieved if

$$\Delta T_{App} - I_{TEMP} \leq 0 \tag{30}$$

where $I_{TEMP} = 0$, unless specified differently in the contact.

9.3.4 Open-circuit, mechanical draft towers — Characteristic curve method

The format of the required curves and tabular data is described in 5.3.6, 5.3.7, and 5.3.9. An example of this procedure is presented in Annex G.

9.3.4.1 Determination of density and specific volume of air at the fans

Using the procedure described in 9.3.3.1.2, determine the psychrometric properties of air entering the fans.

9.3.4.2 Determination of the test *L*/*G*

The test value of *L*/*G* is computed from Formula (31) using the measured test values of re-circulating water flow rate, fan driver power, and the psychrometric properties of air at the fan inlet as determined in 9.3.4.1.

$$\left(\frac{L}{G}\right)_t = \left(\frac{L}{G}\right)_d \left(\frac{Q_{W,t}}{Q_{W,d}}\right)\left(\frac{W_{FM,d}}{W_{FM,t}}\right)^{1/3}\left(\frac{\rho_{A,t}}{\rho_{A,d}}\right)^{1/3}\left(\frac{v_{A,t}}{v_{A,d}}\right) \tag{31}$$

9.3.4.3 Determination of the test value of *KaV*/*L*

Using average test values of hot water, cold water, and wet-bulb temperatures in conjunction with the test value of *L*/*G* determined above, calculate the test value of *KaV*/*L* from Formula (32).

$$KaV/L = \left(c_{\mathrm{P,W}}\right) \int_{T_{\mathrm{CW}}}^{T_{\mathrm{HW}}} \frac{dT}{h_{\mathrm{M}} - h_{\mathrm{A}}} \tag{32}$$

A four-point Tchebycheff method can be used to numerically evaluate this integral, which takes the form of Formula (33).

$$KaV/L = \left(c_{\mathrm{P,W}}\right)\left(\frac{T_{\mathrm{HW}} - T_{\mathrm{CW}}}{4}\right)\left[\left(\frac{1}{\Delta h1}\right)+\left(\frac{1}{\Delta h2}\right)+\left(\frac{1}{\Delta h3}\right)+\left(\frac{1}{\Delta h4}\right)\right] \tag{33}$$

where

Δh_1 is the value of $(h_{\mathrm{M}} - h_{\mathrm{A}})$ at $T_{\mathrm{CW}} + 0{,}1(L/G)\ (T_{\mathrm{HW}} - T_{\mathrm{CW}})$;

Δh_2 is the value of $(h_{\mathrm{M}} - h_{\mathrm{A}})$ at $T_{\mathrm{CW}} + 0{,}4(L/G)\ (T_{\mathrm{HW}} - T_{\mathrm{CW}})$;

Δh_3 is the value of $(h_{\mathrm{M}} - h_{\mathrm{A}})$ at $T_{\mathrm{HW}} - 0{,}4(L/G)\ (T_{\mathrm{HW}} - T_{\mathrm{CW}})$;

Δh_4 is the value of $(h_{\mathrm{M}} - h_{\mathrm{A}})$ at $T_{\mathrm{HW}} - 0{,}1(L/G)\ (T_{\mathrm{HW}} - T_{\mathrm{CW}})$.

Values for the enthalpies, h_{M} and h_{HA}, can be taken from the tables in Annex D or calculated for the specific barometric pressure or site elevation using the program provided.

9.3.4.4 Determination of the tower capability

The point representing values of *L*/*G* and *KaV*/*L* calculated from the test data shall be plotted on the manufacturer's tower characteristic graph. Draw a curve through this test point of the same form and parallel to the original supplied by the manufacturer. Alternatively, points on this curve can be calculated by using Formula (34). The intersection of this test characteristic with the design approach curve determines the value of the intersect $(L/G)_{\mathrm{i}}$ at which the tower would produce design cold water temperature when operating at design conditions. The tower capability, in percent of design water flow, is the ratio of this "intercept" $(L/G)_{\mathrm{i}}$ to the design $(L/G)_{\mathrm{d}}$, multiplied by 100.

$$C_{\mathrm{CAP}} = 100\left[\frac{(L/G)_{\mathrm{i}}}{(L/G)_{\mathrm{d}}}\right] \tag{34}$$

If multiple characteristic curves have been submitted, this design *L*/*G* shall be adjusted to the applicable characteristic curve for the test conditions.

9.3.4.5 Multiple valid test periods

Where there are multiple valid test period results to be averaged, Formula (35) shall apply.

$$\bar{C}_{\mathrm{CAP}} = \left(\frac{1}{\mathrm{n}}\right)\sum_{\mathrm{i}=1}^{\mathrm{n}} C_{\mathrm{CAP(n)}} \tag{35}$$

9.3.4.6 Compliance

The tower shall have achieved the guaranteed condition if

$$C_{CAP} + I_{CAP} \geq 100\,\% \qquad (36)$$

where $I_{CAP} = 0$, unless specified differently in the contract.

9.3.5 Open-circuit, natural draft towers — Performance curve method

The performance of natural draft towers shall be evaluated from test data using the performance curve method. The format of the required curves and data is described in 5.3.4, 5.3.5, and 5.3.9. An example of this methodology is given in Annex H.

9.3.5.1 Evaluation of flow rate capability

The cooling tower performance can be evaluated in terms of flow rate capability which expresses the measured performance as a percentage of the flow rate predicted by the manufacturer's data for the measured test conditions.

9.3.5.1.1 Determination of adjusted test flow rate

The measured water flow rate is used directly in the evaluation. No adjustments are necessary.

9.3.5.1.2 Determination of the predicted flow rate

The manufacturer's performance curves shall be cross-plotted to determine the predicted flow rate for the measured test conditions. Using the test wet-bulb temperature, relative humidity, and cooling range, a crossplot is prepared which relates the leaving water temperature to the flow rate of the circulating water. Enter this crossplot at the corrected test cold water temperature ($T_{CW,\,corr}$) and from the intersection with the curve, determine the predicted flow rate for the measured test conditions.

9.3.5.1.3 Determination of the tower capability

The capability, C_{CAP}, expressed in percent of design circulating flow, is then computed using Formula (37).

$$C_{CAP} = 100\left[\frac{Q_{W,\,t}}{Q_{W,\,pred}}\right] \qquad (37)$$

9.3.5.1.4 Multiple valid test periods

Where there are multiple valid test period results to be evaluated, the average capability of the valid tests shall be calculated using Formula (38).

$$\bar{C}_{CAP} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} C_{CAP(n)} \qquad (38)$$

9.3.5.1.5 Compliance

The tower shall have achieved the guaranteed condition if

$$C_{CAP} + I_{CAP} \geq 100\,\% \tag{39}$$

where $I_{CAP} = 0$, unless specified differently in the contract.

9.3.5.2 Evaluation by approach deviation

Alternatively, the cooling tower performance can be evaluated in terms of approach deviation, the difference between the corrected cold water temperature and the cold water temperature predicted by the manufacturer's data. This comparison can be done at the measured test conditions or at the design conditions. However, when a penalty is contractually specified as a function of degrees deviation, the evaluation shall be made at design conditions per 9.3.5.2.2 below.

9.3.5.2.1 Predicted leaving water temperature at measured test conditions

Using the final crossplot developed in 9.3.5.1.2 relating cold water temperature to water circulation rate, enter the plot at the adjusted test flow, as determined in 9.3.5.1.1, and project a line vertically to intersect the curve. Read the value for the predicted cold water temperature ($T_{CW,\,pred}$) at the point of intersection.

9.3.5.2.1.1 Comparison with measured cold water temperature

Compare the corrected test value for cold water temperature ($T_{CW,\,corr}$) to the predicted cold water temperature ($T_{CW,\,pred}$) determined above, such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CW,\,corr}) - (T_{CW,\,pred}) \tag{40}$$

9.3.5.2.2 Approach deviation at design conditions

To determine the approach deviation at design conditions, first determine the tower capability as described in 9.3.5.1.3. Then, using the manufacturer's performance curves, develop a plot of leaving water temperature as a function of tower capability for design range, relative humidity, and wet-bulb temperature. A suitable procedure consists of first entering the manufacturer's curves at the design wet-bulb temperature and determining the cold water temperate at design range and relative humidity for each flow rate. Using these data, prepare a crossplot relating cold water temperature to the decimal reciprocal of the percentage water circulation rate (e.g. 90 % flow equates to 111,11 % capability, 110 % flow equates to 90,91 % capability). Enter this crossplot at the tower capability as determined in 9.3.5.1.3 and project a line vertically to intersect the curve. At the intersection, read the predicted cold water temperature ($T_{CW,\,pred}$) for the tower at the test capability.

9.3.5.2.2.1 Comparison with design cold water temperature

Compare the predicted cold water temperature ($T_{CW,\,pred}$) determined above to the design value for cold water temperature ($T_{CW,\,d}$) such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CW,\,pred}) - (T_{CW,\,d}) \tag{41}$$

9.3.5.2.3 Multiple valid test periods

When the data from multiple valid test periods are being used to evaluate the tower performance, the approach deviations for the individual tests should be averaged using Formula (42).

$$\overline{\Delta T}_{App} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \Delta T_{App(n)} \quad (42)$$

NOTE If there is any significant deviation between the operating conditions for each valid test period (such as might be the case if the valid tests were performed on different days), the individual approach deviations should be evaluated at the design, not the measured test conditions.

9.3.5.2.4 Compliance

The guaranteed condition has been achieved if

$$\Delta T_{App} - I_{TEMP} \leq 0 \quad (43)$$

where $I_{TEMP} = 0$, unless specified differently in the contract.

9.3.6 Wet/dry towers (open type) — Performance curve method

The performance of a wet/dry, open-type cooling towers shall be evaluated by the performance curve method, with the results expressed in terms of water cooling capability or approach deviation. The terms “wet” and “dry” refer to the separate evaporative and non-evaporative heat exchanger elements incorporated into this type of cooling tower. Format of the required curves and tubular data are in 5.3.3, 5.3.5, and 5.3.9. An example of this evaluation methodology is given in Annex J.

9.3.6.1 Evaluation by flow rate capability

The cooling tower performance can be evaluated in terms of flow capability which expresses the measured performance as a percentage of the flow rate predicted by the manufacturer’s data for the measured test conditions.

9.3.6.1.1 Determination of the predicted flow rate

The manufacturer’s performance curves shall be cross-plotted to determine the predicted flow rate for the measured test conditions. Using the test wet-bulb temperature, relative humidity, and cooling range, a crossplot is prepared which relates the outlet water temperature to the flow rate of the circulating water. The procedure is the same as for open towers except an intermediate step is required which crossplots relative humidity at constant wet-bulb temperature and range. From this graph, the predicted flow rate of the circulating water is determined at the test outlet water temperature.

9.3.6.1.2 Determination of the adjusted test flow rate

For wet/dry tower configurations where a single fan moves air through both the wet and dry sections, the adjusted test flow rate is determined from Formula (23) using the procedure described in 9.3.3.1.2 to determine the density of the air entering the fan(s).

$$Q_{W,t,adj} = Q_{W,t}\left(\frac{W_{FM,d}}{W_{FM,t}}\right)^{1/3}\left(\frac{\rho_{A,t}}{\rho_{A,d}}\right)^{1/3} \tag{44}$$

For the special case where separate fans are employed to move air through the wet and dry portions of a single tower, or through separate wet and dry towers, the following Formula (45) applies.

$$Q_{W,t,adj} = Q_{W,t}\left[\left(\frac{q_{WET}}{q_{TOT}}\right)\left(\frac{W_{FM,WET,d}}{W_{FM,WET,t}}\right)^{1/3}\left(\frac{\rho_{A,WET,t}}{\rho_{A,WET,d}}\right)^{1/3} + \left(\frac{q_{DRY}}{q_{TOT}}\right)\left(\frac{W_{FM,DRY,d}}{W_{FM,DRY,t}}\right)^{y}\left(\frac{\rho_{A,DRY,t}}{\rho_{A,DRY,d}}\right)^{1/3}\right] \tag{45}$$

9.3.6.1.3 Determination of the tower capability

The capability, C_{CAP}, expressed in percent of design circulating flow, is then computed using Formula (24).

$$C_{CAP} = 100\left(\frac{Q_{W,t,adj}}{Q_{w,pred}}\right)$$

9.3.6.1.4 Multiple valid test periods

Where there are multiple valid test period results to be averaged, the Formula (46) shall apply:

$$\bar{C}_{CAP} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} C_{CAP(n)} \tag{46}$$

9.3.6.1.5 Compliance

The tower shall have achieved the guaranteed condition if

$$C_{CAP} + I_{CAP} \geq 100\ \% \tag{47}$$

where $I_{CAP} = 0$, unless specified differently in the contract.

9.3.6.2 Evaluation by approach deviation

Alternatively, the cooling tower performance can be evaluated in terms of approach deviation, the difference between the corrected cold water temperature and the cold water temperature predicted by the manufacturer's data. This comparison can be done at the measured test conditions or at design conditions. However, when a penalty is contractually specified as a function of degrees deviation, the evaluation shall be made at design conditions per 9.3.6.2.2 below.

9.3.6.2.1 Predicted cold water temperature at measured test conditions

Using the final crossplot developed in 9.3.6.1.1 relating cold water temperature to water circulation rate, enter the plot at the adjusted test flow, as determined in 9.3.6.1.2, and project a line vertically to intersect the curve. Read the value for the predicted cold water temperature ($T_{CW, pred}$) at the point of intersection.

9.3.6.2.1.1 Comparison with measured cold water temperature

Compare the corrected test value for cold water temperature ($T_{CW, corr}$) to the predicted cold water temperature ($T_{CW, pred}$) determined above such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CW, corr}) - (T_{CW, pred}) \tag{48}$$

9.3.6.2.2 Approach deviation at design conditions

To determine the approach deviation at design conditions, first determine the tower capability as described in 9.3.6.1. Then, using the manufacturer's performance curves, develop a plot of leaving water temperature as a function of tower capability for design range and wet-bulb temperature. A suitable procedure consists of first entering the manufacturer's curves at the design wet-bulb temperature and determining the cold water temperature at design range for each flow rate. Using these data, prepare a crossplot relating cold water temperature to the decimal reciprocal of the percentage water circulation rate (e.g. 90 % flow equates to 111,11 % capability, 110 % flow equates to 90,91 % capability). Enter this crossplot at the tower capability as determined in 9.3.6.1.3 and project a line vertically to intersect the curve. At the intersection, read the predicted cold water temperature ($T_{CW ,pred}$) for the tower at the test capability.

9.3.6.2.2.1 Comparison with design cold water temperature

Compare the predicted cold water temperature ($T_{CW, pred}$) determined above to the design value for cold water temperature ($T_{CW, d}$) such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CW, pred}) - (T_{CW, d}) \tag{49}$$

9.3.6.2.3 Multiple valid test periods

Where there are multiple valid test period results to be averaged, Formula (50) shall apply.

$$\Delta \bar{T}_{App} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \Delta T_{App(n)} \tag{50}$$

9.3.6.2.4 Compliance

The guaranteed condition has been achieved if

$$\Delta T_{App} - I_{TEMP} \le 0 \tag{51}$$

where $I_{TEMP} = 0$, unless specified differently in the contract.

9.3.7 Closed-circuit, mechanical draft towers – Performance curve method

The performance of closed-circuit cooling towers shall be evaluated from test data using the performance curve method. Format of the required curves and tabular data are set forth in 5.3.2, 5.3.5, and 5.3.9. An example of this evaluation methodology is given in Annex K.

9.3.7.1 Evaluation by flow rate capability

The cooling tower performance can be evaluated in terms of process fluid flow capability where the measured performance is expressed as a percentage of the flow rate predicted by the manufacturer's data for the measured test conditions.

9.3.7.1.1 Determination of the adjusted test flow rate

The adjusted test flow rate is determined from a modified Formula (23), substituting the process fluid flow rate for the re-circulating flow of the open tower and an exponent (Z) supplied by the manufacturer, as shown below. The procedure described in 9.3.7.1.2 is used to determine the density of the air entering the fan(s).

$$Q_{\mathrm{PF,t,adj}} = Q_{\mathrm{PF,t}} \left(\frac{W_{\mathrm{FM,d}}}{W_{\mathrm{FM,t}}}\right)^{Z} \left(\frac{\rho_{\mathrm{A,t}}}{\rho_{\mathrm{A,d}}}\right)^{Z} \quad (52)$$

9.3.7.1.2 Determination of density of air entering fans

The density of the air entering the fans is estimated as follows.

a) Using the measured test values of entering air dry-bulb temperature ($T_{\mathrm{DB,\,t}}$) and entering wet-bulb temperature ($T_{\mathrm{WC,\,t}}$), determine the psychrometric properties of the entering air at the test site barometric pressure from the data in Annex D. For forced draft units, this density can be used directly for ($\rho_{\mathrm{A,\,t}}$) in Formula (37). For induced draft units, continue on with 9.3.7.1.2 b) through 9.3.7.1.2 d).

b) Using the measured test conditions in conjunction with Formula (37), estimate the enthalpy increase of the air flowing through the tower ($\Delta h_{\mathrm{A,\,t}}$) and solve to express this enthalpy change in terms of the specific volume ($v_{\mathrm{A2,\,t}}$) which, after substituting all known terms and simplifying, becomes

$$\Delta h_{\mathrm{A,t}} = (K_1)\,(v_{\mathrm{A2,t}}) \quad (53)$$

c) Determine the enthalpy of the leaving the tower ($h_{\mathrm{A2,\,t}}$) as

$$h_{\mathrm{A2,t}} = h_{\mathrm{A1,t}} + \Delta h_{\mathrm{A,t}} \quad (54)$$

d) At this point, a leaving air temperature is assumed and the associated value for specific volume of saturated air at that temperature ($v_{\mathrm{A2,\,t}}$) is substituted into the expression for ($\Delta h_{\mathrm{A,\,t}}$) and the formula solved for $h_{\mathrm{A2,\,t}}$. This calculated value for enthalpy is then compared to the actual enthalpy for saturated air at the assumed temperature and the process repeated with a new assumed air temperature until the calculated value closely matches the actual value. Then, the density of saturated air at that temperature is used for the density ($\rho_{\mathrm{A,\,t}}$) in Formula (36).

9.3.7.1.3 Determination of the predicted flow rate

The manufacturer's performance curves shall be cross-plotted at test conditions to determine predicted process fluid flow rate at the measured test conditions. A suitable procedure consists of first preparing a crossplot, based on the test wet-bulb temperature, relating cooling range to cold process fluid temperature with the three process fluid flow rates as parameters. From this set of curves, prepare a second crossplot, based on test cooling range, consisting of a single curve relating cold process fluid temperature to process fluid circulation rate. Enter this final curve at the measured test cold process fluid temperature and from the intersection with the curve, determine the predicted process fluid flow rate for the measured test conditions.

9.3.7.1.4 Determination of the tower capability

The capability, C_{CAP}, expressed in percent of design process fluid rate, is then computed using a modified form of Formula (24), which substitutes the process fluid flow rates in lieu of the circulating water of the open tower.

$$C_{CAP} = 100\left(\frac{Q_{PF,t,adj}}{Q_{PF,pred}}\right) \quad (55)$$

9.3.7.1.5 Multiple valid test periods

Where there are multiple valid test period results to be averaged, Formula (56) shall apply.

$$\bar{C}_{CAP} = \left(\frac{1}{n}\right)\sum_{i=1}^{n} C_{CAP(n)} \quad (56)$$

9.3.7.1.6 Compliance

The tower shall have achieved the guaranteed condition if

$$C_{CAP} + I_{CAP} \geq 100\ \% \quad (57)$$

where $I_{CAP} = 0$, unless specified differently in the contract.

9.3.7.2 Evaluation by approach deviation

Alternatively, the closed-circuit cooling tower performance can be evaluated in terms of approach deviation, the difference between the measured cold process fluid temperature and the cold process fluid temperature predicted by the manufacturer's data. This comparison can be made at the measured test conditions or at design conditions. However, when a penalty is contractually specified as a function of degrees deviation, the evaluation shall be made at design conditions per 9.3.7.2.2 below.

9.3.7.2.1 Predicted cold process fluid temperature at measured test conditions

Using the final crossplot developed in 9.3.7.1.2 relating cold process fluid temperature to process fluid circulation rate, enter the plot at the adjusted test flow, as determined in 9.3.7.1.1, and project a line to intersect the curve. Read the value for cold process fluid temperature corresponding to the point of intersection.

9.3.7.2.1.1 Comparison with measured cold process fluid temperature

Compare the measured test value for cold process fluid temperature ($T_{CPF,\,t}$) to the predicted cold process fluid temperature ($T_{CPF,\,pred}$) determined above such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CPF,\,t}) - (T_{CPF,\,pred}) \quad (58)$$

9.3.7.2.2 Approach deviation at design conditions

To determine the approach deviation at design conditions, first determine the tower capability as described in 9.3.7.1. Then, using the manufacturer's performance curves, develop a plot of leaving process fluid temperature as a function of tower capability for the design range and wet-bulb temperature. A suitable procedure consists of first entering the manufacturer's curves at the design wet-bulb temperature and determining the cold process fluid temperature at design range for each flow rate. Using these data, prepare a crossplot relating cold process fluid temperature to the reciprocal of the percentage process fluid circulation rate, expressed as a decimal (e.g. 90 % flow equates to 111,11 % capability, 110 % flow equates to 90,91 % capability). Enter this crossplot at the tower capability as determined in 9.3.7.1.3 and project a line vertically to intersect the curve. At the intersection, read the predicted cold process fluid temperature ($T_{CPF, pred}$) for the tower at the test capability.

9.3.7.2.2.1 Comparison with design cold process fluid temperature

Compare the predicted cold process fluid temperature ($T_{CPF, pred}$) determined above to the design value for cold process fluid temperature ($T_{CPF, d}$) such that the approach deviation (ΔT_{App}) equals:

$$\Delta T_{App} = (T_{CPF, pred}) - (T_{CPF, d}) \tag{59}$$

9.3.7.2.3 Multiple valid test periods

When the data from multiple valid test periods are being used to evaluate the tower performance, the approach deviations for the individual tests should be averaged using Formula (60).

$$\overline{\Delta T}_{App} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \Delta T_{App(n)} \tag{60}$$

NOTE If there is any significant deviation between the operating conditions for each valid test period, (such as might be the case if the valid tests were performed on different days), the individual approach deviations should be evaluated at the design, not the measured test conditions.

9.3.7.2.4 Compliance

The guaranteed condition has been achieved if

$$\Delta T_{App} - I_{TEMP} \leq 0 \tag{61}$$

where I_{TEMP} = 0, unless specified differently in the contract.

9.3.7.3 Wet/dry closed-circuit towers utilizing a wet or dry operating mode

If the requirements of operation and control setting specified by the manufacturer have been met during the test, the procedures specified in 9.3.7.2 and following can be applied.

9.4 Extended thermal performance test evaluation (applicable to natural draft towers, only if required by contract)

9.4.1 Methodology

Test result includes an actual verification of wind effect on tower performances (see 8.2). For each valid test period, calculate the difference between the measured approach and the guaranteed approach adjusted for test period conditions, using data supplied by the manufacturer (see 5.3.8 and 5.3.9).

Then the valid test periods are grouped together into n classes, as a function of the reference wind velocity at 10 m during the test period. In each case, calculate the average approach deviation.

Final test result is the weighted average approach deviation, which results from weighting each wind class average approach deviation (weighting coefficients shall be contractually specified, see 5.3.8).

Since more than 300 valid test periods are required, use of charts is not relevant, so that computational calculation using characteristic equations (Merkel/CTI) is proposed. Only evaluation by approach deviation is suggested.

9.4.2 Test period guaranteed approach

A guaranteed approach value (adjusted for test conditions) shall be calculated for each valid test period.

9.4.2.1 Characteristic equations of the cooling tower

Coefficients are supplied by the manufacturer at the time of submitting the offer (see 5.3.8). In the case of acceptance tests, the coefficients are contractual.

Operating formula:

$$\frac{KaV}{L} = C\left(\frac{L}{G}\right)^{X} \tag{62}$$

Draft formula:

$$\rho_{A,1} - \rho_{A,2} = 0{,}5\left(\frac{\rho_{A,1}}{g_C H}\right) C_F v_A{}^2 \tag{63}$$

9.4.2.2 Simplifying assumptions

a) Hot air is assumed to be saturated.

b) The variation in water flow rate passing through the cooling tower is overlooked in the energy balance. The output transferred therefore is reduced to $L \times C_p (t_h - t_c)$ and hot air enthalpy is

$$h_{A,2} = h_{A,1} + \frac{L}{G} c_{p,W} (T_{HW} - T_{CW}) \tag{64}$$

9.4.2.3 Calculation of *KaV/L*

Value of a *KaV/L* will be used to calculate the test period guaranteed approach. Using 9.4.2.2 assumptions, *KaV/L* is to be calculated between fill inlet and outlet from

$$\frac{KaV}{L} = c_{p,w} \frac{1}{\gamma} \int_{T_{CW}}^{T_{HW}} \frac{dT}{h_M - h_A} \tag{65}$$

where γ is a correction factor depending on the type of device, defined in Annex E.

A Simpson's rule can be used to numerically evaluate any integral. For this International Standard, an eight-point version has been adopted, which takes the form of Formula (66):

$$\int_{t_c}^{t_h} f(t)dt = \frac{p}{3}\left[f(t_c)+4f(t_c+p)+2f(t_c+2p)+\ldots+2f(t_c+2k-2p)+4f(t_c+((2k-1)p)+f(t_h)\right] \quad (66)$$

with

$$p = \frac{T_{HW} - T_{CW}}{8} \quad (67)$$

Since

$$f(\mathrm{t}) = \frac{1}{h_s(\mathrm{t}) - h(\mathrm{t})} \quad (68)$$

mechanical expressions will be required to express air enthalpy in function of measured parameters. These expressions also are given in Annex D.

9.4.2.4 Calculation of the test period guaranteed approach, $a_{pr,\ guar}$

Guaranteed approach shall be adjusted to the test period conditions: water flow rate, cooling range, air inlet dry-bulb temperature, wind speed, atmospheric pressure, and relative humidity.

a) Adjusted dry air mass flow rate and hot air density shall be calculated by successive approximations using Formula (2) and Formula (3) and expression of C_f (see 5.3.8).

b) $KaV/0L$ shall be calculated from Formula (34) and expression of C (see 5.3.8).

c) Adjusted guaranteed cold water temperature is then obtained by successive approximations as illustrated in Figure I1.

d) Test period guaranteed approach, $a_{pr,\ guar}$, is the difference between guaranteed cold water temperature and test period average air inlet wet-bulb temperature.

9.4.3 Test period measured approach, $a_{pr,\ tp}$

For each valid test period, it is the difference between the average corrected cold water temperature and the average air inlet wet-bulb temperature.

9.4.4 Test period approach deviation, $\Delta a_{pr,\ tp}$

For each valid test period, it is the difference between measured approach and guaranteed approach, such as

$$\Delta a_{pr,\ tp} = (\Delta a_{pr,\ tp}) - (\Delta a_{pr,\ guar}) \quad (69)$$

9.4.5 Test result — "weighted average approach deviation", Δa_{pr}

Extended thermal performance test evaluation requires the conducting of at least 300 valid test periods.

9.4.5.1 Classification of test period

Test periods and corresponding approach deviations shall be grouped together into n classes ($n \leq 5$) as a function of the average test period wind velocity at 10 m during the test period, such as:

a) Class 1: $0 \leq V10 < 2$ m/s m1 test periods;

b) Class 2: $2 \leq V10 < 4$ m/s m2 test periods;

c) Class 3: $4 \leq V10 < 6$ m/s m3 test periods;

d) Class 4: $6 \leq V10 < 8$ m/s m4 test periods;

e) Class 5: $8 \leq V10 < 10$ m/s m5 test periods.

The spread of each class is 2 m/s.

The number of classes and weighting coefficients of each shall be contractually specified, understanding that if $n < 5$, the classes considered shall include the first one and be consecutive.

NOTE The specified number of classes actually fixes the minimum average velocity for a test period to be valid. As an example, if $n = 3$, V10 < 6m/s for any valid test period.

9.4.5.2 Number of valid test period in a class

a) Only classes filled with enough number of valid test periods shall be taken into consideration; a class including four valid test periods or less shall be considered as not filled.

b) If a class is not filled, the weighting coefficient corresponding to filled classes shall be corrected so that their sum reaches 100 %, by respecting the relative initial weight of each filled class.

c) For each filled wind class, valid test periods can be divided into two groups, provided that test periods number in both groups exceeds 30 % of the total wind class test periods number (if not, all the test periods of a wind class shall be considered as one group): entering air wet-bulb temperature increasing during the period and entering air wet-bulb temperature decreasing during the period (comparison of the first recording and the last recording of the period).

9.4.5.3 Calculation of the class average approach deviation, $\Delta a_{pr,\,i}$

One deviation shall be calculated for each class.

a) If the class is divided into two groups, including $m_{i,1}$ and $m_{i,2}$ test periods ($m_{i,1} + m_{i,2} = m_i$):

$$\overline{\Delta a_{pr}}_{\,m1} = \left(\frac{1}{n}\right)\sum_{n=1}^{n} \Delta a_{pr\,m1(n)} \tag{70}$$

and

$$\overline{\Delta a_{pr}}_{\,A,m} = \left(\frac{1}{2}\right)\left(\Delta a_{pr\,A,m1} + \Delta a_{pr\,A,m2}\right) \tag{71}$$

b) If all the test periods of the class shall be considered as one group:

$$\overline{\Delta a_{pr\,m}} = \frac{1}{n}\sum_{n=1}^{n} \Delta a_{pr\,m(n)} \tag{72}$$

9.4.5.4 Calculation of the “weighted average approach deviation”, Δa_{pr}

The weighting coefficients ±n (see 9.4.5.1) are introduced.

$$\Delta a_{pr} = \sum_{i=1}^{i=n} \alpha_i \Delta a_{pr,i} \tag{73}$$

9.4.5.5 Compliance

The tower shall have achieved the guaranteed condition if

$$\Delta a_{pr} - I_{TEMP} \leq 0 \tag{74}$$

where $I_{TEMP} = 0$, unless specified differently in the contract.

10 Reporting of results

10.1 General

Upon completion of the test, the test data sheets shall be authenticated by the signatures of the representatives of the parties to the test which can be the manufacturer, the test purchaser, and the testing agent, each of whom shall receive a copy. Also, a preliminary determination of the test result shall be prepared and distributed to the authorized representatives of the parties to the test.

10.2 Final report

Within a reasonable period after the completion of the test, the test agent shall prepare and submit to the parties to the test a final report of the results of the performance test, which shall include:

a) a brief description of the purpose of the test, the results, and the conclusions;

b) a listing of the parties to the test and their relationships to the project;

c) a description of the cooling tower tested including the design conditions and the principle dimension;

d) a sketch of the installation noting the location of the water flow and temperature measurement points as well as any building, obstructions, or other equipment in the immediate vicinity of the tower tested. Particular note should be made of any equipment or facilities discharging heat or vapour in the immediate vicinity of the tower;

e) a description of the instruments used and any methods of measurement not prescribed by this code;

f) the data submitted by the manufacturer that was used to evaluate the test;

g) a listing of the measured test data, a summary of the measurements used to evaluate the test, computations and calculations made in evaluating the test, and the test result and conclusions;

h) a statement of compliance with the provisions of this International Standard (i.e. ISO 16345) and, when applicable, a description of those instances where the test deviated from the provisions of this International Standard (i.e. ISO 16345).

10.3 Security

Information on the test shall be available only to the purchaser of the test, the manufacturer, and the test agent. No further distribution of the information shall be made without the written agreement of all parties to the test.

10.4 Limitations

Adherence to the limits imposed by this International Standard on wet-bulb temperature, dry-bulb temperatures, cooling range, circulating water flow, etc. will yield results with accuracy commensurate with the stability of the test conditions and the accuracy of the instruments specified for measurements. When test conditions fall outside these limitations, errors can be introduced due to one or more of the following considerations (in accordance to 4.4).

The formulae and/or graphs used to adjust the test data cannot adequately provide for the effects of the wide deviations from design in the following variables:

a) water circulation rate;

b) water temperatures;

c) airflow rate;

d) air wet-bulb temperature;

e) air dry-bulb temperature;

f) strong and/or gusting winds are likely to affect cooling tower performance adversely;

g) poor air and/or water distribution will result in malperformance.

11 Published ratings

The term "published ratings," as used in this International Standard, pertains to the thermal performance ratings of series cooling towers (presented in printed form or as computer output) as made available upon request to contractors, distributors, consultants, engineers, and owners for selecting equipment for applications. The published ratings for mechanical draft cooling towers shall consist of mapped ratings and application ratings, expressed as the flow rate capacity of water or process fluid at a specific combination of entering and leaving water/process fluid, at a specific combination of entering and leaving water/process fluid temperatures, entering air wet-bulb and dry-bulb temperatures, and fan power consumption.

Annex A
(normative)

Instruments and measurements

A.1 Calibration

A.1.1 General

All instrumentation employed during the course of the test shall be calibrated prior to the test. Calibration shall be traceable to primary or secondary standards calibrated by a recognized authority, such as a national standards authority, or derived from accepted values of natural physical constants. Instruments shall be re-calibrated on a regular schedule appropriate for the respective instrument and full calibration records shall be maintained. The minimum calibration frequencies shall be as shown in Table A.1. An instrument shall also be re-calibrated whenever it is damaged or its accuracy is called into question for any other reason. Additionally, at the request and expense of the test purchaser, any and all instrumentation used on a test can be calibrated before and/or after a test.

Table A.1 — Frequency of calibration

Instrument	Minimum calibration frequency
Temperature sensors	Within 3 mo prior to use
Pressure devices	Yearly
Flow measurement devices	3 y, if undamaged
Electric power meters	Yearly
Wind speed and direction devices	Yearly

A.1.2 Records of calibration

The test agent shall have a written procedure for calibrating each instrument, shall maintain records showing the calibration history for each instrument, and make them available upon request to the parties to the test. Identification (e.g. serial number) and location of each individual instrument used on the test shall be recorded and included in the test report so the calibration date and history can be traced.

A.2 Flow measurements

A.2.1 General

All tests require measurement of the main circulating water or process fluid flow rate. Measurement of the makeup water flow rate and the blowdown water flow rate might be necessary, depending upon the tower operating mode during the test. The flow rates shall be measured using any of the methods specified in A.2.2. The method employed and location of measurement will depend upon the nature of the installation and the importance of the measurement to the test result.

A.2.2 Re-circulating water/process fluid flow rate measurement

The flow rate of the re-circulating water/process fluid shall be measured at a point where a well-developed velocity profile exists, preferably in the piping leading to the tower. Measurement stations with insufficient upstream and downstream distances will have significant, adverse impact on the velocity profile and the accuracy of the measurement should be resolutely avoided.

The instrument shall be accurate to 1,0 % of the quantity being measured, with such adjustments and corrections as are necessary to account for the temperature and physical properties of the fluid. With such calibrations, the overall uncertainty of the flow measurement should be in the order of 2,5 % to 3 %. Acceptable methods and instruments include Pitot tube (traverse method), orifice plates, venturies, nozzles, and other flowmeters that demonstrate the ability to measure flow rate precisely and accurately. These include, but are not limited to, Coriolis, turbine, magnetic flow meter, and transient time ultra sonic meters, with their associated electronic systems. Detailed and authoritative information of the use of various flowmeters are described in the Bibliography, References [1] to [32].

Flowmeters, whether temporarily or permanently installed, shall be inspected prior to the test for dimensional conformity and functionality.

A.2.3 Makeup and blowdown flow rate measurement

If not stopped for the duration of the test, the makeup and blowdown rates shall be measured with an instrument accurate to 2,0 % of the quantity being measured. With such calibration, the overall uncertainty of the flow measurement should be in the order of 4,0 % to 5,0 %.

A.3 Temperature measurements

A.3.1 General

Temperature measurements shall be made using any instruments or instrument systems meeting the following requirements.

a) The indicator or recorder shall be graduated in increments of not more than 0,1 °C and be readable to ±0,05 °C.

b) The temperature-sensitive element shall be accurate to ±0,05 °C.

c) The temperature-sensitive elements shall be carefully located to ensure the measurement is representative of the true bulb temperature of the fluid at the point of measurement.

A.3.2 Entering air wet-bulb temperature

The entering air wet-bulb temperature shall be measured with mechanically aspirated psychrometers, each meeting the following requirements.

a) The temperature-sensitive element shall be shielded from direct sunlight or from other significant sources of radiant heat. The shielding device shall be within 1 °C of the surrounding dry-bulb temperature.

b) The temperature-sensitive element shall be covered with a wick that is continuously wetted from a reservoir of distilled water.

c) The temperature of the distilled water used to wet the wick shall be approximately the wet-bulb temperature being measured. This can be obtained in practice by allowing adequate ventilated wick between the water supply and the temperature-sensitive element.

d) The wick shall fit snugly over the temperature-sensitive element and extend at least 2 cm past the element over the stem. It shall be kept clean while in use.

e) The air velocity over the temperature-sensitive element shall be maintained between 3 m/s and 6 m/s.

The entering air wet-bulb temperature shall also be determined with a measurement of the entering dry-bulb temperature and of the air relative humidity.

A.3.3 Manual readings

For manually recorded data, three successive observations at 10 s intervals shall be taken at each station, the average of which shall be considered the temperature readings at that time, at that instrument station.

A.3.4 Entering air dry-bulb temperature

The inlet dry-bulb temperature shall be measured with mechanically aspirated, wickless psychrometers, each meeting the following requirements.

a) The indicator or recorder shall be graduated in increments of not more than 0,1 °C.

b) The temperature-sensitive element shall be accurate to ±0,05 °C.

c) The temperature-sensitive element shall be shielded from direct sunlight or from other significant sources of radiant heat. The temperature of the shielding device shall be within 1 °C of the surrounding dry-bulb temperature.

d) In the case of the use of a dry-bulb temperature probe, the shielding device shall enable air circulation resulting from the tower draft around the probe.

A.3.5 Ambient dry bulb

The dry-bulb temperature of the ambient air shall be measured, if mandatory, at a fixed meteorological mast of 10 m height, located at least 300 m from the tower. One probe is required, three probes being preferable. The probes shall be shielded and protected from the rain, as typically done for meteorological purposes.

A.3.6 Atmospheric gradient (natural draft and fan-assisted natural draft)

The atmospheric gradient, where direct measurement is possible, shall be determined by use of dry-bulb temperature, measurements taken at no more than 60 m vertical increments using a meteorological tower, tethersonde, or other similar means.

A.3.7 Measurement bulb accuracy

When the entering air dry-bulb temperature measurement is for the sole purpose of determining the physical properties of the entering air on a mechanical draft tower, a measurement accuracy of 1 °C to 3 °C for the average dry-bulb temperature is usually acceptable. In most cases, this can be achieved by means of a single measurement station, or at most two stations. A mechanically aspirated psychrometer of the type described above shall be used, with the wick removed. Each shall meet the following requirements.

a) The temperature-sensitive element shall be shielded from direct sunlight or from other significant sources of radiant heat. The shielding device shall be within 1 °C of the surrounding dry-bulb temperature.

b) The air velocity over the temperature-sensitive element should be at least 2 m/s and preferably the same as the wet-bulb psychrometer.

A.4 Pressure measurements

A.4.1 General

Pressures shall be measured using manometer, gages, transducers, or other instruments or instrument systems as appropriate for the magnitude of the pressure to be measured.

A.4.2 Accuracy and scales

Instrument accuracy and maximum scale intervals shall comply with the values listed in Table A.2 for the measurement range of the device.

Table A.2 — Instrument accuracies and scale intervals

Range Pa	Accurarcy Pa	Maximum scale interval Pa
250 to 500	2	5
501 to 1 000	5	10
1 000	10	20

A.4.3 Pressure taps

Tappings into conduits for pressure measurements shall be as small as practicable and be free of burrs and other irregularities.

A.4.4 Heat exchanger pressure drop

Stations for measuring the pressure drop of the process fluid across the heat exchanger of a closed-circuit or wet/dry tower shall be located as closely as possible to the contractual inlet and outlet nozzles of the heat exchanger(s). When the working fluid does not change state, the conduit size shall be the same at both the inlet and outlet stations, or the readings shall be corrected for the difference in velocity at the points of measurement. Corrections shall be made for fitting or any other losses that produce pressure differences between the point of measurement and the nozzles. If separate measurements are taken at the inlet and outlet nozzles, the measured differences shall be adjusted for the difference in elevation between the two measurement points.

A.4.5 Atmospheric pressure

Atmospheric pressure shall be measured with a standard barometer, accurate to ±0,1 % of the reading.

A.5 Fan driver output power

A.5.1 General

The output power of the fan driver shall be determined from the measured power input, adjusted for the efficiency of the driver or motor.

A.5.1.1 Power input

In the case of electric motors, power input shall be determined by direct measurement of the power input to the motor in kilowatts at a location such that the instrumentation can accurately measure the total power input to the device. Instrumentation used shall measure the true route mean square power to an accuracy of 0,1 % of the quantity measured. If the distance between the point of measurement and the motor warrants, a line loss correction shall be made, unless otherwise agreed by all parties.

A.5.1.2 Variable frequency drive

If the electric motor is equipped with a variable frequency drive (VFD) or other power altering device, appropriate actions (such as bypassing the device) shall be taken to ensure an accurate measurement and that no speed changes are made to the fan over the duration of the test.

A.5.2 Efficiencies

The efficiencies stated by the manufacturer of the fan driver can be used to calculate the driver output from the measurement input.

A.6 Wind velocity

A.6.1 General

Wind velocity shall be measured with a meteorological type anemometer and wind vane, preferably remote reading and recording. The number of measurement stations and their location is dependent upon the type of tower under test.

A.6.2 Mechanical draft towers

For mechanical draft towers, the wind velocity measurement shall be made in an open and unobstructed location, upwind of the tower and beyond the influence of the inlet-air approach velocity. Care shall be taken to ensure the recorded wind speed and direction are representative of wind conditions affecting the tower. Placement of the wind measurement device shall be subject to mutual agreement by all parties to the test. Wind direction shall be recorded in compass degrees with the reference north clearly indicated.

A.6.2.1 For cooling towers with an overall height of 6 m or less, the wind velocity shall be measured 1,5 m above the elevation of the basin curb, at a point within 15 m to 30 m of the tower, if practical.

A.6.2.2 Where the distance between basin curb and the discharge elevation exceeds 6 m, the wind velocity shall be measured at a height above the curb elevation that is approximately one-half the difference between the curb and discharge elevations and at a distance of at least 30 m from the tower, if practical.

A.6.3 Natural draft towers

A.6.3.1 For natural draft towers, the wind velocity shall be measured at two locations.

A.6.3.2 Shell opening: in a horizontal plane extending through the discharge opening at the top of the shell at a point within 45 m to 450 m from the edge of the shell, if practical.

A.6.3.2.1 In cases where it is not practical to measure the wind speed at the top of the shell, an indicator of the wind conditions at the top of the shell shall be the appearance of plume at the exit. For an acceptable test, visual observations of the plume shall indicate that the plume completely fills the shell outlet and rises vertically for a minimum distance of approximately one-half of the outlet diameter. Top of shell wind speed is not relevant in the case of extended tests.

A.6.3.2.2 At a height equal to one-half the inlet height and a distance from the cooling tower that is at least twice the air inlet height and no less than a quarter of the base diameter of the tower.

A.7 Measurements for tower pumping head

Two measurements are required for determining tower pumping head:

a) the gage static pressure at the centreline of the re-circulating water inlet connection, expressed in metres of water;

b) the measured, vertical distance between the top of the basin curb and the centreline of the re-circulating water inlet connection, expressed in metres.

A.8 Time measurements

Time measurements, if used to determine flow rate or power, shall be made with instruments having accuracies with ±0,5 % of the elapsed time measured. This accuracy shall include any uncertainty errors associated with starting and stopping the instrument.

A.9 Water analysis

A sample of the circulating water and, where applicable, the process fluid, shall be taken during the test. If there are any questions concerning the quality of the circulating water or process fluid the sample shall be analysed by a reputable testing laboratory to determine the composition of the fluid.

Annex B
(normative)

Wet-bulb determination

B.1 General

Annex B specifies methods and apparatus to accurately measure wet-bulb temperature/relative humidity for the purpose of cooling tower testing. It does not specify the full details of the devices required so as to ensure well-designed instruments, which have gained acceptance in different countries, are not arbitrarily excluded.

This approach, specifying only the essential features of a few important types of psychrometers and hygrometers, necessarily has some limitations. It should be understood, therefore, that good practice should be followed, both in implementing the requirements of Annex B and in detailing aspects of the design and procedure that are not specified.

B.2 Definitions

For the purposes of Annex B, the following definitions shall apply:

Aspirated psychrometer: A psychrometer which includes a provision for mechanically drawing air across the thermometers at some predetermined velocity;

Dewpoint: Temperature at which water vapour has reached the saturation point (100 % relative humidity);

Dry-bulb temperature: The temperature of air measured by a thermometer with a dry sensor, shielded from extraneous radiation;

Hygrometer: An instrument to directly determine the relative humidity level of moist air;

Psychrometer: An instrument for determining relative humidity by using two thermometers to measure the wet-bulb and dry-bulb temperatures of air;

Relative humidity: The ratio, in percent, of the mole fraction of water vapour in an air sample to the mole fraction in a saturated sample at the same temperature and pressure;

Saturation vapour pressure: The maximum vapour pressure that can be supported by an air sample at a given temperature and pressure;

Sling psychrometer: A psychrometer wherein the air movement over the thermometers is produced by rapidly whirling the instrument, typically manually;

Stem: The portion of a thermometer that does not contain the sensor;

Thermometer: Any temperature measuring device or system;

Vapour pressure: The fraction of the ambient pressure that is due to the fraction of water vapour in the air sample;

Wet-bulb depression: The temperature difference between the dry-bulb temperature and wet-bulb temperature of an air sample;

Wet-bulb temperature: The equilibrium temperature measured by a thermometer with a sensor, shielded from extraneous radiation and covered with a wetted wick, placed in a moving airstream.

It closely approximates, but is not equal to, the thermodynamic wet-bulb temperature (which is fully adiabatic).

B.3 References

See References [33] to [36].

B.4 Psychrometers

B.4.1 General

B.4 addresses the use of mechanically aspirated psychrometers to determine the wet-bulb and/or dry-bulb temperature of air over a span of temperatures of the air ranging from ±5 °C of expected test conditions.

B.4.2 Principle

Industrial psychrometers, if properly designed and utilized, are rugged and well suited for cooling tower testing. Typically, they consist of one or two thermometers, one of which is maintained in a wetted condition with a moistened wick over the sensor. The sensor portions of the thermometers are well shielded from extraneous radiation and a blower is utilized to ventilate the device at a specific velocity of air over the sensors. Evaporation from the surface of the wet sensor into the airstream cools the sensor to a steady temperature through evaporation such that there is a balance between the heat lost through evaporation and that gained through convection and radiation.

NOTE Radiation shielding is extremely important in psychrometers used in conjunction with on-site cooling tower testing since the psychrometer is usually exposed to strong sunlight and wet-bulb depressions as great as 20 °C can be encountered.

B.4.3 Thermometers

B.4.3.1 General

Thermometers can be mercury-in-glass (in which case they shall be the partial immersion type), electrical resistance, or other types complying with A.3.1, with a range expanding at least 5 °C above and below the expected range of test measurement. The accuracy shall be such that the uncertainty in the value of wet-bulb depression is no greater than ±0,1 °C, including any uncertainty associated with the calibration.

B.4.3.2 Temperature sensors

The temperature sensors shall be essentially cylindrical, supported on a stem which is essentially co-axial with the sensor. The diameter of the sensors, typically about 6 mm, due in part for the need for ruggedness, shall not differ substantially from that of the stem. The free end of the sensor shall be smoothly rounded.

B.4.3.3 Mounting thermometers

The thermometers shall be mounted with the axes of the sensors parallel and separated by a distance of not less than three times the overall diameter of the wet sensor (including the wet-bulb covering) and so that a line drawn to connect the free ends of the sensors is perpendicular to the axes.

B.4.3.4 Thermometer clearance

The stem of each thermometer shall be clear of obstructions and freely exposed to the airstream over a length, measured from the sensor, of not less than 1,5 times the length of the wicking covering the sensor as described in B.4.4.4.

B.4.3.5 Electrical connecting wire

The connecting wires of electrical thermometers shall be contained within the supporting stems and shall be isolated from the moisture in the wet-bulb covering.

B.4.4 Wet-bulb covering, wick, and water reservoir

B.4.4.1 Wet-bulb covering

The wet-bulb covering shall be fabricated from hydrophilic, undressed, white cotton muslin made from thread of linear density between 1 tex and 15 tex and having 20 threads to 25 threads per cm warp and weft. A seamless sleeve is preferred, but a seam is permitted provided that it does not add appreciably to the general roughness that the weave imparts to the surface.

B.4.4.2 Cleaning of fabricated covering

After fabrication, the covering and wick shall be washed in a dilute solution of sodium carbonate and thoroughly rinsed with distilled water. Subsequently, the wicks should not be touched with bare fingers.

B.4.4.3 Fit of fabricated covering

The covering shall completely and snugly cover the sensor. It shall extend onto the stem for such distance that the error in the observed wet-bulb temperature due to heat conduction along the stem does not exceed 0,05 °C. The wick shall be tied with cotton thread, and turned inside out, so that the excess past the tie-off is inside against the tip of the sensor. This reduces any void area between the tip of the sensor and the wick.

B.4.4.4 Wick placement

The wick connecting the covering to the water reservoir shall consist of twisted threads of white cotton and shall have the minimum cross section consistent with an adequate water feed to the wet-bulb for the highest rates of evaporation. The free length of the wick shall be at least twice the diameter of the wet-bulb and at least three times the wick diameter to ensure the water arriving at the covering is already nearly at the wet-bulb temperature. The wick shall be limp.

B.4.4.5 Elimination of air contact with wet-bulb

Other than in the immediate proximity of the connection to the covering, air that passes over the wick shall not impinge on the wet-bulb. With axial ventilation, the wick shall be attached to that part of the covering that extends onto the stem.

B.4.4.6 Water reservoir system

The water reservoir shall contain sufficient volume of water to adequately supply water to the wick and wet-bulb covering for a period of at least 1 h at the highest rates of evaporation. To ensure an adequate flow of water to the covering, the water level in the reservoir shall be not more that 25 mm below the level of the lowest part of the wet-bulb.

B.4.4.7 Elimination of airflow with water reservoir

The water reservoir shall not obstruct the airflow through the psychrometer and its contents shall not affect the humidity of the sample air.

B.4.5 Airflow

B.4.5.1 Aspiration of psychrometer

The psychrometer shall be mechanically aspirated, preferably by an electrically driven fan, producing a steady velocity of air over the dry and wet bulbs ranging between 3 m/s and 6 m/s.

B.4.5.2 Direction of airflow

The direction of airflow shall be from the free end of each sensor toward the support end. The sample air shall not pass over any obstruction or through a fan before it passes over the wet and dry bulbs.

B.4.5.3 Elimination of airflow on dry bulb

No air that has been cooled by the wet-bulb or by the wick shall impinge on the dry bulb. Air that has been discharged from the instrument shall not return locally to the incoming air.

B.4.6 Radiation shields

B.4.6.1 Dimensions of radiation shields

Radiation shields shall be metal, 0,4 mm to 0,8 mm thick. Surfaces that shall be polished shall be made of a bare, brightness-retaining metal.

B.4.6.2 Concentric radiation shield with axial ventilation

With axial ventilation, concentric radiation shields, polished inside and out, shall be provided for the wet and dry bulbs. (The shield around the wet-bulb plays a vital role in reducing the radiative heat transfer between the bulb and its surroundings, by approximately a factor of three). The diameter of the shield shall be not less than 1,8*d* and not greater than 2,5*d*, where *d* is the overall diameter of the wet-bulb, including the covering. Its length and position shall be such that its projection beyond each end of the wet covering is not less than *d* and not greater than 3*d*. The entrance to the shield should be flared to form a bellmouth to prevent the flow separation from the inside of the shield. The shield also can serve as a duct for the airflow.

If a second pair of concentric cylindrical radiation shields is provided outside the first, they shall be polished inside and out, and the inner shields shall be uniform cylinders over their whole length. The entrance of each outer shield shall be slightly forward of the entrance of the inner shield and flared to form a bellmouth. The design should produce an air velocity between the inner and outer shields that is equivalent to that in the inner shield.

B.4.6.3 Parallel plate radiation shield for transverse ventilation

With traverse ventilation, radiation shields in the form of parallel plates shall be provided to shield the wet and dry sensors from extraneous radiation. A shield can also be provided between sensors. The shields shall be flared outward at the entrance to prevent flow separation on the inside and shaped to direct the airstream over the entire sensor and that part of the stem and wick which lie within the shield. Any shield surface which faces one or both of the sensors shall be flat black; all other surfaces shall be polished.

B.5 Hygrometers

B.5.1 General

B.5 addresses the use of hygrometers to determine the ambient or entering air relative humidity. The range of determination is site dependent, and can be contractually specified. Otherwise it shall be spanning no less than 30 % to 95 % over a span of temperatures of the air ranging from ±5 °C of expected test conditions.

B.5.2 Overview of existing devices

B.5.2.1 Hygrometers

Hygrometers are industrial devices, well suited for cooling tower testing, as long as they are properly used. Several types of hygrometers are available, the more widespread being resistive hygrometers and capacitance hygrometers.

B.5.2.2 Necessity for hygrometer adjustment

The principle of measurement relies on the manufacturer's know-how, the latter guaranteeing any measured value over a specific span of dry-bulb temperature and relative humidity. Nevertheless it is necessary to check the adjustment of such devices before using it, due to the fact that output signals can differ between two devices from a same category. Adjustment checking of any hygrometer is time and money consuming, because it ideally requires adjusting several relative humidity values for any dry-bulb temperature.

B.5.2.3 Selection of hygrometer

Experience shows that capacitance hygrometers are more reliable and generally of better quality than resistive hygrometers. As a result, it seems that capacitance hygrometers are the most suitable devices allowing relative humidity measurement or cooling tower testing, up to now.

B.5.3 Capacitance hygrometers

B.5.3.1 Range

Their range of use spans from 0 % to 100 % relative humidity, for a range of dry-bulb temperatures from −40 °C to 100 °C. Their response time is around a few seconds, but can be higher when relative humidity is over 90 %. Typically, the accuracy is ±3,0 %.

B.5.3.2 Adjustment

Practical adjustment checking only requires three points: it is suitable to adjust 20 %, 50 %, and 80 % relative humidity at a sole value of dry-bulb temperature, which can be 23 °C, or any other site-dependent value.

B.5.3.3 Shielding

Capacitance hygrometers shall be shielded from extraneous radiation and protected from rain, as well as from strong wind, in order to avoid any vibration of the sensing element that could result in false capacities. Air circulation around the hygrometer within the protecting device shall be allowed.

B.5.3.4 Placement

When hygrometers are at the air inlet to measure entering air relative humidity, suitable air circulation is directly provided from the draft. When hygrometers are on top of a meteorological mast to measure ambient air relative humidity, a blower should be used to ventilate the hygrometer within the protecting device, with a velocity of air of around 2 m/s.

B.5.3.5 Errors induced by condensation

Users of capacitive devices should be aware that if condensation occurs on the device (e.g. passing below the dewpoint), the readings are unreliable until after the device becomes fully dried out.

Annex C
(normative)

Inlet-air temperature measurement locations

C.1 Location of wet-bulb instrumentation (or dry-bulb and relative humidity)

C.1.1 Air inlet wet-bulb temperature (or dry-bulb and relative humidity)

For the measurement of inlet wet-bulb temperature, the instruments shall be located approximately 1,5 m outside the air intake(s). Care should be taken to ensure that splashing at the air inlet does not affect the instruments. A sufficient number of measurement stations shall be applied to ensure that the test average is an accurate presentation of the true average inlet wet-bulb temperature. The number of instrumentation stations is determined as follows by tower type. An instrumentation grid can then be developed for location of wet-bulb stations on the air inlet of the tower. The same principles apply to location of dry bulb and relative humidity instruments used in lieu of wet-bulb instruments. In that case, the minimum number of horizontal levels for relative humidity shall be one.

C.1.2 Measurement stations

Sufficient measurement stations shall be employed on each tower inlet face to ensure the test measurement is representative of the entering wet-bulb temperature. When determining the number of measurement points on a given face, particular attention should be given to the possible presence of re-circulation and interference. In any case, the number of measurement points on any air inlet face shall not be less than N_{wb} as determined below, rounded upward to the next integer.

Mechanical draft cooling tower	$N_{wb} = 0,65\ (A)^{0,33}$	
Wet/dry cooling tower	$N_{wb} = 0,65\ (A)^{0,33}$	
Closed circuit	$N_{wb} = 0,65\ (A)^{0,33}$	
Round or polygonal mechanical draft cooling tower	$N_{wb} = 0,65\ (A)^{0,4}$	
Natural draft tower	$H_{ai} < 12$ m	$N_{wb} = 12$
	$H_{ai} > 12$ m	$N_{wb} = 16$

NOTE With N_{wb} = minimum number of wet-bulb instruments and A = area of air inlet face, expressed in square metres.

C.1.3 Horizontal levels

C.1.3.1 Mechanical draft

C.1.3.1.1 Grid lines

Wet-bulb instrument stations should be located at the intersection of vertical and horizontal grid lines determined from the total number of wet-bulb stations above and the vertical air inlet height. The number of horizontal levels (GL_h) is determined from the following guideline.

For air inlet height	**Number of horizontal grid levels** (GL)
< 4 m	GL = 1
< 8 m	GL = 2
< 15 m	GL = 3
> 15 m	GL = 3

C.1.3.1.2 Horizontal grids

The horizontal grid lines are to be located based on the following formulae.

Number of horizontal grid levels (G/L)	**Height of grid levels** (H_i)
GL = 1	$H1 = H_{ai} \times 0{,}5$
GL = 2	$H1 = H_{ai} \times 0{,}25$, $H2 = H_{ai} \times 0{,}75$
GL = 3	$H1 = H_{ai} \times 0{,}167$, $H2 = H_{ai} \times 0{,}5$, $H3 = H_{ai} \times 0{,}833$
GL = 4	$H1 = H_{ai} \times 0{,}125$, $H2 = H_{ai} \times 0{,}375$
	$H3 = H_{ai} \times 0{,}625$, $H4 = H_{ai} \times 0{,}875$

where

H1 through H4 is the height of each horizontal grid line;

H_{ai} is the air inlet height.

C.1.3.2 Natural draft

Wet-bulb instrument locations should be located at the intersect of vertical and horizontal grid lines.

C.1.3.2.1 Horizontal levels

As in C.1.3.1.1, the number of horizontal levels (GL) is determined from the following guideline.

For air inlet height	**Number of horizontal grid levels (G/L)**
< 12 m	GL = 3
> 12 m	GL = 4

C.1.3.2.2 Horizontal grid lines

The horizontal grid lines are to be located based on the following formulae.

Horizontal grid levels (G/L)	Height of grid levels (s)
GL = 3	$H1 = H_{ai} \times 0{,}167$, $H2 = H_{ai} \times 5$, $H3 = H_{ai} \times 0{,}833$
GL = 4	$H1 = H_{ai} \times 0{,}125$, $H2 = H_{ai} \times 0{,}375$, $H3 = H_{ai} \times 0{,}625$, $H4 = H_{ai} \times 0{,}875$

C.1.4 Vertical grid strings

The number of equally spaced vertical grid strings (GS) is then determined from the Formula (G.1).

$$GS = N_{wb} / GL \tag{G.1}$$

where

GS is the number of grid strings;

N_{wb} is the measurement point;

GL is the number of grid lines.

C.1.5 Position of instruments in equal area sections

If practical, the air temperature shall be measured at the centre of equal-area air inlet sections. In case of wet/dry cooling towers, the instruments shall be located both in front of wet and dry section air inlets, treated as separate faces.

C.2 Location of inlet-air dry-bulb instrumentation

For the measurement of inlet dry-bulb temperature on wet/dry, natural draft, and fan-assisted natural draft towers, the instruments shall be located on the same basis as for the wet-bulb temperature.

Annex D
(normative)

Thermodynamic properties of moist air

D.1 General

Annex D provides reliable psychrometric data, developed from the perfect gas law relationships for dry and moist air with corrections to account for the effect of dissolved gases on properties of condensed phase, the effect of pressure on properties of condensed phase, and the effect of intermolecular force on properties of moisture itself. The data are provided in two forms, the computer program listing in "BASIC" (below) and representative tabular values.

D.2 Psychrometric data

These psychrometric data are provided, not in the belief they are any more accurate than other systems, but rather to provide a convenient resource for all parties to the test, the use of which will ensure consistent and reproducible test evaluations.

PSYCH program v3.5	**RSB 1/30/97**
The program follows ASHRAI 1989 fundamental implementation of the psychrometric properties of moist air. It assumes ideal gas laws modified by experimental factor, Fs. The Fs table has an improved curve fit from Hyland-Wexler values by RHH (1–97). Major modifications to separate SI property functions and calculate all SI properties explicitly according to 1993 ASHRAE equations. SI formulation still uses RHH Fs fit (IP units). All other values strictly adhere to ASHRAE 1993 SI.	

DEF FNFs (t, P)

NEW IMPROVED FS Enhancement Factor 0 – 200 °F — RHH 1-19-97

C1 = 1,000119

C2 = 9,184907E-06

C3 = 1,286098E-11

C4 = −1,593274E-13

C5 = 2,872637E-04

C6 = −1,618048E-06

C7 = 1,467535E-08

C8 = 2,41896E-12

C9 = −1,371762E-10

C10 = −8,565893E-10

C11 = 1,229524E-10

C12 = −2,336628E-11

FS1# = C1 + C2 * t + C3 * t ^ 4 + C4 * t ^ 5 + C5 * P + C6 * P * t

FS1# = FS1# + C7 * P * t ^ 2 + C8 * P * t ^ 4 + C9 * t * P ^ 4

FNFs = FS1# + C10 * t ^ 2 * P ^ 2 + C11 * t ^ 2 * P ^ 3 + C12 * P ^ 2 * t ^ 3

END DEF

Function calculates IP Vapour pressure of Water Vapour (–148 °F to 392 °F)

DEF FNIPPws (tair!)

Calculate saturation pressure at t!

IF tair! ≤ 32, then

C8 = –10 440,397 08#

C9 = –11,294 649 6#

C10 = –0,027 022 355#

C11 = 0,000 012 890 36#

C12 = –0,000 000 002 478 068#

C13 = 6,545 967 3#

t = tair! + 459,67

LnPws = C8 / t + C9 + C10 * t + C11 * t * t + C12 * t * t * t + C13 * LOG(t)

FNIPPws = EXP(LnPws) ‘ASHRAE Formula (4)

ELSE

C1 = –10 214,164 62#

C2 = –4,893 503 01#

C3 = –0,005 376 579 44#

C4 = 0,000 000 192 023 769#

C5 = 3,557 583 16D-10

C6 = –9,034 468 83D-14

C7 = 4,163 501 9#

t = tair! + 459,67

LnPws = C1 / t + C2 + C3 * t + C4 * t * t + C5 * t * t * t + C6 * t * t * t * t + C7 * LOG(t)

FNIPPws = EXP(LnPws) ‘ASHRAE Formula (3)

END IF

END DEF

Function calculates SI Vapour pressure of Water Vapour (–100° to 200°)

DEF FNSIPws (tair!)

Calculate saturation pressure at t!

IF tair! > = 0 THEN

```
        C8 = −5 800,220 6#
        C9 = −5,516 256#
        C10 = −0,048 640 239#
        C11 = 0,000 041 764 768#
        C12 = −0,000 000 014 452 093#
        C13 = 6,545 967 3#
                t = tair! + 273,15
LnPws = C8 / t + C9 + C10 * t + C11 * t * t + C12 * t * t * t + C13 * LOG(t)
        FNSIPws = EXP(LnPws) 'ASHRAE Formula (4)
ELSE
        C1 = −5 674,535 9#
        C2 = −0,515 230 58#
        C3 = −0,009 677 843#
        C4 = 0,000 000 622 157 01#
        C5 = 0,000 000 002 074 782 5#
        C6 = −9,484 024 000 000 001D-13
        C7 = 4,163 501 9#
                t = tair! + 273,15
LnPws = C1 / t + C2 + C3 * t + C4 * t * t + C5 * t * t * t + C6 * t * t * t * t + C7 * LOG(t)
                FNSIPws = EXP(LnPws) 'ASHRAE Formula (3)
        END IF
END DEF
DIM UNITS$(8)
UNITS$(1) = "BTU/lbm dry air": UNITS$(2) = "kJ/kg dry air"
UNITS$(3) = "lb mix/ft^3": UNITS$(4) = "kg mix/m^3"
UNITS$(5) = "ft^3/lb dry air": UNITS$(6) = "m^3/kg dry air"
UNITS$(7) = "lb water/lb dry air": UNITS$(8) = "kg water/kg dry air"
COLOUR 15, 1, 1
main:
CLS: PRINT: PRINT
        INPUT "IP or SI Units (I or S)", UNIT$
IF UCASE$(UNIT$) = "S" THEN
        I % = 2
```

INPUT “Barometric Pressure (kPa), Wet Bulb (C), Dry Bulb (C)= “; P!, wbC, dbC

GOTO SICalc

ELSE

I % = 1

INPUT “Barometric Pressure (in Hg), Wet Bulb (F), Dry Bulb (F) “; in Hg, wbF, dbF

Psi = 14,696 * inHg / 29,921

GOTO IPCalc

END IF

Given WB and DB Calculate IP psychrometric properties routine

IPCalc:

P! = Psi: twb! = wbF: tdb! = dbF

Calculate vapour pressure and Fs factor at wb and db temperature

Pws.db = FNIPPws(tdb!)

Pws.wb = FNIPPws(twb!)

Fs.db = FNFs(tdb!, P!)

Fs.wb = FNFs(twb!, P!)

Calculate saturated humidity ratio at twb using saturation pressure (Pws) at twb,

and Fs correction factor at twb

Ws.wb = 0,621 98 x Pws.wb * Fs.wb / (P! - Pws.wb * Fs.wb) ‘ASHRAE Formula (21a)

Calculate humidity ratio of the mixture

HUMIDRATIO = ((1 093 – 0,556 * twb!) * Ws.wb – 0,24 * (tdb! - twb!)) / (1 093 + 0,444 * tdb! - twb!) ‘ASHRAE Formula (33)

IF HUMIDRATIO < 0, THEN PRINT “Humid Ratio < 0 INVALID CONDITIONS” GOTO CHOICE

Calculate saturated humidity ratio at tdb using saturation pressure(Pws) at tdb and correction factor Fs at tdb

Ws.db = 0,62198 * Pws.db * Fs.db / (P! - Pws.db * Fs.db) ‘ASHRAE Formula (21a)

Calculate degree of saturation

DegofSat = HUMIDRATIO / Ws.db ‘ASHRAE Formula (10)

Calculate relative humidity

RelHumid = DegofSat / (1 - (1 - DegofSat) * (Fs.db * Pws.db / P!)) ‘ASHRAE Formula (23a)

Calculate specific volume

Ra = 53,352 / 144 ‘ to change gas constant to psi per foot

SpVolume = Ra * (tdb! + 459,67) * (1 + 1,6078 * HUMIDRATIO) / P! ‘ASHRAE Formula (26)

Calculate density

```
        Density = (1 + HUMIDRATIO) / SpVolume
Calculate enthalpy
        Enthalpy = 0,24 * tdb! + HUMIDRATIO * (1 061 + 0,444 * tdb!) 'ASHRAE Formula (30)
GOTO PRINTVAL
```

Given WB and DB Calculate SI psychometric properties routine

SICalc:

```
        twb! = wbC: tdb! = dbC
Calculate vapour pressure and Fs factor at wb and db temperature
        Pws.db = FNSIPws(tdb!)
        Pws.wb = FNSIPws(twb!)
        tF! = tdb! * 1,8 + 32
        Ppsi! = 14,696 * P! / 101,325
        Fs.db = FNFs(tF!, Ppsi!)
        tF! = twb! * 1,8 + 32
        Fs.wb = FNFs(tF!, Ppsi!)
Calculate saturated humidity ratio at twb using saturation pressure (Pws) at twb,and Fs correction factor at twb
        Ws.wb = 0,62198 * Pws.wb * Fs.wb / (P! - Pws.wb * Fs.wb) 'ASHRAE Formula (21a)
Calculate humidity ratio of the mixture
        HUMIDRATIO = ((2 501 – 2,381 * twb!) * Ws.wb - (tdb! - twb!)) / (2 501 + 1,805 * tdb! – 4,186 * twb!) 'ASHRAE Formula (33)
IF HUMIDRATIO < 0, THEN PRINT "HumidRatio < 0 INVALID CONDITIONS": GOTO CHOICE
Calculate saturated humidity ratio at tdb using saturation pressure(Pws) at tdb and correction factor Fs at tdb
        Ws.db = 0,62198 * Pws.db * Fs.db / (P! - Pws.db * Fs.db) 'ASHRAE Formula (21a)
Calculate degree of saturation
        DegofSat = HUMIDRATIO / Ws.db 'ASHRAE Formula (10)
Calculate relative humidity
        RelHumid = DegofSat / (1 - (1 - DegofSat) * (Fs.db * Pws.db / P!)) 'ASHRAE Formula (23a)
Calculate specific volume
        Ra = 287,055 / 1 000 ' to change gas constant units convert kPa to Pa
        SpVolume = Ra * (tdb! + 273,15) * (1 + 1,6078 * HUMIDRATIO) / P! 'ASHRAE Formula (26)
Calculate density
        Density = (1 + HUMIDRATIO) / SpVolume
```

```
Calculate enthalpy
        Enthalpy = 1,006 * tdb! + HUMIDRATIO * (2 501 + 1,805 * tdb!) 'ASHRAE Formula (30)
PRINTVAL:
        PRINT: PRINT USING "Enthalpy = ####.#### &"; Enthalpy; UNITS$(I %)
        PRINT USING "Density = #.##### &"; Density; UNITS$(I % + 2)
        PRINT USING "Specific Volume = ###.#### &"; SpVolume; UNITS$(I % + 4)
        PRINT USING "Humidity Ratio = #.##### &"; HUMIDRATIO; UNITS$(I % + 6)
        PRINT USING "Relative Humidity = ###.## percent"; RelHumid * 100
CHOICE:
        PRINT: PRINT "Press any Key to Continue"
        DO
                CHOICE$ = INKEY$
                LOOP UNTIL CHOICE$ < > ""
GOTO main
```


Table D.1 — Enthalpy of saturated air — Water vapour mixtures at 101,325 kPa (sea level)

°C	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	°C
0	9,4783	9,6490	9,8203	9,9920	10,164	10,337	10,510	10,684	10,858	11,032	0
1	11,207	11,383	11,559	11,736	11,913	12,090	12,268	12,447	12,626	12,805	1
2	12,985	13,166	13,347	13,529	13,711	13,894	14,077	14,261	14,445	14,630	2
3	14,816	15,002	15,188	15,375	15,563	15,751	15,940	16,129	16,319	16,510	3
4	16,701	16,892	17,085	17,277	17,471	17,665	17,859	18,055	18,250	18,447	4
5	18,644	18,842	19,040	19,239	19,438	19,638	19,839	20,041	20,243	20,445	5
6	20,649	20,853	21,057	21,263	21,469	21,675	21,883	22,091	22,299	22,509	6
7	22,719	22,930	23,141	23,353	23,566	23,780	23,994	24,209	24,424	24,641	7
8	24,858	25,076	25,294	25,514	25,734	25,954	26,176	26,398	26,621	26,845	8
9	27,070	27,295	27,521	27,748	27,976	28,204	28,434	28,664	28,895	29,126	9
10	29,359	29,592	29,826	30,061	30,297	30,533	30,771	31,009	31,248	31,488	10
11	31,729	31,971	32,213	32,457	32,701	32,946	33,192	33,439	33,687	33,936	11
12	34,185	34,436	34,687	34,939	35,193	35,447	35,702	35,958	36,215	36,473	12
13	36,732	36,992	37,253	37,515	37,777	38,041	38,306	38,572	38,838	39,106	13
14	39,375	39,645	39,915	40,187	40,460	40,734	41,009	41,285	41,562	41,840	14
15	42,119	42,399	42,680	42,962	43,246	43,530	43,816	44,103	44,390	44,679	15
16	44,969	45,260	45,553	45,846	46,141	46,436	46,733	47,031	47,330	47,631	16
17	47,932	48,235	48,539	48,844	49,150	49,458	49,767	50,077	50,388	50,700	17
18	51,014	51,329	51,645	51,963	52,282	52,602	52,923	53,246	53,569	53,895	18
19	54,221	54,549	54,878	55,209	55,541	55,874	56,208	56,544	56,882	57,220	19
20	57,560	57,902	58,245	58,589	58,935	59,282	59,630	59,980	60,332	60,685	20
21	61,039	61,395	61,752	62,111	62,471	62,833	63,196	63,561	63,927	64,295	21

Table D.1 *(continued)*

°C	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	°C
22	64,664	65,035	65,408	65,781	66,157	66,534	66,913	67,293	67,675	68,059	22
23	68,444	68,831	69,220	69,610	70,001	70,395	70,790	71,187	71,585	71,986	23
24	72,388	72,791	73,197	73,604	74,012	74,423	74,835	75,250	75,666	76,083	24
25	76,503	76,924	77,347	77,772	78,199	78,628	79,058	79,491	79,925	80,361	25
26	80,800	81,240	81,682	82,125	82,571	83,019	83,469	83,920	84,374	84,830	26
27	85,287	85,747	86,209	86,673	87,138	87,606	88,076	88,548	89,022	89,499	27
28	89,977	90,457	90,940	91,425	91,912	92,401	92,892	93,385	93,881	94,379	28
29	94,879	95,381	95,886	96,392	96,902	97,413	97,927	98,443	98,961	99,482	29
30	100,01	100,53	101,06	101,59	102,12	102,66	103,19	103,73	104,28	104,82	30
31	105,37	105,92	106,47	107,02	107,58	108,14	108,70	109,27	109,84	110,41	31
32	110,98	111,55	112,13	112,71	113,30	113,88	114,47	115,06	115,66	116,25	32
33	116,85	117,46	118,06	118,67	119,28	119,89	120,51	121,13	121,75	122,38	33
34	123,01	123,64	124,27	124,91	125,55	126,19	126,84	127,49	128,14	128,79	34
35	129,45	130,11	130,78	131,44	132,12	132,79	133,47	134,15	134,83	135,52	35
36	136,21	136,90	137,60	138,29	139,00	139,70	140,41	141,13	141,84	142,56	36
37	143,29	144,01	144,74	145,48	146,21	146,95	147,70	148,45	149,20	149,95	37
38	150,71	151,47	152,24	153,01	153,78	154,56	155,34	156,13	156,91	157,71	38
39	158,50	159,30	160,11	160,91	161,72	162,54	163,36	164,18	165,01	165,84	39
40	166,68	167,52	168,36	169,21	170,06	170,92	171,78	172,64	173,51	174,38	40
41	175,26	176,14	177,03	177,92	178,81	179,71	180,62	181,52	182,44	183,35	41
42	184,27	185,20	186,13	187,07	188,01	188,95	189,90	190,85	191,81	192,78	42
43	193,74	194,72	195,70	196,68	197,67	198,66	199,66	200,66	201,67	202,68	43
44	203,70	204,72	205,75	206,78	207,82	208,87	209,91	210,97	212,03	213,09	44
45	214,16	215,24	216,32	217,41	218,50	219,60	220,70	221,81	222,93	224,05	45
46	225,18	226,31	227,45	228,59	229,74	230,89	232,06	233,22	234,40	235,58	46
47	236,76	237,95	239,15	240,36	241,57	242,78	244,01	245,24	246,47	247,71	47
48	248,96	250,22	251,48	252,75	254,02	255,30	256,59	257,89	259,19	260,50	48
49	261,81	263,14	264,47	265,80	267,14	268,50	269,85	271,22	272,59	273,97	49
50	275,36	276,75	278,15	279,56	280,98	282,40	283,83	285,27	286,72	288,18	50
51	289,64	291,11	292,59	294,07	295,57	297,07	298,58	300,10	301,63	303,16	51
52	304,71	306,26	307,82	309,39	310,97	312,55	314,15	315,75	317,36	318,99	52
53	320,62	322,25	323,90	325,56	327,23	328,90	330,59	332,28	333,98	335,70	53
54	337,42	339,15	340,89	342,64	344,41	346,18	347,96	349,75	351,55	353,36	54
55	355,18	357,01	358,86	360,71	362,57	364,44	366,33	368,22	370,13	372,04	55
56	373,97	375,91	377,86	379,82	381,79	383,77	385,77	387,77	389,79	391,82	56
57	393,86	395,91	397,98	400,05	402,14	404,24	406,36	408,48	410,62	412,77	57
58	414,93	417,11	419,29	421,49	423,71	425,94	428,18	430,43	432,70	434,98	58
59	437,27	439,58	441,90	444,23	446,58	448,95	451,32	453,72	456,12	458,54	59
60	460,98	463,43	465,89	468,37	470,87	473,38	475,90	478,44	481,00	483,57	60
61	486,16	488,76	491,38	494,02	496,67	499,34	502,02	504,72	507,44	510,18	61
62	512,93	515,70	518,49	521,29	524,12	526,96	529,81	532,69	535,58	538,50	62

Table D.1 *(continued)*

°C	0,0	0,1	0,2	0,3	0,4	0,5	0,6	0,7	0,8	0,9	°C
63	541,43	544,38	547,35	550,34	553,34	556,37	559,41	562,48	565,57	568,67	63
64	571,80	574,94	578,11	581,30	584,50	587,73	590,98	594,25	597,54	600,86	64
65	604,20	607,55	610,93	614,34	617,76	621,21	624,68	628,18	631,70	635,24	65
66	638,81	642,40	646,01	649,65	653,32	657,01	660,72	664,46	668,23	672,02	66
67	675,84	679,68	683,55	687,45	691,37	695,33	699,31	703,31	707,35	711,41	67
68	715,51	719,63	723,78	727,96	732,17	736,41	740,69	744,99	749,32	753,69	68
69	758,08	762,51	766,97	771,46	775,99	780,55	785,14	789,76	794,43	799,12	69
70	803,85	808,61	813,41	818,25	823,12	828,03	832,98	837,96	842,99	848,04	70

Table D.2 — Properties of saturated air-water vapour mixtures at 101,325 kPa (sea level)

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
0	9,478 3	1,289 3	0,778 55	0,003 79	0	—	—	—	—	—	—
1	11,207	1,284 4	0,781 76	0,004 08	1	36	136,21	1,116 332	0,930 697 9	0,038 967 5	36
2	12,985	1,279 5	0,784 99	0,004 38	2	37	143,29	1,111 305	0,937 011 8	0,041 305 8	37
3	14,816	1,274 6	0,788 26	0,004 71	3	38	150,71	1,106 242	0,943 532 6	0,043 775 1	38
4	16,701	1,269 7	0,791 55	0,005 05	4	39	158,50	1,101 140	0,950 272 4	0,046 382 6	39
5	18,644	1,264 9	0,794 87	0,005 42	5	40	166,68	1,095 996	0,957 244 4	0,049 136 2	40
6	20,649	1,260 1	0,798 23	0,005 82	6	41	175,26	1,090 809	0,964 462 3	0,052 044 2	41
7	22,719	1,255 2	0,801 63	0,006 24	7	42	184,27	1,085 575	0,971 941 1	0,055 115 5	42
8	24,858	1,250 4	0,805 06	0,006 68	8	43	193,74	1,080 293	0,979 696 6	0,058 359 4	43
9	27,070	1,245 7	0,808 53	0,007 16	9	44	203,70	1,074 959	0,987 745 8	0,061 786 2	44
10	29,359	1,240 9	0,812 05	0,007 66	10	45	214,16	1,069 571	0,996 106 9	0,065 406 7	45
11	31,729	1,236 1	0,815 61	0,008 20	11	46	225,18	1,064 125	1,004 799	0,069 232 5	46
12	34,185	1,231 4	0,819 22	0,008 77	12	47	236,76	1,05 862	1,013 844	0,073 276 1	47
13	36,732	1,226 6	0,822 88	0,009 37	13	48	248,96	1,053 052	1,023 264	0,077 550 9	48
14	39,375	1,221 9	0,826 59	0,010 01	14	49	261,81	1,047 419	1,033 084	0,082 071 2	49
15	42,119	1,217 2	0,830 37	0,010 69	15	50	275,36	1,041 717	1,043 328	0,086 852 8	50
16	44,969	1,212 4	0,834 20	0,011 41	16	51	289,64	1,035 943	1,054 027	0,091 912 1	51
17	47,932	1,207 7	0,838 09	0,012 18	17	52	304,71	1,030 095	1,065 21	0,097 267 7	52
18	51,014	1,203 0	0,842 06	0,012 99	18	53	320,62	1,024 168	1,076 912	0,102 938 9	53
19	54,221	1,198 3	0,846 09	0,013 85	19	54	337,42	1,018 161	1,089 167	0,108 947 2	54
20	57,560	1,193 5	0,850 20	0,014 76	20	55	355,18	1,012 069	1,102 015	0,115 315 7	55
21	61,039	1,188 8	0,854 39	0,015 72	21	56	373,97	1,00 589	1,115 499	0,122 069 8	56
22	64,664	1,184 1	0,858 67	0,016 74	22	57	393,86	0,999 619 8	1,129 667	0,129 237 1	57
23	68,444	1,179 4	0,863 03	0,017 82	23	58	414,93	0,993 255 1	1,144 568	0,136 847 6	58
24	72,388	1,174 6	0,867 49	0,018 96	24	59	437,27	0,986 792 4	1,160 259	0,144 934 5	59
25	76,503	1,169 8	0,872 05	0,020 17	25	60	460,98	0,980 2282	1,176 802	0,153 534 1	60
26	80,800	1,165 1	0,876 72	0,021 45	26	61	486,16	0,973 5589	1,194 264	0,162 686 4	61
27	85,287	1,160 3	0,881 50	0,022 80	27	62	512,93	0,966 7809	1,212 721	0,172 435 7	62
28	89,977	1,155 5	0,886 39	0,024 22	28	63	541,43	0,959 8905	1,232 256	0,182 830 9	63
29	94,879	1,150 7	0,891 41	0,025 73	29	64	571,80	0,952 884	1,252 961	0,193 926 3	64
30	100,01	1,145 9	0,896 56	0,027 33	30	65	604,20	0,945 757 3	1,274 938	0,205 782 3	65
31	105,37	1,141 0	0,901 85	0,029 01	31	66	638,81	0,938 506 8	1,298 303	0,218 466 7	66

Table D.2 *(continued)*

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
32	110,98	1,136 1	0,907 29	0,030 79	32	67	675,84	0,931 128 4	1,323 185	0,232 055	67
33	116,85	1,131 2	0,912 89	0,032 67	33	68	715,51	0,923 618 3	1,349 727	0,246 632 6	68
34	123,01	1,126 3	0,918 65	0,034 66	34	69	758,08	0,915 972 4	1,378 093	0,262 295 2	69
35	129,45	1,121 3	0,924 58	0,036 75	35	70	803,85	0,908 18	1,408 46	0,279 15	70

Table D.3 — Properties of saturated air-water vapour mixtures at 98,00 kPa

°C	Enthalpy	Density	Sp Vol	→HR	°C	°C	Enthalpy	Density	Sp Vol	→HR	°C
0	9,800 8	1,246 9	0,805 13	0,003 92	0	—	—	—	—	—	—
1	11,555	1,242 1	0,808 46	0,004 21	1	36	139,81	1,078 866	0,964 319 1	0,040 371 3	36
2	13,359	1,237 4	0,811 82	0,004 53	2	37	147,12	1,073 96	0,970 984 9	0,042 799 4	37
3	15,218	1,232 6	0,815 21	0,004 87	3	38	154,80	1,069 017	0,977 873 7	0,045 364 1	38
4	17,133	1,227 9	0,818 63	0,005 23	4	39	162,85	1,064 035	0,984 998 9	0,048 073 1	39
5	19,108	1,223 2	0,822 09	0,005 61	5	40	171,31	1,059 01	0,992 374 7	0,050 934 7	40
6	21,148	1,218 6	0,825 58	0,006 02	6	41	180,19	1,053 941	1,000 016	0,053 957 7	41
7	23,255	1,213 9	0,829 11	0,006 45	7	42	189,52	1,048 824	1,007 94	0,057 151 5	42
8	25,433	1,209 2	0,832 68	0,006 91	8	43	199,33	1,043 658	1,016 162	0,060 526	43
9	27,686	1,204 6	0,836 29	0,007 40	9	44	209,65	1,038 44	1,024 703	0,064 0921	44
10	30,020	1,200 0	0,839 95	0,007 92	10	45	220,50	1,033 167	1,033 581	0,067 861 1	45
11	32,437	1,195 4	0,843 66	0,008 48	11	46	231,93	1,027 835	1,042 818	0,071 845 5	46
12	34,944	1,190 8	0,847 42	0,009 07	12	47	243,96	1,022 444	1,052 438	0,076 058 5	47
13	37,545	1,186 2	0,851 23	0,009 69	13	48	256,63	1,016 989	1,062 464	0,080 514 3	48
14	40,244	1,181 6	0,855 10	0,010 36	14	49	269,99	1,011 468	1,072 924	0,085 228 4	49
15	43,049	1,177 0	0,859 04	0,011 06	15	50	284,08	1,005 877	1,083 848	0,090 217 4	50
16	45,964	1,172 4	0,863 04	0,011 81	16	51	298,94	1,000 214	1,095 265	0,095 499 2	51
17	48,996	1,167 8	0,867 10	0,012 60	17	52	314,63	0,994 476	1,107 209	0,101 093 2	52
18	52,151	1,163 2	0,871 24	0,013 44	18	53	331,21	0,988 659 3	1,119 719	0,107 020 6	53
19	55,436	1,158 6	0,875 46	0,014 33	19	54	348,74	0,982 760 7	1,132 833	0,113 304 2	54
20	58,858	1,154 0	0,879 75	0,015 27	20	55	367,28	0,976 777 3	1,146 596	0,119 969 2	55
21	62,424	1,149 4	0,884 14	0,016 27	21	56	386,91	0,970 705 6	1,161 055	0,127 042 6	56
22	66,143	1,144 8	0,888 61	0,017 32	22	57	407,71	0,964 542 2	1,176 262	0,134 554 4	57
23	70,022	1,140 2	0,893 18	0,018 44	23	58	429,76	0,958 283 8	1,192 274	0,142 537 1	58
24	74,071	1,135 6	0,897 85	0,019 62	24	59	453,16	0,951 926 9	1,209 155	0,151 026 9	59
25	78,298	1,131 0	0,902 63	0,020 87	25	60	478,01	0,945 467 9	1,226 972	0,160 063	60
26	82,714	1,126 4	0,907 52	0,022 20	26	61	504,44	0,938 903 3	1,245 804	0,169 689 3	61
27	87,328	1,121 7	0,912 53	0,023 60	27	62	532,58	0,932 229 3	1,265 734	0,179 953 9	62
28	92,152	1,117 0	0,917 67	0,025 08	28	63	562,55	0,925 442 3	1,286 856	0,190 910 6	63
29	97,197	1,112 4	0,922 95	0,026 64	29	64	594,54	0,918 538 6	1,309 274	0,202 619	64
30	102,47	1,107 6	0,928 36	0,028 29	30	65	628,71	0,911 514 4	1,333 107	0,215 145 8	65
31	108,00	1,102 9	0,933 93	0,030 04	31	66	665,27	0,904 365 7	1,358 483	0,228 565 6	66
32	113,78	1,098 2	0,939 65	0,031 89	32	67	704,43	0,897 088 6	1,385 551	0,242 962 4	67
33	119,84	1,093 4	0,945 54	0,033 84	33	68	746,46	0,889 679 3	1,414 477	0,258 431 1	68

Table D.3 *(continued)*

°C	Enthalpy	Density	Sp Vol	→HR	°C	°C	Enthalpy	Density	Sp Vol	→HR	°C
34	126,18	1,088 6	0,951 61	0,035 90	34	69	791,65	0,882 133 7	1,445 448	0,275 078 7	69
35	132,83	1,083 7	0,957 86	0,038 07	35	70	840,30	0,874 44	1,478 67	0,293 02	70

Table D.4 — Properties of saturated air - Water vapour mixtures at 94,00 kPa

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
0	10,219	1,195 9	0,839 62	0,004 09	0	—	—	—	—	—	—
1	12,005	1,191 3	0,843 11	0,004 39	1	36	144,50	1,033 795	1,008 131	0,042 208	36
2	13,844	1,186 7	0,846 63	0,004 72	2	37	152,12	1,029 035	1,015 268	0,044 753	37
3	15,739	1,182 2	0,850 18	0,005 08	3	38	160,12	1,024 236	1,022 651	0,047 446	38
4	17,694	1,177 7	0,853 77	0,005 45	4	39	168,52	1,019 397	1,030 293	0,050 282	39
5	19,711	1,173 1	0,857 40	0,005 85	5	40	177,34	1,014 515	1,038 212	0,053 285	40
6	21,795	1,168 6	0,861 06	0,006 27	6	41	186,62	1,009 588	1,046 423	0,056 465	41
7	23,950	1,164 2	0,864 77	0,006 73	7	42	196,37	1,004 612	1,054 945	0,059 812	42
8	26,179	1,159 7	0,868 52	0,007 21	8	43	206,63	0,999 586 2	1,063 797	0,063 364	43
9	28,486	1,155 2	0,872 32	0,007 72	9	44	217,42	0,994 507 1	1,072 999	0,067 116	44
10	30,878	1,150 8	0,876 17	0,008 26	10	45	228,79	0,989 372 1	1,082 576	0,071 072	45
11	33,357	1,146 3	0,880 07	0,008 84	11	46	240,76	0,984 178 5	1,092 549	0,075 265	46
12	35,929	1,141 9	0,884 02	0,009 46	12	47	253,37	0,978 923 4	1,102 946	0,079 70	47
13	38,599	1,137 5	0,888 04	0,010 11	13	48	266,67	0,973 604 3	1,113 794	0,084 399	48
14	41,373	1,133 0	0,892 12	0,010 80	14	49	280,70	0,968 217 9	1,125 124	0,089 371	49
15	44,257	1,128 6	0,896 27	0,011 54	15	50	295,51	0,962 761 5	1,136 968	0,094 635	50
16	47,256	1,124 2	0,900 49	0,012 32	16	51	311,14	0,957 231 9	1,149 361	0,100 208	51
17	50,378	1,119 8	0,904 78	0,013 14	17	52	327,67	0,951 626 3	1,162 342	0,106 121	52
18	53,628	1,115 4	0,909 15	0,014 02	18	53	345,14	0,945 941 3	1,175 953	0,112 386	53
19	57,014	1,110 9	0,913 60	0,014 95	19	54	363,63	0,940 173 7	1,190 24	0,119 033	54
20	60,543	1,106 5	0,918 15	0,015 93	20	55	383,20	0,934 320 6	1,205 252	0,126 097	55
21	64,224	1,102 1	0,922 78	0,016 98	21	56	403,95	0,928 378 3	1,221 044	0,133 599	56
22	68,064	1,097 6	0,927 52	0,018 08	22	57	425,96	0,922 343 7	1,237 676	0,141 567	57
23	72,073	1,093 2	0,932 36	0,019 25	23	58	449,31	0,916 213 2	1,255 214	0,150 044	58
24	76,259	1,088 7	0,937 31	0,020 48	24	59	474,14	0,909 983 6	1,273 729	0,159 078	59
25	80,632	1,084 3	0,942 38	0,021 79	25	60	500,54	0,903 651 1	1,293 303	0,168 698	60
26	85,203	1,079 8	0,947 58	0,023 17	26	61	528,64	0,897 212 3	1,314 024	0,178 963	61
27	89,982	1,075 3	0,952 90	0,024 64	27	62	558,61	0,890 663 6	1,335 99	0,189 923	62
28	94,981	1,070 8	0,958 36	0,026 19	28	63	590,59	0,884 001 1	1,359 311	0,201 632	63
29	100,21	1,066 2	0,963 97	0,027 82	29	64	624,77	0,877 221 2	1,384 11	0,214 174	64
30	105,69	1,061 7	0,969 74	0,029 55	30	65	661,34	0,870 320 1	1,410 524	0,227 611	65
31	111,42	1,057 1	0,975 67	0,031 38	31	66	700,54	0,863 293 9	1,438 707	0,242 034	66
32	117,43	1,052 5	0,981 77	0,033 31	32	67	742,62	0,856 138 9	1,468 835	0,257 532	67
33	123,72	1,047 9	0,988 06	0,035 35	33	68	787,88	0,848 850 9	1,501 106	0,274 225	68
34	130,32	1,043 2	0,994 54	0,037 51	34	69	836,64	0,841 426 1	1,535 743	0,292 214	69
35	137,24	1,038 5	1,001 2	0,039 79	35	70	889,28	0,833 86	1,573	0,311 67	70

Table D.5 — Properties of saturated air - Water vapour mixtures at 90,00 kPa

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
0	10,675	1,144 9	0,877 19	0,004 27	0	—	—	—	—	—	—
1	12,496	1,140 5	0,880 86	0,004 59	1	36	149,64	0,988 724	1,056 113	0,044 204 5	36
2	14,373	1,136 1	0,884 55	0,004 94	2	37	157,60	0,984 109 2	1,063 784	0,0468 79 5	37
3	16,308	1,131 7	0,888 29	0,005 30	3	38	165,95	0,979 455 2	1,071 725	0,049 707	38
4	18,305	1,127 4	0,892 06	0,005 69	4	39	174,74	0,974 759 7	1,079 954	0,052 695 9	39
5	20,368	1,123 0	0,895 88	0,006 11	5	40	183,97	0,970 020 4	1,088 488	0,055 855 7	40
6	22,501	1,118 7	0,899 73	0,006 55	6	41	193,68	0,965 234 7	1,097 346	0,059 196 5	41
7	24,707	1,114 4	0,903 63	0,007 03	7	42	203,89	0,960 400 1	1,106 548	0,062 729 1	42
8	26,992	1,110 1	0,907 59	0,007 53	8	43	214,65	0,955 514 2	1,116 117	0,066 465 3	43
9	29,359	1,105 8	0,911 59	0,008 07	9	44	225,97	0,950 574 2	1,126 074	0,070 417 3	44
10	31,813	1,101 6	0,915 65	0,008 64	10	45	237,90	0,945 577 5	1,136 447	0,074 598 8	45
11	34,359	1,097 3	0,919 76	0,009 24	11	46	250,48	0,940 521 4	1,147 262	0,079 024	46
12	37,003	1,093 0	0,923 94	0,009 88	12	47	263,74	0,935 402 9	1,158 548	0,083 708 7	47
13	39,749	1,088 8	0,928 18	0,010 57	13	48	277,73	0,930 219 5	1,170 336	0,088 669 6	48
14	42,605	1,084 5	0,932 49	0,011 29	14	49	292,51	0,924 968 1	1,182 662	0,093 924 9	49
15	45,575	1,080 3	0,936 87	0,012 06	15	50	308,12	0,919 645 8	1,195 563	0,099 494 4	50
16	48,666	1,076 0	0,941 33	0,012 87	16	51	324,61	0,914 249 6	1,209 078	0,105 399 5	51
17	51,885	1,071 7	0,945 88	0,013 74	17	52	342,06	0,908 776 5	1,223 253	0,111 663 4	52
18	55,239	1,067 5	0,950 51	0,014 66	18	53	360,53	0,903 223 3	1,238 134	0,118 311 7	53
19	58,736	1,063 2	0,955 23	0,015 63	19	54	380,10	0,897 586 8	1,253 775	0,125 371 8	54
20	62,383	1,059 0	0,960 04	0,016 66	20	55	400,84	0,891 863 8	1,270 233	0,132 874 4	55
21	66,189	1,054 7	0,964 96	0,017 75	21	56	422,85	0,886 051	1,287 57	0,140 852 6	56
22	70,162	1,050 4	0,969 99	0,018 90	22	57	446,21	0,880 145 1	1,305 856	0,149 343	57
23	74,312	1,046 1	0,975 14	0,020 13	23	58	471,05	0,874 142 8	1,325 168	0,158 385 9	58
24	78,648	1,041 8	0,980 40	0,021 42	24	59	497,48	0,868 040 3	1,345 59	0,168 026	59
25	83,181	1,037 5	0,985 80	0,022 79	25	60	525,63	0,861 834 5	1,367 214	0,178 312 6	60
26	87,922	1,033 2	0,991 33	0,024 24	26	61	555,65	0,855 521 6	1,390 147	0,189 300 5	61
27	92,882	1,028 9	0,997 00	0,025 78	27	62	587,70	0,849 098	1,414 502	0,201 050 9	62
28	98,073	1,024 5	1,002 8	0,027 40	28	63	621,97	0,842 560 1	1,440 41	0,213 632 1	63
29	103,51	1,020 1	1,008 8	0,029 11	29	64	658,65	0,835 904 1	1,468 016	0,227 120 9	64
30	109,20	1,015 7	1,015 0	0,030 93	30	65	697,99	0,829 126 4	1,497 484	0,241 603 3	65
31	115,17	1,011 3	1,021 3	0,032 84	31	66	740,23	0,822 222 9	1,528 998	0,257 177	66
32	121,42	1,006 8	1,027 8	0,034 87	32	67	785,69	0,815 189 8	1,562 768	0,273 952 4	67
33	127,98	1,002 4	1,034 6	0,037 01	33	68	834,69	0,808 023 3	1,599 033	0,292 055 5	68
34	134,85	0,9978 5	1,041 5	0,039 28	34	69	887,61	0,800 719 3	1,638 065	0,311 630 2	69
35	142,07	0,993 30	1,048 7	0,041 67	35	70	944,91	0,793 27	1,680 17	0,332 84	70

Table D.6 — Properties of saturated air - Water vapour mixtures at 86,00 kPa

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
0	11,174	1,093 9	0,918 28	0,004 47	0	—	—	—	—	—	—
1	13,033	1,089 6	0,922 14	0,004 81	1	36	155,30	0,943 652 8	1,108 891	0,0464 086	36
2	14,950	1,085 4	0,926 04	0,005 17	2	37	163,63	0,939 183 4	1,117 169	0,0492 268	37
3	16,929	1,081 3	0,929 97	0,005 55	3	38	172,38	0,934 674	1,125 748	0,0522 07	38

Table D.6 *(continued)*

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
4	18,974	1,077 1	0,933 95	0,005 96	4	39	181,58	0,930 122 1	1,134 645	0,0553 586	39
5	21,087	1,073 0	0,937 97	0,006 40	5	40	191,27	0,925 525 5	1,143 882	0,0586 92	40
6	23,273	1,068 8	0,942 04	0,006 86	6	41	201,46	0,920 881 7	1,153 479	0,0622 18	41
7	25,536	1,064 7	0,946 16	0,007 36	7	42	212,19	0,916 188	1,163 46	0,0659 484	42
8	27,881	1,060 6	0,950 33	0,007 88	8	43	223,49	0,911 442 1	1,173 849	0,069 895 8	43
9	30,313	1,056 4	0,954 56	0,008 45	9	44	235,41	0,906 641 3	1,184 673	0,074 073 8	44
10	32,836	1,052 3	0,958 85	0,009 04	10	45	247,97	0,901 782 8	1,195 961	0,078 497	45
11	35,456	1,048 2	0,963 20	0,009 68	11	46	261,22	0,896 864 2	1,207 743	0,083 181 1	46
12	38,178	1,044 2	0,967 62	0,010 35	12	47	275,21	0,891 882 4	1,220 052	0,088 143 1	47
13	41,008	1,040 1	0,972 12	0,011 06	13	48	289,98	0,886 834 7	1,232 926	0,093 401 5	48
14	43,953	1,036 0	0,976 68	0,011 82	14	49	305,59	0,881 718 3	1,246 403	0,0989 763	49
15	47,017	1,031 9	0,981 33	0,012 63	15	50	322,09	0,876 530 2	1,260 526	0,104 889 1	50
16	50,209	1,027 8	0,986 06	0,013 48	16	51	339,56	0,871 267 4	1,275 342	0,111 163 5	51
17	53,536	1,023 7	0,990 89	0,014 39	17	52	358,05	0,865 926 8	1,290 9	0,117 825 3	52
18	57,004	1,019 6	0,995 80	0,015 35	18	53	377,65	0,860 505 4	1,307 258	0,124 902 6	53
19	60,622	1,015 5	1,000 8	0,016 37	19	54	398,43	0,854 999 9	1,324 475	0,132 426 1	54
20	64,398	1,011 4	1,005 9	0,017 45	20	55	420,49	0,849 407 1	1,342 619	0,140 429 8	55
21	68,341	1,007 3	1,011 2	0,018 60	21	56	443,92	0,843 723 9	1,361 761	0,148 950 7	56
22	72,461	1,003 2	1,016 5	0,019 81	22	57	468,83	0,837 946 8	1,381 985	0,158 029 8	57
23	76,766	0,999 09	1,022 0	0,021 09	23	58	495,35	0,832 072 5	1,403 378	0,167 712 5	58
24	81,268	0,994 95	1,027 6	0,022 45	24	59	523,62	0,826 097 4	1,426 041	0,178 049 1	59
25	85,977	0,990 79	1,033 4	0,023 89	25	60	553,77	0,820 018 2	1,450 084	0,189 095 3	60
26	90,905	0,986 62	1,039 3	0,025 41	26	61	585,97	0,813 831 2	1,475 63	0,200 913 4	61
27	96,063	0,982 44	1,045 4	0,027 02	27	62	620,42	0,807 533	1,502 816	0,213 573 2	62
28	101,47	0,978 23	1,051 6	0,028 73	28	63	657,32	0,801 119 7	1,531 797	0,227153	63
29	107,13	0,974 00	1,058 0	0,030 53	29	64	696,90	0,794 587 7	1,562 748	0,241 740 7	64
30	113,06	0,969 75	1,064 6	0,032 44	30	65	739,44	0,787 933 3	1,595 866	0,257 436 1	65
31	119,28	0,965 48	1,071 4	0,034 45	31	66	785,23	0,781 152 5	1,631 374	0,274 352 3	66
32	125,80	0,961 17	1,078 5	0,036 58	32	67	834,63	0,774 241 6	1,669 528	0,292 618 3	67
33	132,65	0,956 84	1,085 7	0,038 84	33	68	888,02	0,767 196 6	1,710 62	0,312 381 9	68
34	139,83	0,952 48	1,0932	0,041 22	34	69	945,85	0,760 013 7	1,754 985	0,333 813	69
35	147,38	0,948 08	1,100 9	0,043 74	35	70	1 008,67	0,752 68	1,803 01	0,357 1	70

Table D.7 — Properties of saturated air - Water vapour mixtures at 82,00 kPa

°C	Enthalpy	Density	Sp Vol	HR	°C	°C	Enthalpy	Density	Sp Vol	HR	°C
0	11,721	1,042 8	0,963 41	0,004 69	0	—	—	—	—	—	—
1	13,623	1,038 8	0,967 49	0,005 04	1	36	161,55	0,898 581 6	1,167 222	0,048 844 5	36
2	15,585	1,034 8	0,971 60	0,005 42	2	37	170,29	0,894 257 7	1,1761 96	0,051 822 2	37
3	17,612	1,030 8	0,975 76	0,005 82	3	38	179,48	0,889 892 8	1,1855 05	0,054 972 4	38
4	19,708	1,026 8	0,979 97	0,006 25	4	39	189,16	0,885 484 5	1,1951 71	0,058 305 4	39
5	21,876	1,022 9	0,984 22	0,006 71	5	40	199,35	0,881 030 6	1,205 216	0,061 832 4	40
6	24,121	1,018 9	0,988 52	0,007 20	6	41	210,08	0,876 528 6	1,215 665	0,065 565 3	41
7	26,447	1,014 9	0,992 89	0,007 72	7	42	221,38	0,871 975 9	1,226 544	0,069 516 8	42
8	28,859	1,011 0	0,997 31	0,008 27	8	43	233,30	0,867 37	1,237 881	0,073 700 7	43
9	31,362	1,007 1	1,001 8	0,008 86	9	44	245,88	0,862 708 3	1,249 706	0,078 131 8	44
10	33,961	1,003 1	1,006 3	0,009 49	10	45	259,15	0,857 988 2	1,262 052	0,082 826	45
11	36,662	0,999 21	1,011 0	0,010 15	11	46	273,16	0,853 207	1,274 955	0,087 800 8	46
12	39,471	0,995 29	1,015 6	0,010 86	12	47	287,96	0,848 361 8	1,288 453	0,093 074 7	47
13	42,393	0,991 37	1,020 4	0,011 61	13	48	303,61	0,843 450 1	1,302 588	0,098 668 1	48
14	45,435	0,987 45	1,025 3	0,012 41	14	49	320,16	0,838 468 7	1,317 405	0,104 603	49
15	48,604	0,983 54	1,030 2	0,013 26	15	50	337,68	0,833 414 7	1,332 954	0,110 903 4	50
16	51,907	0,9796 2	1,035 3	0,014 16	16	51	356,24	0,828 285 2	1,349 288	0,117 595 6	51
17	55,351	0,975 70	1,040 4	0,015 11	17	52	375,91	0,823 077 3	1,366 467	0,124 708 2	52
18	58,945	0,971 77	1,045 6	0,016 12	18	53	396,79	0,817 787 6	1,384 556	0,132 272 5	53
19	62,697	0,967 84	1,051 0	0,017 19	19	54	418,95	0,812 413 2	1,403 624	0,140 323	54
20	66,616	0,963 91	1,056 5	0,018 33	20	55	442,50	0,806 950 7	1,423 752	0,148 897 7	55
21	70,711	0,959 96	1,062 1	0,019 53	21	56	467,56	0,801 397	1,445 024	0,158 038 3	56
22	74,992	0,956 00	1,067 8	0,020 81	22	57	494,25	0,795 748 8	1,467 538	0,167 791 3	57
23	79,469	0,952 04	1,073 7	0,022 16	23	58	522,70	0,790 002 5	1,491 398	0,178 208	58
24	84,153	0,948 05	1,079 7	0,023 59	24	59	553,07	0,784 154 9	1,516 723	0,189 345 6	59
25	89,056	0,944 06	1,085 8	0,025 10	25	60	585,53	0,778 202 4	1,543 645	0,201 267 8	60
26	94,190	0,940 04	1,092 2	0,026 70	26	61	620,26	0,772 141 5	1,572 311	0,214 046 3	61
27	99,569	0,936 01	1,098 7	0,028 40	27	62	657,49	0,765 968 6	1,602 887	0,227 761 2	62
28	105,21	0,931 96	1,105 4	0,030 19	28	63	697,45	0,759 68	1,635 561	0,242 503 1	63
29	111,12	0,927 89	1,112 3	0,032 09	29	64	740,43	0,753 272 1	1,670 545	0,258 374 6	64
30	117,31	0,923 79	1,119 4	0,034 10	30	65	786,72	0,746 741 1	1,708 078	0,275 492 1	65
31	123,82	0,919 66	1,126 7	0,036 23	31	66	836,68	0,740 083 2	1,748 437	0,293 988 6	66
32	130,64	0,915 51	1,134 3	0,038 47	32	67	890,73	0,733 294 5	1,791 936	0,314 016 8	67
33	137,80	0,911 33	1,142 1	0,040 85	33	68	949,34	0,726 371 2	1,838 939	0,335 752 5	68
34	145,33	0,907 12	1,150 2	0,043 37	34	69	1 013,03	0,719 309 4	1,889 867	0,359 399	69
35	153,24	0,902 87	1,158 6	0,046 03	35	70	1 082,46	0,712 1	1,945 21	0,385 19	70

Annex E
(informative)

Values of crossflow correction factor

This procedure is applicable to extended thermal performance test evaluations (see 9.4).

— For counterflow devices, $\gamma = 1$.

— For crossflow devices, the value of γ is given by Table E.1 as a function of two coefficients μ and ν calculated from the initial condition and final condition of the two fluids.

Table E.1 — Correction factor γ for wet crossflow cooling towers

ν	μ									
	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

NOTE 1 The table gives μ as a function of γ and ν. The values of the parameters μ and ν are respectively:

$$\mu = \frac{h_2 - h_1}{h_{S1} - h_1} \text{ and } \nu = \frac{h_{S1} - h_{S2}}{h_2 - h_1}$$

where

h_2 is the enthalpy of hot air;

h_1 is the enthalpy of cold air;

h_{s1} is the enthalpy of air at hot water temperature;

h_{s2} is the enthalpy of air at cold water temperature.

NOTE 2 The air is assumed to be saturated.

Table E.1 *(continued)*

ν	μ									
	0,500	**0,550**	**0,600**	**0,650**	**0,700**	**0,750**	**0,800**	**0,850**	**0,900**	**0,950**
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 1 The table gives μ as a function of γ and ν. The values of the parameters μ and ν are respectively:

$$\mu = \frac{h_2 - h_1}{h_{S1} - h_1} \text{ and } \nu = \frac{h_{S1} - h_{S2}}{h_2 - h_1}$$

where

h_2 is the enthalpy of hot air;

h_1 is the enthalpy of cold air;

h_{s1} is the enthalpy of air at hot water temperature;

h_{s2} is the enthalpy of air at cold water temperature.

NOTE 2 The air is assumed to be saturated.

Annex F
(informative)

Example evaluation of an open-circuit, mechanical draft cooling tower test using the performance curve method

F.1 General

Annex F is given to describe and illustrate the performance curve methodology for evaluating a thermal performance test on an open-circuit, mechanical draft cooling tower, as described in 9.3.3 of this International Standard.

F.2 Design and test values

The design and measured test values for the open-circuit, mechanical draft cooling tower are summarized in Table F.1.

Table F.1 — Cooling tower design and design measured

Parameter	Values	Test values
Water flow rate (Q_w)	3 583 L/s	3 623 L/s
Hot water temp. (T_{hw})	49,40 °C	46,50 °C
Cold water temp. (T_{cw})	30,60 °C	29,04 °C
Cooling range (R)	18,80 °C	17,46 °C
Inlet wet-bulb temp. (T_{wb})	26,00 °C	24,53 °C
Inlet dry-bulb temp. (T_{db})	30,20 °C	25,52 °C
Fan driver power (W)	107,00 kW	113,00 k
Barometric pressure (P_{bp})	101,325 kPa	W
Liquid to gas ratio (L/G)	1,300	98,80 kPa

In accordance with 5.3.2, the manufacturer has submitted performance curves with cold water presented as a function of wet-bulb temperature range and water flow rate as parameters (see Figure F.1, Figure F.2, and Figure F.3).

F.3 Evaluation by flow rate capability

F.3.1 Evaluation test steps

The steps to be followed in evaluating the test in terms of flow rate capability are as follows.

F.3.1.1 Step 1: Determine the predicted cold water temperatures

Subscribe the submitted performance curves vertically at the test wet-bulb temperature (24,53 °C) to determine the predicted cold water temperatures associated with the test wet bulb at each of the three range and three flow rate conditions included on the performance curves.

Values of these predicted cold water temperatures are tabulated in Table F.2.

Table F.2 — Curve points for cold-water temperature versus range at 24,53 °C test wet bulb

Range	90 % flow	100 % flow	110 % flow
17,0 °C	28,64	29,43	30,24
18,8 °C	28,86	29,65	30,50
21,0 °C	29,09	29,88	30,76

F.3.1.2 Step 2: First crossplot

Create the first crossplot by plotting these values of cold water temperature as a function of range using flow rate as a parameter (see Figure F.4).

Then, scribe Figure F.4 vertically at the test range (17,46 °C) to determine the predicted cold water temperatures at each of the three circulating flow rates. Values of these predicted cold water temperatures are tabulated in Table F.3 below.

Table F.3 — Curve points for cold water temperature versus flow at 24,53 °C test wet bulb and 17,46 °C test range

90 % flow	100 % flow	110 % flow
28,69	29,49	30,31

F.3.1.3 Step 3: Second crossplot

Using the values of cold water temperature in Table F.3, plot the temperature as a function of the flow rate, expressed as a percentage (see Figure F.5).

F.3.1.4 Step 4: Determination of predicted flow rate

On Figure F.5, scribe a line at the corrected test cold water temperature to intersect the curve. At the intersection, project a line vertically downward to find the predicted circulating water flow rate associated with the test wet bulb, range, and cold water temperature.

$$Q_{\text{wpred}} = 94{,}39\ \%\ \text{design flow} = 3\ 382\ \text{L/s}$$

F.3.1.5 Step 5: Calculate the adjusted test water flow rate

The adjusted test flow rate is computed from Formula (23), using the values for air density at the fan inlet and the fan driver output power, at both test and design conditions.

To comply with this International Standard, the design and test values for the density (ρ), specific volume (v), and enthalpy (h) of air are to be determined using the psychrometric tables in Annex D of this International Standard or computed using the program listing on which Annex D is based. For this example, the computer program of Annex D was used to generate all psychrometric properties.

Since the evaluation is based upon the psychrometric properties of air at the fan inlet, different procedures shall be employed for forced draft and included draft towers.

F.3.2 Forced draft tower

For a forced draft tower, the fan inlet-air conditions are the same as the tower inlet-air conditions. Therefore the test density (ρ_t) and the test specific volume (v_t) are computed directly from the measured test values of wet-bulb, dry-bulb, and barometric pressure. The design conditions at the tower's air inlet have been supplied by the manufacturer, in accordance with 5.3 or derived according to Annex D.

Table F.4 — Design and test values for air characteristics

Parameter	Design	Test values
Barometric pressure (*P*)	101,325 kPa	98,80 kPa
Ent. wet-bulb temp. (T_{wb})	26,00 °C	24,53 °C
Ent. dry-bulb temp. (T_{db})	30,20 °C	25,52 °C
Humidity ratio (HR)	0,019 66 kg/kg	0,019 69 kg/kg
Specific volume (n)	0,886 56 m^3/kg	0,895 23 m^3/kg
Enthalpy (*h*)	80,630 7 kJ/kg	75,821 1 kJ/kg
Density (*r*)	1,501 3 kg/m^3	1,139 02 kg/m^3
Relative humidity (RH)	71,98 %	92,36 %

F.3.3 Induced draft tower

F.3.3.1 For the induced draft, the fan air conditions are the tower discharge conditions. The discharge air properties are determined, for both the design and test conditions, by an iterative heat balance calculation as described below.

F.3.3.2 The heat balance formula states that the heat gain of the air as it moves through the cooling tower equals the heat loss of the water such that

$$L(c_{p,w})(T_{HW}-T_{CW})=G(h_{A,2}-h_{A,1}) \quad \text{(F.1)}$$

Rearranging terms to isolate for the exit air enthalpy, this formula becomes

$$h_{A,2}=(L/G)(c_{p,w})(T_{HW}-T_{CW})+h_{A,1} \quad \text{(F.2)}$$

For the design conditions, all values are given by the cooling tower manufacturer, except the exit enthalpy. For the example, one calculates it by

$$h_{A,2}=(1{,}3)\ (4{,}186)\ (49{,}40-30{,}60)+80{,}6307=182{,}936 \quad \text{kJ/kg}$$

F.3.3.3 Assuming the discharge air at this enthalpy is saturated, determine from thermodynamics given in Annex D.

$T_{fan,d}$ = 41,85 °C

$\rho_{fan,d}$ = 1,086 34 kg/m^3

$v_{fan,d}$ = 0,970 84 m^3/kg

Next we need to calculate the discharge air characteristics at test conditions. First calculate the test *L*/*G* by substituting all known values into Formula (31).

$$\left(\frac{L}{G}\right)=1{,}300\left(\frac{3\,623}{3\,583}\right)\left(\frac{\rho_t}{1{,}086\,34}\right)^{1/3}\left(\frac{107{,}0}{113{,}0}\right)^{1/3}\left(\frac{v_t}{0{,}970\,84}\right)=1{,}293\,4\,(\rho_t)^{1/3}\,v_t \quad \text{(F.3)}$$

Substitute this *L*/*G* expression into heat balance Formula (F.2).

$$h_{A,2}=1{,}293\,4\,(\rho_t)^{1/3}\,(v_t)\ 4{,}186\ (46{,}5-29{,}04)+75{,}821\,1$$

$$h_{A,2} = 94{,}1250\,(\rho_t)^{1/3}(v_t) + 75{,}821\,1$$

At this point, guess at a discharge air temperature and, assuming saturation, determine ρ and v at that temperature. Then, substituting these values into the final heat balance formula, calculate an h_{exit}.

Compare this calculated value for h_{exit} to the actual value for enthalpy at the assumed temperature and continue iterating discharge air temperature until a suitable temperature is selected for which the calculated value of h_{exit} matches the actual value.

For the first estimate of leaving air temperature, use the average of T_{HW} and T_{CW} at test conditions. Typical iteration values for this example are given in Table F.5 for barometric pressure of 98,80 kPa.

Table F.5 — Iteration on enthalpy of leaving air

T_{ext}	ρ_t	V_t	h_{exit} actual	h_{exit} computed	Error %
38,00	1,077 97	0,969 38	153,79	169,78	+10,40 %
40,00	1,067 91	0,983 69	170,16	170,87	+0,416 %
41,00	1,062 81	0,991 22	178,97	171,44	−4,20 %
40,09	1,067 45	0,984 36	170,94	170,92	−0,009 %

F.3.4 Calculate the tower capability

Substituting the psychrometric values at 40,09 °C into Formula (23), the adjusted flow rate is now calculated using Formula (F.4).

$$Q_{wt_{adj}} = 3\,623\left(\frac{107{,}0}{113{,}0}\right)^{1/3}\left(\frac{1{,}067\,45}{1{,}086\,34}\right)^{1/3} = 3\,537\ \text{L/s} \qquad \text{(F.4)}$$

For the forced draft example here above, the adjusted flow rate is

$$Q_{wt_{adj}} = 3\,623\left(\frac{107{,}0}{113{,}0}\right)^{1/3}\left(\frac{1{,}139\,02}{1{,}150\,13}\right)^{1/3} = 3\,546\ \text{L/s} \qquad \text{(F.5)}$$

The next steps are the same for forced and induced draft. Let's continue with the example of an induced draft.

The capability is then computed by Formula (24).

$$C_{CAP} = 100\left[\frac{3\,537}{3\,382}\right] = 104{,}6\ \% \qquad \text{(F.6)}$$

The tower compliance is then determined from Formula (26) and assuming in this example that the tolerance I_{TEM} has been contractually set to 0:

$C_{CAP} + I_{TEM}$ is greater than 100 %: the thermal guarantee is achieved.

F.4 Evaluation by approach deviation

F.4.1 To evaluate the tower performance in terms of leaving cold water temperature, follow the same steps as above to determine the adjusted flow rate (Formula (23)).

Enter Figure F.6 at the adjusted test flow rate (3 537 L/s) and scribe a line vertically upward to intersect the curve. At the point of intersection, read the corresponding predicted leaving cold water temperature as 29,39 °C.

Compare the corrected cold water temperature to the predicted cold water temperature according to Formula (48).

$$\Delta T_{App} = (T_{CW,\,corr} - T_{cw,\,pred}) = 29{,}04 - 29{,}39\ °C = 0\ °C)$$

Assuming that no tolerance were agreed (I_{TEMP} = 0), the compliance condition in Formula (61)

$$\Delta T_{App}\ - I_{TEMP} = -\ 0{,}35 \leq 0$$

is verified: the guaranteed conditions have been achieved.

F.4.2 To evaluate the tower performance in terms of leaving cold water temperature, follow the same steps as above to determine the adjusted test flow rate (Formula (23)).

Enter Figure F.6 at the adjusted test flow rate (3 466 L/s) and scribe a line vertically upward to intersect the curve. At the point of intersection, read the corresponding predicted leaving cold water temperature as 29,18 °C.

Compare the predicted cold water temperature to the measured test value of cold water temperature such that, using Formula (28),

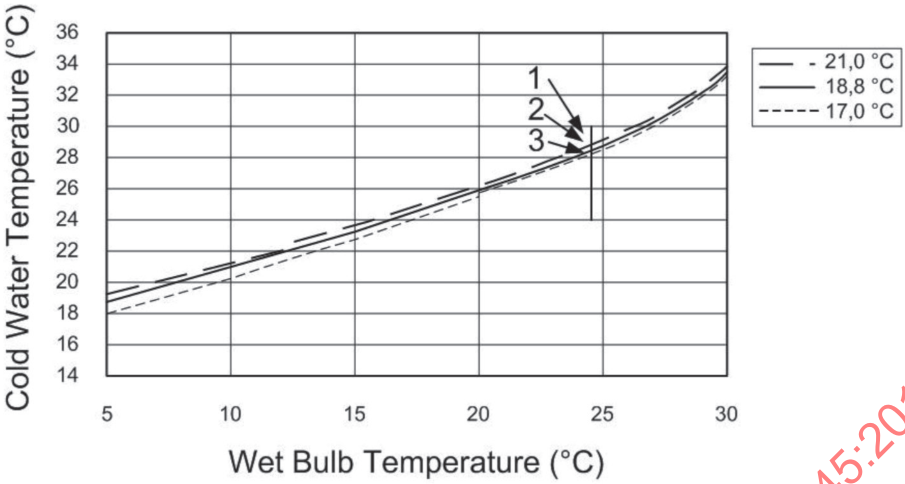
$$\Delta T_{cw} = (T_{cw,pred}) - (T_{cw,\,t})$$

$$\Delta T_{cw} = (29{,}18) - (29{,}04) = +0{,}14$$

and since Δt_{cw} = +0,14 – 0, the guaranteed condition has been achieved.

Table F.6 — Iteration for enthalpy of leaving air

T_a	ρ_t	v_t	$h_{o,t}$ actual	$h_{o,t}$ computed	Error %
38,00	1,077 97	0,969 38	153,79	176,34	+14,66 %
40,00	1,067 91	0,983 69	170,16	177,50	+4,32 %
41,00	1,068 21	0,991 22	178,97	178,12	−0,47 %
40,90	1,063 32	0,990 46	178,07	178,06	+0,01 %



Cooling range shown in figure box.	
Design Conditions:	
	Water flowrate: 3 583 L/s
	Cooling range: 18,9 °C
	Cold water: 30,6 °C
	Wet bulb = 26,0 °C
	Dry bulb = 30,2 °C
	Barometric pressure = 101,325 kPa°

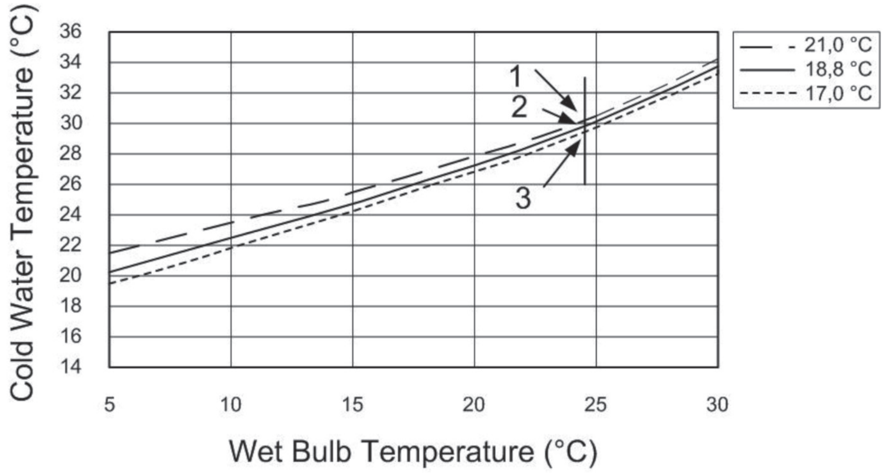
Key

1 29,09 °C at 21,0 range

2 28,86 °C at 18,8 range

3 28,64 °C at 17,0 range

Figure F.1 — Cooling range at water flow rate = 3 225 L/s (90 %) at test wet bulb 24,54 °C



Cooling range shown in figure box.	
Design Conditions:	
	Water flowrate: 3 583 L/s
	Cooling range: 18,9 °C
	Cold water: 30,6 °C
	Wet bulb = 26,0 °C
	Dry bulb = 30,2 °C
	Barometric pressure = 101,325 kPa°

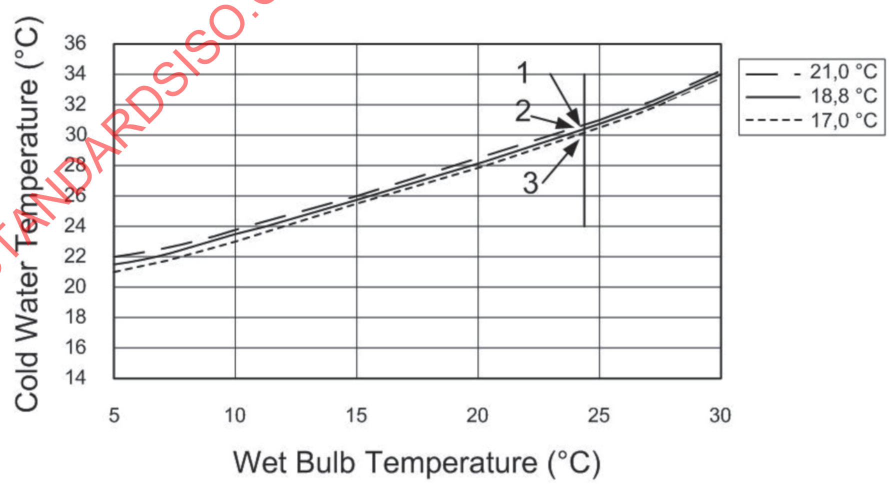
Key

1 29,88 °C at 21,0 range

2 29,65 °C at 18,8 range

3 29,43 °C at 17,0 range

Figure F.2 — Cooling range at water flow rate = 3 583 L/s (100 %) at test wet bulb 24,54 °C



Cooling range shown in figure box.	
Design Conditions:	
	Water flowrate: 3 583 L/s
	Cooling range: 18,9 °C

	Cold water: 30,6 °C
	Wet bulb = 26,0 °C
	Dry bulb = 30,2 °C
	Barometric pressure = 101,325 kPa°
Test Wet Bulb = 24,53 °C Cold water temperatures	
	29,88 at 21,0 range
	29,65 at 18,8 range
	29,43 at 17,0 range

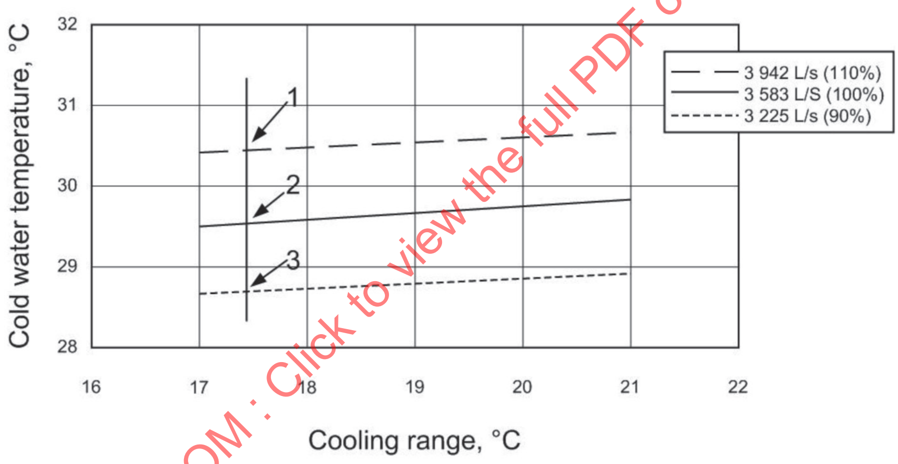
Key

1 30,76 °C at 21,0 range

2 30,50 °C at 18,8 range

3 30,24 °C at 17,0 range

Figure F.3 — Cooling range for water flow rate = 3 942 L/s (110 %) at test wet bulb 24,54 °C



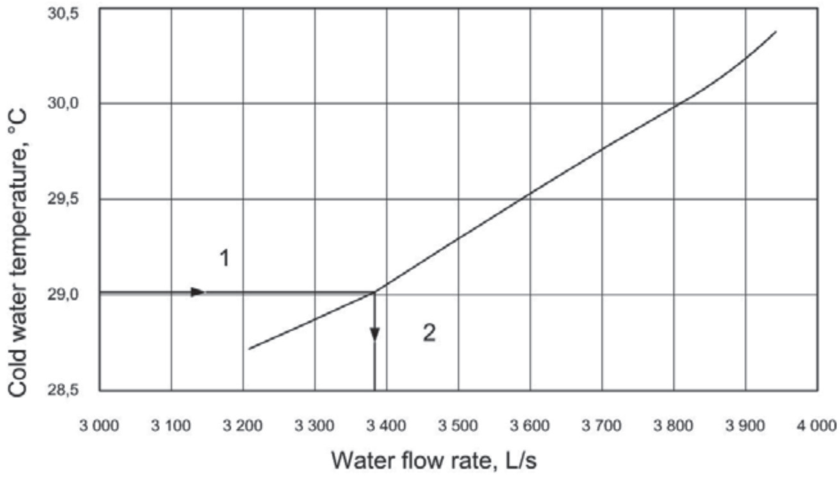
Key

1 30,31 °C at 110 % range

2 29,49 °C at 100 % range

3 28,69 °C at 90 % range

Figure F.4 — Crossplot 1, wet bulb = 24,53 °C at test wet bulb 24,54 °C

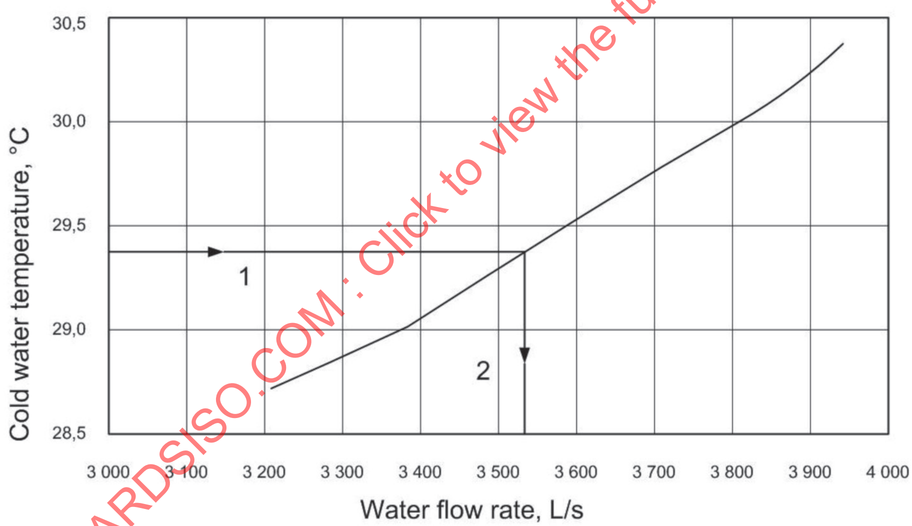


Key

1 predicted cold water = 29,38 °C

2 adjusted test water flow rate = 3 537 L/s

Figure F.5 — Crossplot 2, wet bulb = 24,53 °C, range = 17,46 °C



Key

1 predicted cold water = 29,38 °C

2 adjusted test water flow rate = 3 537 L/s

Figure F.6 — Crossplot 2, wet bulb = 24,53 °C, range = 17,46 °C

Annex G
(informative)

Example evaluation of an open-circuit, mechanical draft cooling tower test using the characteristic curve method

G.1 General

The purpose of Annex G is to describe and illustrate the characteristic curve methodology of evaluating a thermal performance test on a mechanical draft cooling tower, as described in Clause 9 of this International Standard.

G.2 Design and test values

Design and measured test values for the mechanical draft cooling tower are summarized in the following table.

Table G.1 — Mechanical draft cooling tower, design and measured test values

Parameter	Design values	Measure test values
Water flow rate (Q_{wt})	220 L/s	209 L/s
Hot water temp. (T_{hw})	36 °C	33,4 °C
Cold water temp. (T_{cw})	30 °C	27,1 °C
Entering wet-bulb temp. (T_{wb})	25 °C	21,1 °C
Entering dry-bulb temp. (T_{db})	31 °C	30,6 °C
Total fan driver ower (W_t)	60 kW	57,6 kW
Barometric pressure (P_{bp})	101,325 kPa	101,325 kPa
Liquid to gas ratio (L/G)	1,700	—

In accordance with 5.3.6 of this International Standard, the manufacturer has submitted characteristic curve shown in Figure G.1.

G.3 Evaluation procedure

G.3.1 Step 1: Determine the test L/G

The test value of L/G is computed using the test values of hot water temperature, cold water temperature, entering dry-bulb and wet-bulb temperatures, barometric pressure, test flow, and test total fan driver power.

To comply with this International Standard, the design and test values for density (ρ), specific volume (v), and enthalpy (h) of air shall be determined using the psychrometric tables or source codes set forth in Annex D. For this example, the source code of Annex D was used to generate all psychrometric properties.

Since the evaluation is based upon the psychrometric properties of air at the fan inlet, different procedures shall be employed to compute the L/G for forced draft and induced draft towers.

G.3.2 Forced draft tower

For a forced draft tower, the fan inlet-air conditions are the same as the tower inlet-air conditions. Therefore the test density (ρ_t) and the test specific volume (v_t) are computed directly from the measured test wet-bulb temperature, dry-bulb temperature, and barometric pressure. The design conditions at the tower's air inlet shall be supplied by the manufacturer per 5.3.

Given the design and measured test values for wet-bulb and dry-bulb temperatures and the barometric pressure, determine the density and specific volume of the inlet air.

At design values of 25 °C wet-bulb, 31 °C dry-bulb, 101,325 kPa barometric pressure:

$\rho_t = 1{,}1485\ \text{kg/m}^3$

$v_t = 0{,}883\ 09\ \text{m}^3/\text{kg}$

$h = 76{,}274\ \text{kJ/Kg}$

At test values of 21,1 °C wet-bulb, 30,6 °C dry-bulb, 101,325 kPa barometric pressure:

$\rho_t = 1{,}153\ 9\ \text{kg/m}^3$

$v_t = 0{,}876\ 94\ \text{m}^3/\text{kg}$

$h = 61{,}102\ \text{kJ/Kg}$

Using these data, calculate the test L/G from Formula (31) substituting r values

$$\left(\frac{L}{G}\right)_t = \left(\frac{L}{G}\right)_d \left(\frac{Q_{W,t}}{Q_{W,d}}\right)\left(\frac{W_{FM,d}}{W_{FM,t}}\right)^{1/3}\left(\frac{\rho_{A,t}}{\rho_{A,d}}\right)^{1/3}\left(\frac{v_{A,t}}{v_{A,d}}\right)$$

$$\left(\frac{L}{G}\right)_t = (1{,}70)\left(\frac{209}{220}\right)\left(\frac{60{,}0}{57{,}6}\right)^{1/3}\left(\frac{1{,}153\ 9}{1{,}148\ 5}\right)^{1/3}\left(\frac{0{,}876\ 94}{0{,}886\ 09}\right)$$

$$\left(\frac{L}{G}\right)_t = 1{,}623$$

G.3.3 Induced draft tower

For the induced draft tower, the conditions at the inlet to the fan are the tower's discharge conditions. The code requires that both the design and test discharge air properties be determined by a heat balance calculation. Calculating design discharge air properties is a straightforward procedure while calculating test discharge air properties requires combining the heat balance Formula (G.1) with Formula (31) and iterating for a solution.

The heat balance Formula (G.1) below simply states that the heat gain of the air equals the heat loss of the water.

$$L\,(c_{\mathrm{p,w}})\,(T_{\mathrm{HW}} - T_{\mathrm{CW}}) = G\,(h_{\mathrm{A,2}} - h_{\mathrm{A,1}}) \tag{G.1}$$

Rearranging to separate the exit air enthalpy, the heat balance Formula (G.1) becomes

$$h_{\mathrm{A,2}} = (L/G)\,(c_{\mathrm{p,w}})\,(T_{\mathrm{HW}} - T_{\mathrm{CW}}) + h_{\mathrm{A,1}}$$

For the design conditions, all values are given by the cooling tower manufacturer; the inlet-air enthalpy is to be calculated from Annex D. For the example, one calculates the exit air enthalpy by Formula (G.2).

$$h_{\mathrm{A,2}} = (1{,}7)\,(4{,}186)\,(36 - 30) + 76{,}274 = 118{,}971 \ \text{kJ/kg} \tag{G.2}$$

Assuming the discharge air at this enthalpy is saturated, determine from thermodynamics given in Annex D.

$T_{\mathrm{fan,d}}$ = 33,35 °C

$\rho_{\mathrm{fan,d}}$ = 1,086 34 kg/m^3

$v_{\mathrm{fan,d}}$ = 0,970 8 m^3/kg

Next, calculate the discharge air characteristics at test conditions. First calculate the test L/G by substituting all known values into Formula (31).

$$\left(\frac{L}{G}\right) = 1{,}700\left(\frac{209}{220}\right)\left(\frac{\rho_t}{1{,}129\,5}\right)^{1/3}\left(\frac{60{,}0}{57{,}6}\right)^{1/3}\left(\frac{v_t}{0{,}914\,88}\right) = 1{,}718\,3\,(\rho_t)^{1/3}\,v_t \tag{G.3}$$

Substitute this L/G expression into heat balance Formula (G.2).

From Annex D, calculate enthalpy at inlet for test conditions = 61,102 kJ/kg

$$h_{A,2} = 1{,}7183\,(\rho_t)^{1/3}(v_t)\;4{,}86\,(33{,}4 - 27{,}1) + 61{,}102$$

$$h_{A,2} = 45{,}3147\,(\rho_t)^{1/3}(v_t) + 61{,}102 \tag{G.4}$$

At this point, guess at a discharge air temperature and, assuming saturation, determine ρ and v at that temperature. Then, substituting these values into final heat balance Formula (G.4), calculate an h_{exit}.

Compare this calculated value for h_{exit} to the actual value for enthalpy at the assumed temperature and continue iterating discharge air temperature until a suitable temperature is selected for which the calculated value of h_{exit} matches the actual value.

For the first estimate of leaving air temperature, use the average of T_{HW} and T_{CW} at test conditions. Typical iteration values for this example are given in Table G.2 for barometric pressure of 101,325 kPa.

Table G.2 — Iteration on enthalpy of leaving air

T_{exit}	ρ_t	v_t	h exit actual	h exit computed	Error %
30,00	1,145 9	0,896 56	100,005	103,616	+3,60 %
31,00	1,141 0	0,901 85	105,638	103,806	−1,48 %
30,70	1,142 5	0,900 25	103,733	103,749	+0,015 %

A leaving air temperature of 30,7 °C is sufficiently accurate. Now determine the test L/G by substituting the psychrometric values for saturated air at 30,7 °C into Formula (G.3) and solve

$$\left(\frac{L}{G}\right)=(1{,}718\,3)\ (1{,}142\,8)^{1/3}(0{,}900\,2)=1{,}617$$

G.3.4 Step 2: Calculate *KaV*/*L* at the test *L*/*G*

Once the test L/G is determined, the procedure for calculating KaV/L is identical for forced draft and induced draft towers. The KaV/L calculation is computed using the saturated enthalpy values at the wet-bulb temperatures. Continuing with the induced draft example, the value KaV/L is computed in the following manner according to 9.3.4.3.

For T_{HW} = 33,4 and T_{CW} = 27,1, the enthalpy of the exit air is calculated by

$$h_{A,2}=h_{A,1}+(L/G)*(c_{p,w})*(T_{HW}-T_{CW})=61{,}395+4{,}186\times 6{,}3=104{,}038$$

At a given step (x) of the heat exchange, the air enthalpy is $h_a=x*(L/G)*(c_{p,w})*(T_{HW}-T_{CW})$.

The water temperature is $T_W=T_{CW}+x*(T_{HW}-T_{CW})$.

	X	Air enthalpy h_a	Water temperature T_W	Air enthalpy at T w h_w	Δh = $h_w - h_a$	$1/\Delta h$
Initial	0	61,102	27,1			
At 10 %	0,1	65,659	27,73	88,690	23,031	0,0434 2
At 40 %	0,4	78,452	29,62	90,030	19,578	0,0510 8
At 60 %	0,6	86,981	30,88	104,711	17,731	0,0564 0
At 90 %	0,9	99,774	32,77	115,479	15,795	0,0636 7
Final	1,0	104,038	33,4			$\Sigma\frac{1}{\Delta h}=0{,}214\,57$

$$KaV/L=\left(cp_W\right)\left(\frac{T_{HW}-T_{CW}}{4}\right)\left(\Sigma\frac{1}{\Delta h}\right)=\left(4{,}186\right)\left(\frac{6{,}3}{4}\right)\ \left(0{,}214\,57\right)=1{,}415$$

G.3.5 Step 3: Determine the intersect $(L/G)_t$

At the $(L/G)_t$ calculated from G.3.1 Step 1 and the KaV/L calculated from G.3.4 Step 2, plot the test performance point on the manufacturer's characteristic curve, as shown in Figure G.2. A curve is drawn through this point parallel to the tower characteristic curve. This parallel curve intersects the 5 °C design approach curve at $(L/G)_p$ = 1,72. This is the predicted L/G, which is the L/G that the tower would produce if operating at design conditions.

G.3.6 Step 4: Calculate the tower capability

As set forth in 9.3.4.4, the tower capability, C, is the ratio of the predicted L/G to the design L/G.

$$C = 100\{(L/G)_1 \; / \; (L/G)_d\}$$

$$C = 100 \; (1{,}72 \; / \; 1{,}70) = 101{,}2 \; \%$$

Based on the test performed, the tower is capable of cooling 223 L/s from 36 °C to 30 °C at design wet-bulb temperature 25 °C and design total fan driver power of 60 kW.

If additional valid test periods were to be averaged, say for additional test periods with capability of 100,5 and 101,9, the average is calculated per Formula (G.X) below.

$$\bar{C} = \frac{C_1 + C_2 + C_3 \ldots C_n}{n}$$

$$\bar{C} = (101{,}2 + 100{,}5 + 101{,}9)/3 = 101{,}2$$

G.3.7 Step 5: Compliance

Assuming that no tolerance was in the contract, $T\text{cap} = 0$, the compliance criteria is per Formula (26).

$$C + T\text{cap} \geq 100 \; \%$$

$$101{,}2 + 0 \geq 100 \; \%$$

Therefore, the tower has achieved the guaranteed condition.

Using the same final plot as in G.3.5 Step 3, enter at the adjusted test L/G, and read the predicted cold water temperature on the original manufacturer's curve. Compare the predicted cold water temperature with the measured cold water temperature such that the approach deviation equals:

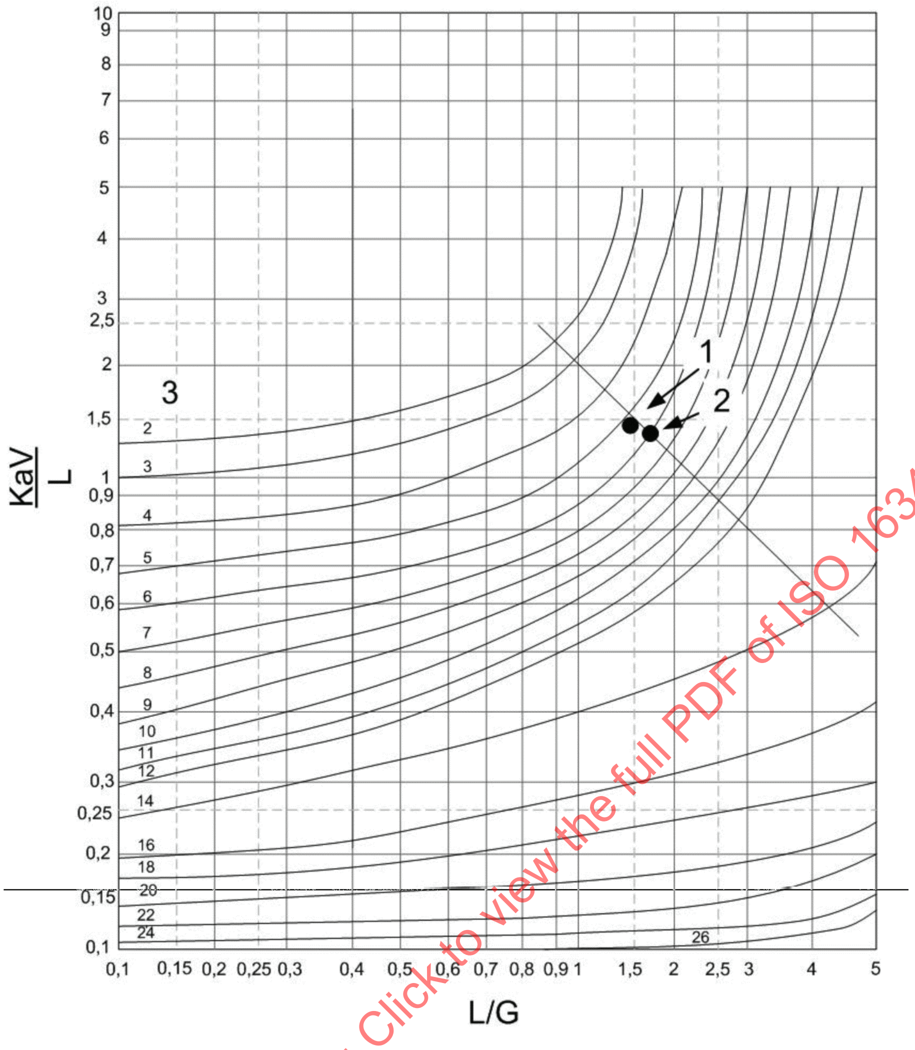
$$\Delta A_{cw} = (T_{cw,\,t}) - (T_{cw,\,pred})$$

For multiple test periods, the average can be calculated per 9.3.3.1.5.

$$\Delta\bar{A} = \left(\frac{1}{n}\right) \sum_{i=1}^{n} \Delta A_i$$

Compliance has been achieved if

$$\Delta A - \tau_{temp} < 0$$



Design Conditions	
Flow	220 L/s
Hot water temperature	36 °C
Cold water temperature	30 °C
WBT	25 °C
Fan power	60 kW
Motor efficiency	91 %
Barometer reading	101,3 kPa
L/G	1,70

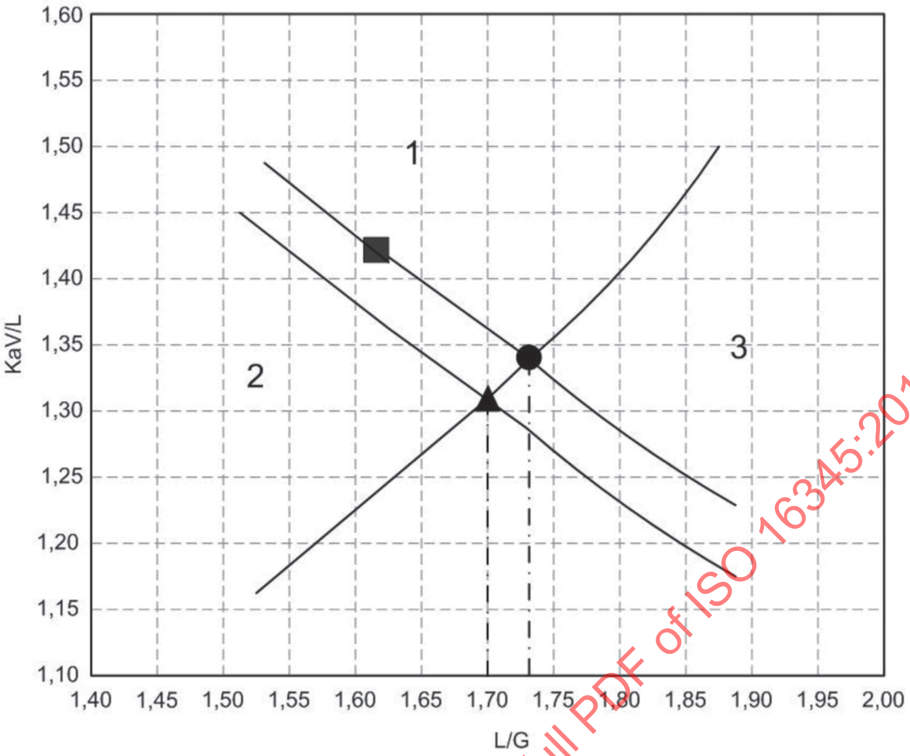
Key

1 test point

2 design point

3 approach temperature

Figure G.1 — Design crossplot



Key

1 test L/G = 1,617; KaV/L = 1,415

2 design L/G = 1,700; KaV/L = 1,305

3 intercept with design approach curve: L/G = 1,728

Figure G.2 — Test crossplot

Annex H
(normative)

Example evaluation of a natural draft cooling tower test using the performance curve method

H.1 General

The purpose of Annex H is to describe and illustrate the performance curve methodology for evaluating a thermal performance test on a natural draft cooling tower, as described in 9.3.5 of this International Standard.

H.2 Design and measured test values

The design and measured test valves for a natural draft cooling tower are summarized in Table H.1.

Table H.1 — Cooling tower design and measured test values

Parameter	Design values	Measure test values
Water flow rate (Q_{wt})	23,889 L/s	22,299 L/s
Hot water temp. (T_{hw})	32,80 °C	27,80 °C
Cold water temp. (Tcw)	25,40 °C	20,50°C
Cooling range (R)	7,40 °C	7,30°C
Entering wet-bulb temp. (Twb)	16,00 °C	9,5 °C
Entering dry-bulb temp. (Tdb)	18,20 °C	13,40 °C
Total fan driver power (Wt)	60 kW	57,6 kW
Barometric pressure (Pbp)	101,325 kPa	101,70 kPa
Relative humidity (RH)	80,17 %	60,42

In accordance with 5.3.4 of this International Standard, the manufacturer has submitted performance curves presenting cold water temperature as a function of the air dry-bulb temperature with the relative humidity of the air as a parameter (see Figures H.1 through Figure H.9).

Figure H.1 to Figure H.3 for 90 % of design water circulation rate

Figure H.4 to Figure H.6 for 100 % of design water circulation rate

Figure H.7 to Figure H.9 for 110 % of design water circulation rate

H.3 Evaluation by flow rate capability

The steps to be followed in evaluating the test in terms of flow rate capability are as follows.

H.3.1 Step 1: First crossplot

Using the nine performance curves, three for each of the three water circulation rates, enter the curves at the test dry-bulb temperature (13,40 °C) and determine the cold water temperature for 60 %, 80 %, and 100 % relative humidity at each flow rate and range.

Table H.2 — Curve points for cold water temperature versus range and relative humidity at 13,40 °C test dry bulb

Range	RH %	90 % flow	100 % flow	110 % flow
6,70	60	20,24	21,11	21,94
	70	20,69	21,53	22,38
	80	21,10	21,94	22,78
	100	21,95	22,78	23,63
7,40	60	20,46	21,38	22,17
	70	20,90	21,79	22,60
	80	21,31	22,20	23,02
	100	22,16	23,03	23,86
8,10	60	20,59	20,59	22,41
	70	21,01	21,98	22,83
	80	21,44	21,44	23,24
	100	22,30	22,30	24,06

Then for each flow and range, prepare a crossplot of cold water temperature as a function of the relative humidity, with the cooling range as a parameter (see Figure H.10 through Figure H.12).

H.3.2 Step 2: Second crossplot

Using these new curves, enter each at the test relative humidity (60,42 %) and determine the cold water temperature for each flow rate and range.

Table H.3 — Curve points for cold water temperature versus flow at 13,40 °C test dry bulb and 60,42 % test relative humidity

Range	90 % flow	100 % flow	110 % flow
6,7 °C	20,26	21,13	21,95
7,4 °C	20,48	21,39	22,19
8,1 °C	20,61	21,58	22,43

Then, develop a second crossplot of the cold water temperature as a function of the cooling range (see Figure H.13).

H.3.3 Step 3: Third crossplot

Enter Figure H.13 at the test range (7,30 °C) and determine the cold water temperature for each of the three flow rates, as listed in Table H.4.

Table H.4 — Curve points for cold water temperature versus water flow at 13,40 °C test dry bulb and 60,42 % RH and 7,30 °C test range

90 % flow	100 % flow	110 % flow
20,45	21,36	22,16

Then crossplot the water flow rate as a function of the cold water temperature (see Figure H.14).

H.3.4 Step 4: Determination of predicted flow rate

Enter Figure H.14 at the measured cold water temperature (20,50 °C) and from the intersection with the curve, determine the predicted water flow rate at the test cold water temperature as 21 639 L/s.

H.3.5 Step 5: Determination of cooling tower capability

Using Formula (32), find the cooling tower thermal performance capability as

$$C = 100 \frac{Q_{\text{wt, adj}}}{Q_{\text{pred}}} = 100 \left(\frac{22\,299\ \text{L/s}}{21\,639\ \text{L/s}} \right) = 102{,}7\ \%$$

NOTE The above graphical interpolation can be done mathematically.

H.4 Evaluation by cold water temperature

To evaluate the tower performance in terms of leaving cold water temperature, follow the same steps as above to develop the third crossplot (Figure H.15).

Then, enter Figure H.15 at the measured test flow rate (22 299 L/s) and scribe a line vertically upward to intersect the curve. At the point of intersection, read the corresponding predicted leaving cold water temperature as 20,75 °C.

Compare the predicted cold water temperature to the measured test value for cold water temperature such that:

$$T_{\text{cw}} = (T_{\text{cw, t}}) - (T_{\text{cw, pred}})$$

$$T_{\text{cw}} = (20{,}50) - (20{,}75) = -0{,}25$$

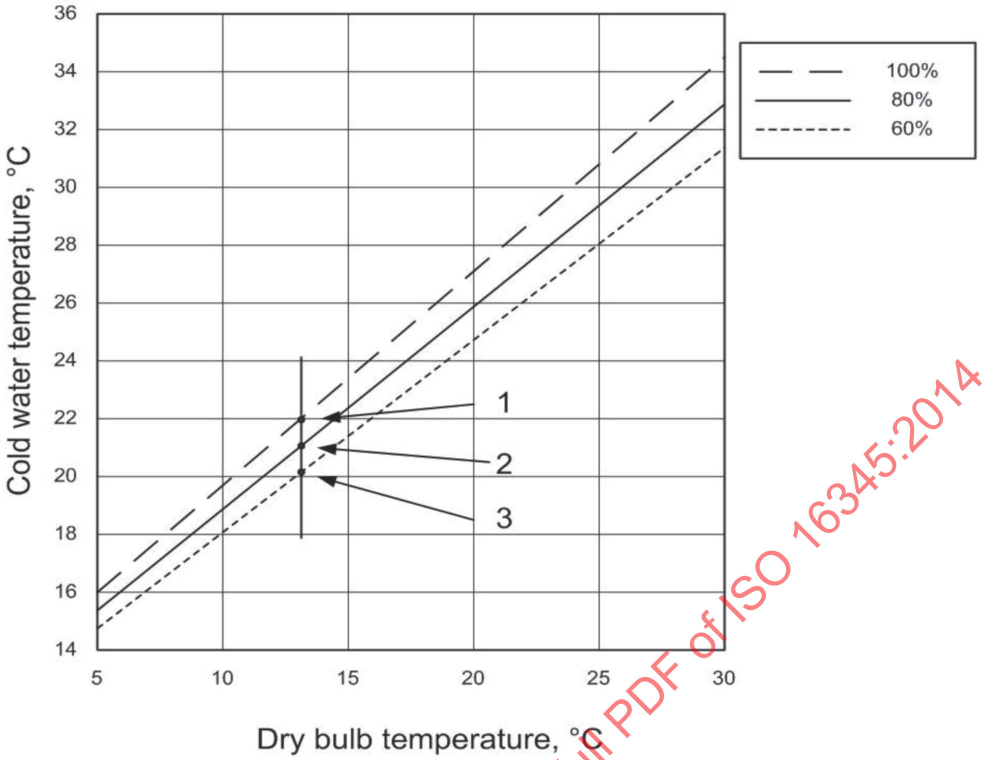
and since $\Delta t_{\text{cw}} < 0$, guaranteed condition has been achieved.

H.5 Average capability

For multiple points, see Formula (38).

H.6 Average cold water

For multiple points, see Formula (41).



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

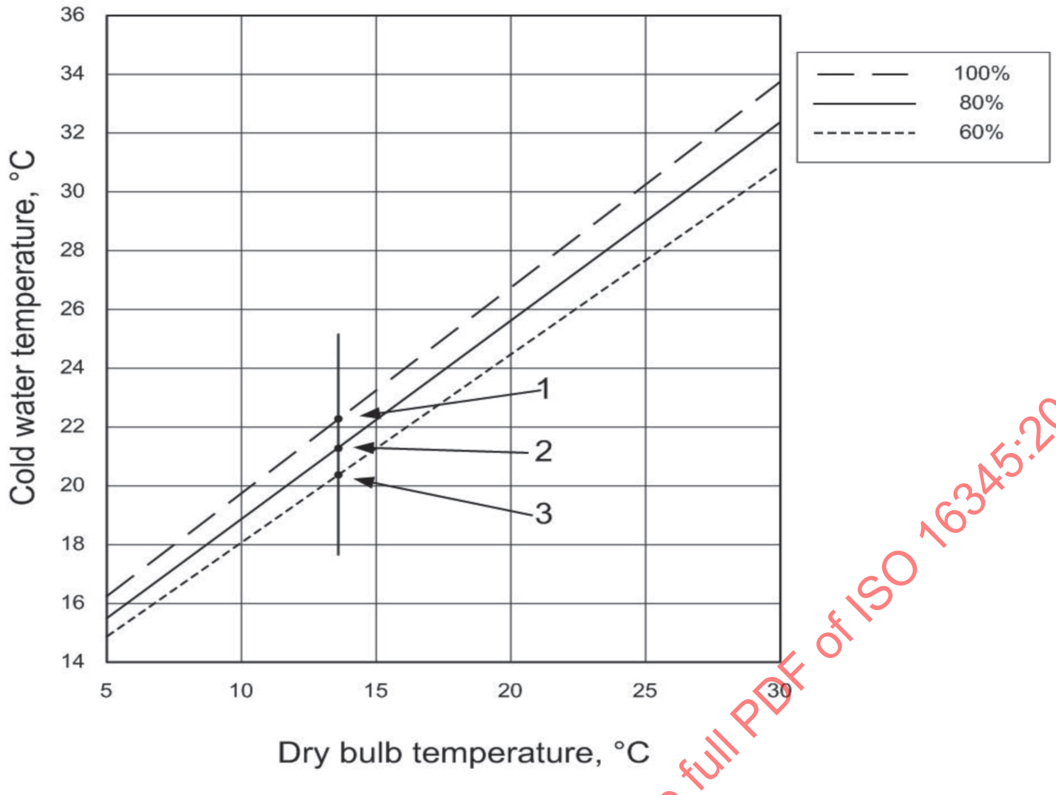
Key

1 21,95 °C (cold water temperature)

2 21,10 °C (cold water temperature)

3 20,24 °C (cold water temperature)

Figure H.1 — Water flow rate = 21 500 L/s (90 %) and range = 6,7 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

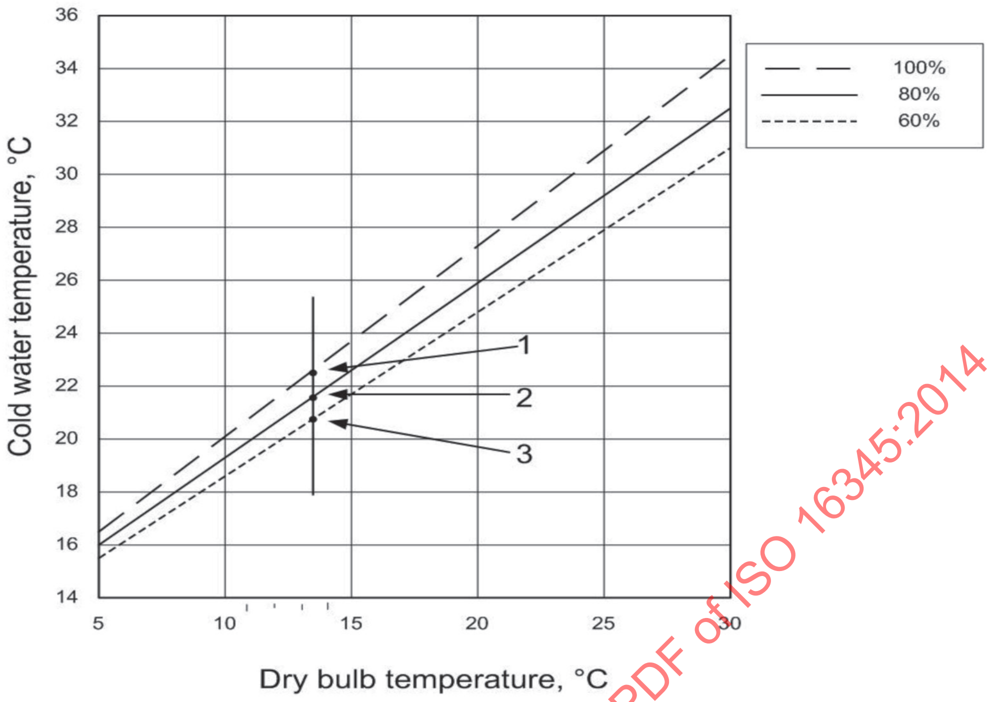
Key

1 22,16 °C (cold water temperature)

2 21,31 °C (cold water temperature)

3 20,46 °C (cold water temperature)

Figure H.2 — Water flow rate = 21 500 L/s (90 %) and range = 7,4 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

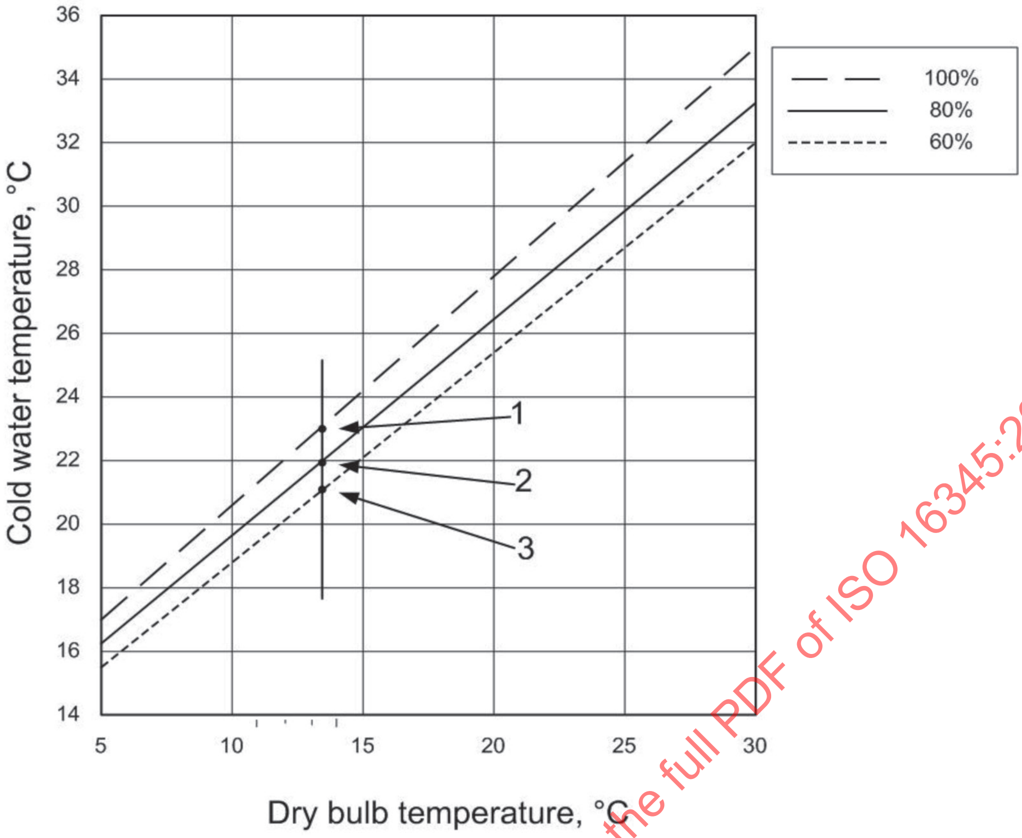
Key

1 22,30 °C (cold water temperature)

2 21,44 °C (cold water temperature)

3 20,59 °C (cold water temperature)

Figure H.3 — Water flow rate = 21 500 L/s (90 %) and range = 8,1 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

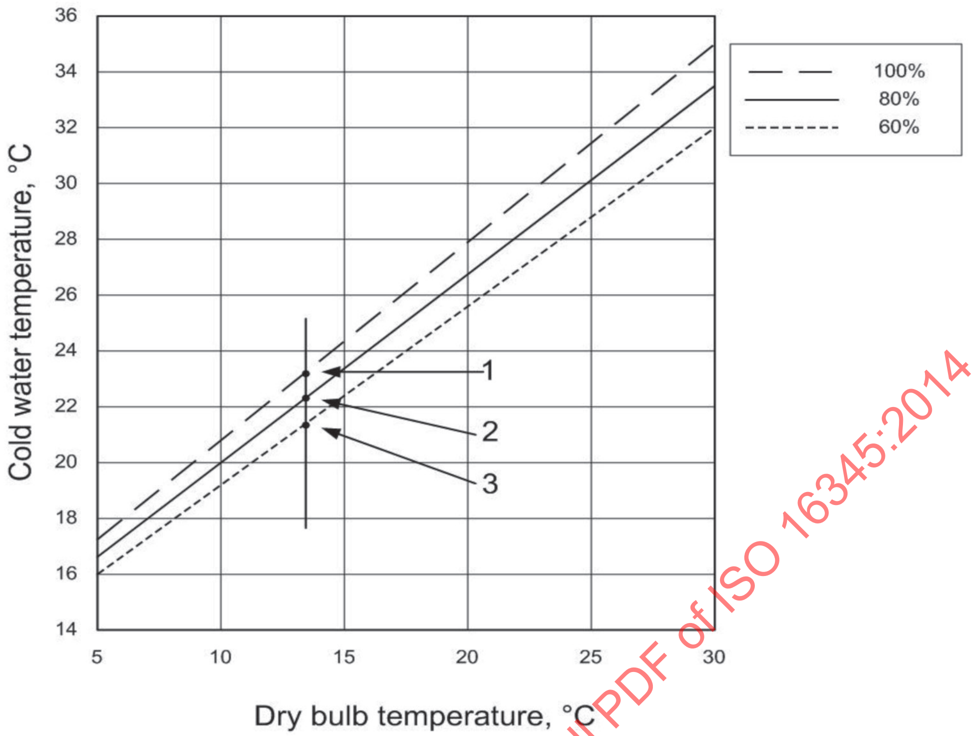
Key

1 22,78 °C (cold water temperature)

2 21,94 °C (cold water temperature)

3 21,11 °C (cold water temperature)

Figure H.4 — Water flow rate = 23 889 L/s (100 %) and range = 6,7°C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

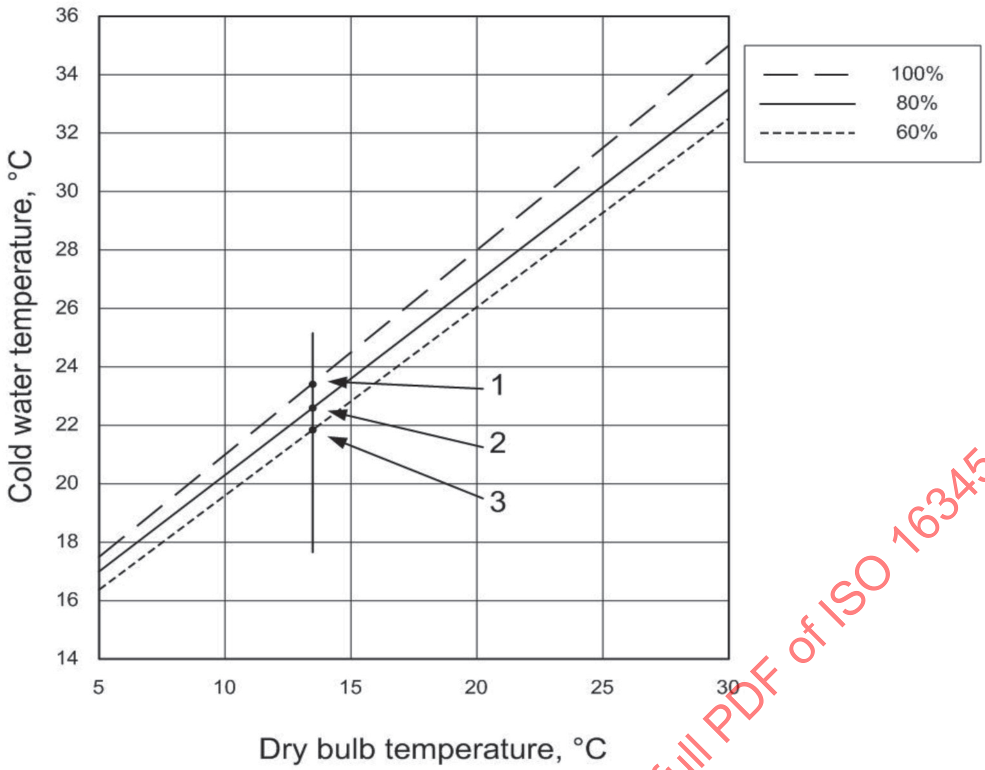
Key

1 23,03 °C (cold water temperature)

2 22,20 °C (cold water temperature)

3 21,38 °C (cold water temperature)

Figure H.5 — Water flow rate = 23 889 L/s (100 %) and range = 7,4 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

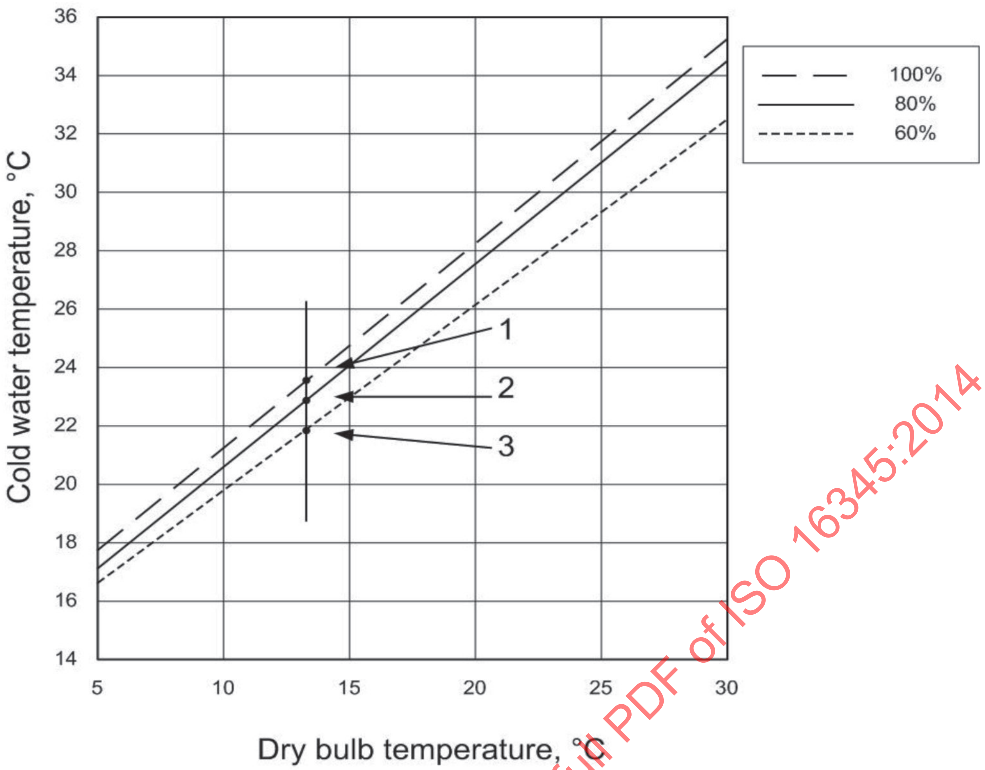
Key

1 23,23 °C (cold water temperature)

2 22,39 °C (cold water temperature)

3 21,56 °C (cold water temperature)

Figure H.6 — Water flow rate = 23 889 L/s (100 %) and range = 8,1 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

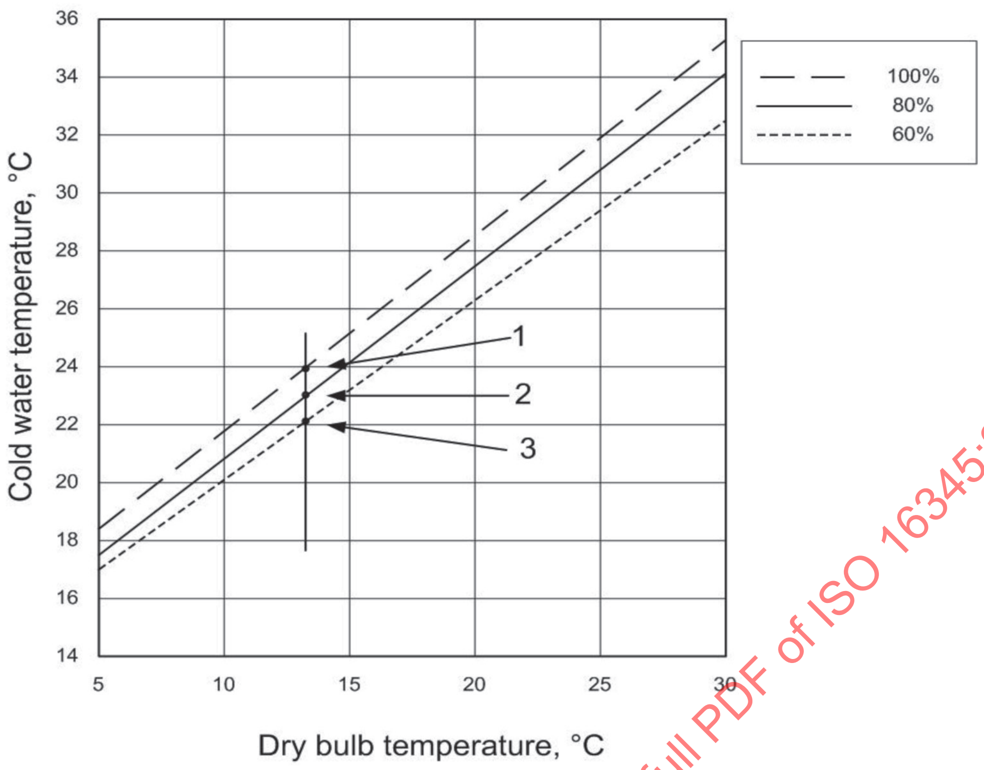
Key

1 23,63 °C (cold water temperature)

2 22,78 °C (cold water temperature)

3 21,94 °C (cold water temperature)

Figure H.7 — Water flow rate = 26 278 L/s (110 %) and range = 6,7 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

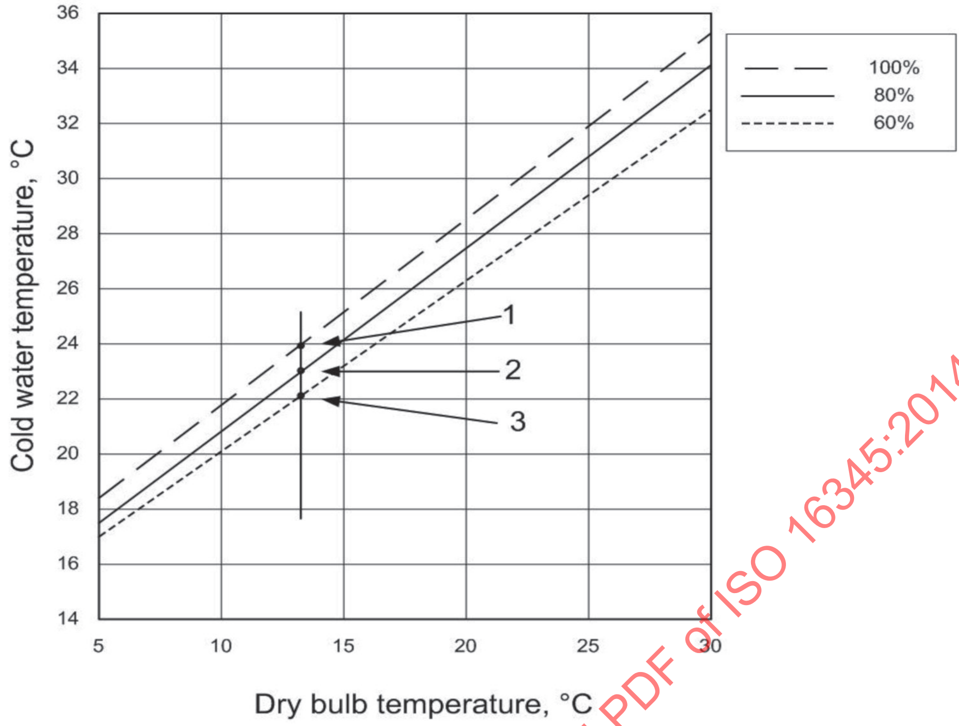
Key

1 23,86 °C (cold water temperature)

2 23,02 °C (cold water temperature)

3 22,17 °C (cold water temperature)

Figure H.8 — Water flow rate = 26 789 L/s (110 %) and range = 7,4 °C at test dry bulb = 13,4 °C



Design conditions	
Water flow rate	23 889 L/s
Cooling range	7,4 °C
Cold water	25,4 °C
Wet bulb	16,0 °C
Dry bulb	18,2 °C
Relative humidity	80,17 %
Barometric pressure	101,325 kPa

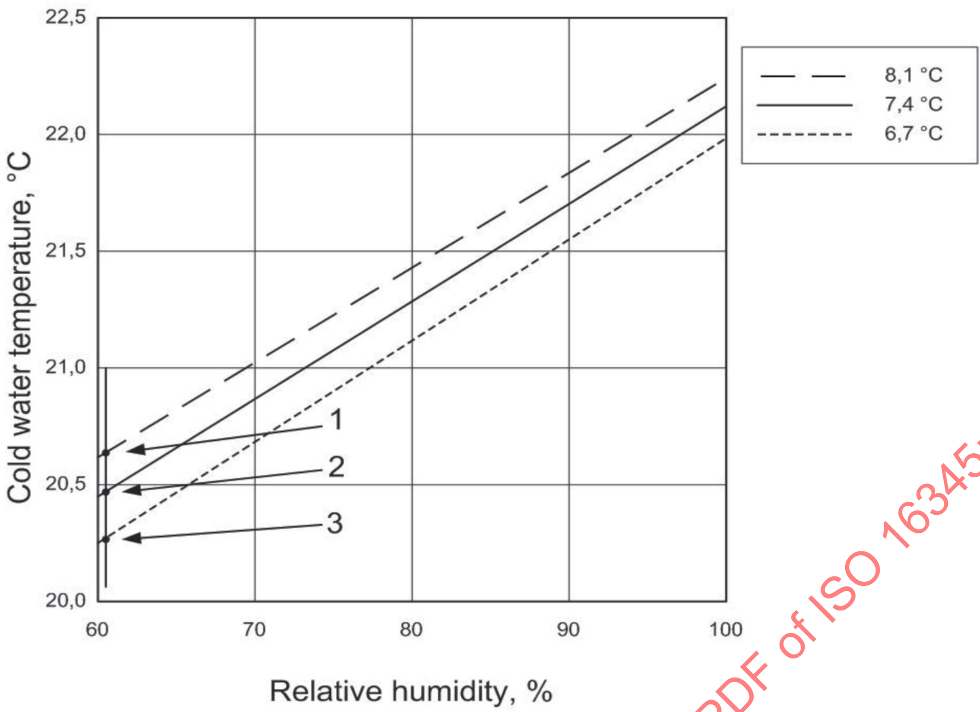
Key

1 24,06 °C (cold water temperature)

2 23,24 °C (cold water temperature)

3 22,41 °C (cold water temperature)

Figure H.9 — Water flow rate = 26 278 L/s (110 %) and range = 8,1 °C at test dry bulb = 13,4 °C



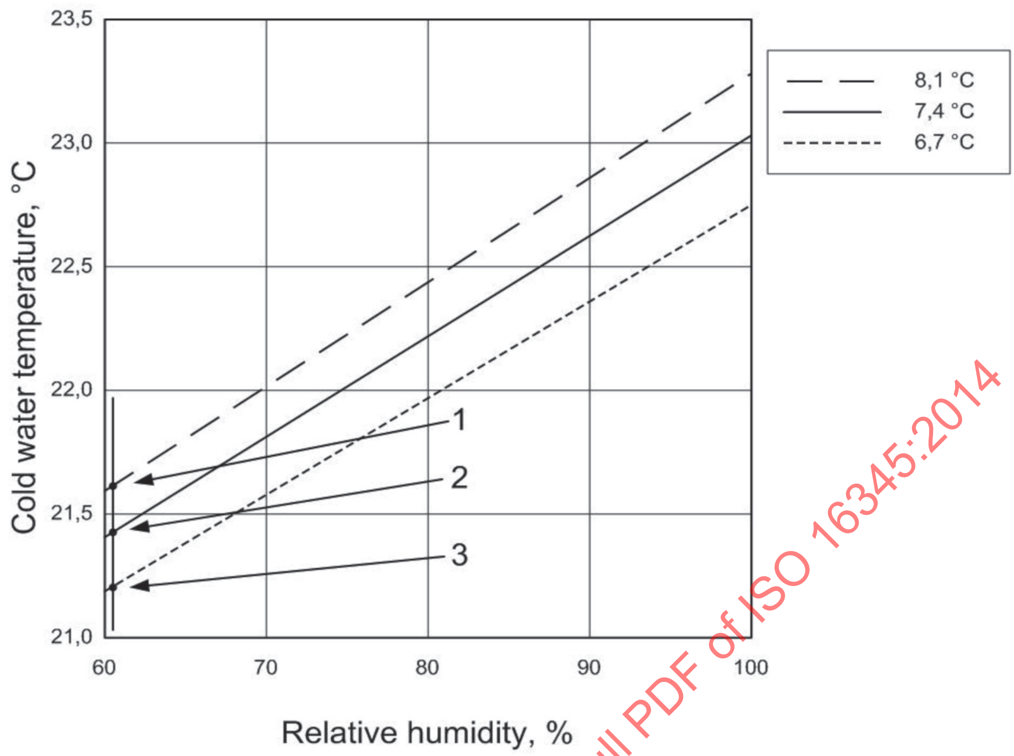
Key

1 20,61 at 8,10 range

2 20,48 at 7,40 range

3 20,26 at 6,70 range

Figure H.10 — Crossplot 1a:Dry bulb = 13,4 °C and water flow rate = 21 500 L/s (90 %) at test relative humidity = 60,42 %



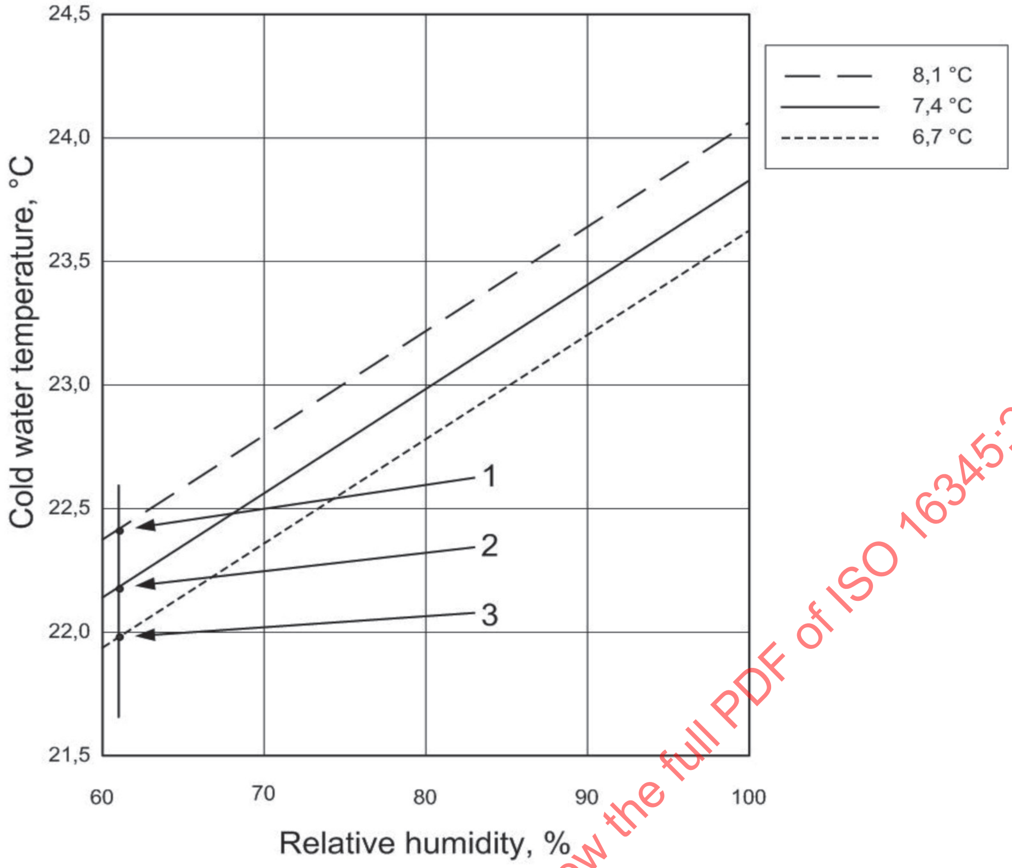
Key

1 21,58 at 8,10 range

2 21,39 at 7,40 range

3 21,13 at 6,70 range

Figure H.11 — Crossplot 1b:Dry bulb = 13,4 °C and water flow rate = 23 889 L/s (100 %) at test relative humidity = 60,42 %



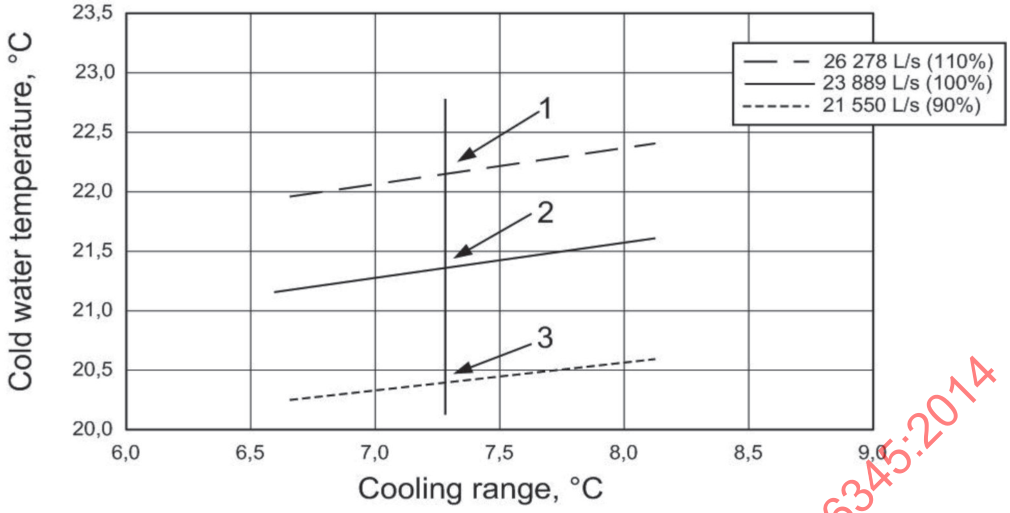
Key

1 22,43 at 8,10 range

2 22,19 at 7,40 range

3 21,95 at 6,70 range

Figure H.12 — Crossplot 1c Dry bulb = 13,4 °C and water flow rate = 26 278 L/s (110 %) at test relative humidity = 60,42 %



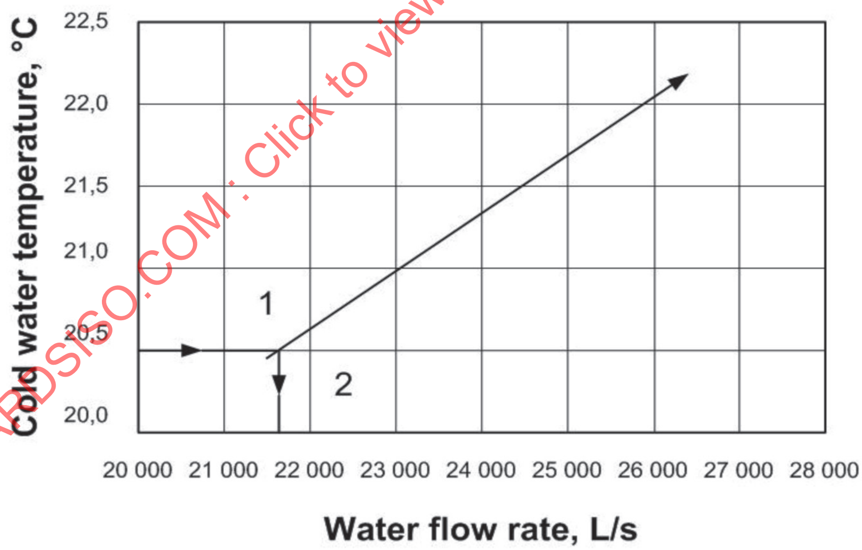
Key

1 22,16 at 110 % flow

2 21,36 at 100 % flow

3 21,95 at 90 % flow

Figure H.13 — Crossplot 2: Dry bulb = 13,4 °C and relative humidity = 60,42 % at test range = 7,3 °C

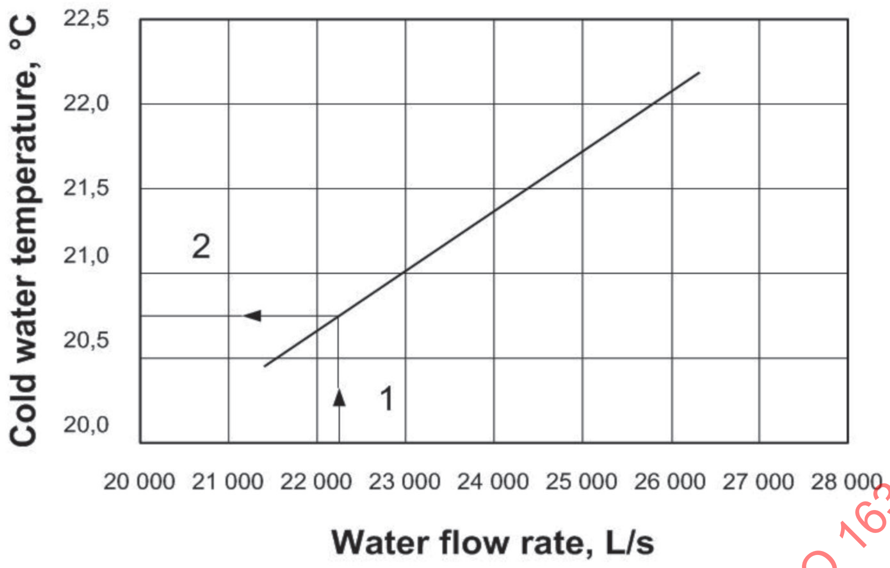


Key

1 measure test cold water = 20,50 °C

2 predicted water flow rate = 21 639 L/s

Figure H.14 — Crossplot 3: Dry bulb = 13,4 °C and relative humidity = 60,42 % at test range = 7,3 °C



Key

1 measured test water flow rate = 22 299 L/s

2 predicted cold water temperature = 20,75 °C

Figure H.15 — Crossplot 3: Dry bulb = 13,4 °C, relative humidity = 60,42 %, and range = 7,3 °C

Annex I
(normative)

Example evaluation of a natural draft cooling tower using the extended test method

I.1 General

Annex I describes and illustrates the extended test methodology for evaluating a thermal performance on an open-circuit natural draft cooling tower as described in 9.4 of this International Standard.

I.2 Design and test condition for a single valid test period

Design conditions for the natural draft cooling tower evaluated are summarized in Table I.1.

Table I.1 — Natural draft cooling tower design and test data

Parameter	Design value	Test value
Water flow rate (Q_{wt})	48 350 L/s	48 350 L/s
Hot water temperature (T_{hw})	35,15 °C	36,08 °C
Cold water temperature (T_{cw})	21,65 °C	22,75 °C
Inlet wet-bulb temperature (T_{wb})	10 °C	11 °C
Inlet dry-bulb temperature ($\mathrm{T_{db}}$)	11 °C	12,44 °C
Wind velocity (V_w)	4 m/s	0,1 m/s
Barometric pressure (P_{bp})	100,400 kPa	101,580 kPa

I.3 Test period approach in a single valid test period

I.3.1 All the following methodology is performed on a single valid test period according to the rules described in the 8.1 of this International Standard.

I.3.2 The following coefficients are supplied by the manufacturer at the time of submitting the offer (see 5.3.8).

Operating formula (thermal performance)

$$\left(\frac{KaV}{L}\right)_{\text{pred}} = C\left(\frac{L}{G}\right)^{*} \tag{I.1}$$

C and Π are given by the manufacturer. L and G are evaluated by calculation using design and test data. In this case, the following values shall be used:

a) C = 2,609 126

b) Π = – 0,705 710

c) L: evaluated by calculation using Q_{wt} and ρ_w at the T_{hwA}

d) G: evaluated by calculation (see step 2)

$\left(\frac{KaV}{L}\right)_t$ can be evaluated in test condition using Formula (I.2).

$$\left(\frac{KaV}{L}\right)_t = C_{\text{p,w}} \frac{1}{\gamma} \int_{T_{\text{cw}}}^{T_{\text{hw}}} \frac{dT}{h_{\text{M}} - h_{\text{A}}} \tag{I.2}$$

Simpson's rule is used to numerically evaluate the integral expression (see 9.4.2.3 for further explanations of this method). In our case, γ is equal to 1.

$\rho_{\text{A,2, pred}}$ is given by the draft formula:

$$\rho_{A,2,pred} = \rho_{A,1}\left(1 - \frac{1}{2}\frac{C_F}{g_c H} V_A^2\right) \tag{I.3}$$

where h and the expression of C_{F} are given by the manufacturer at the time of submitting the offer.

In this example, H is equal to 164,62 m and the C_{F} expression is:

$$C_{\text{F}} = C_{\text{FO}} \times C_{\text{V}}$$

with $C_{\text{FO}} = 499{,}783\,2 - 793{,}006\,8V_{\text{A}} + 538{,}529\,8V_{\text{A}}^2 - 165{,}889\,1V_{\text{A}}^3 - 19{,}280\,75V_{\text{A}}^4$

and

$$C_V = 1 + 0{,}034\,616\,95\frac{V_{10}}{V_A} - 0{,}045\,160\,10\left(\frac{V_{10}}{V_A}\right)^2 + 0{,}059\,123\,16\left(\frac{V_{10}}{V_A}\right)^3 - 0{,}0185\,534\,1\left(\frac{V_{10}}{V_A}\right)^4$$

$$+0{,}002\,282\,291\left(\frac{V_{10}}{V_A}\right)^5 - 0{,}000\,099\,724\,23\left(\frac{V_{10}}{V_A}\right)^6$$

where V_{10} is the wind velocity at 10 m height.

$\rho_{\text{A,2,t}}$ is provided by the test conditions using the value of the hot air temperature given by the hot air enthalpy value.

The hot air enthalpy is calculated by using Formula (I.4).

$$h_{\text{a,2}} = h_{\text{A,1}} + C_{\text{p,w}} \frac{L}{G}(T_{\text{hw}} - T_{\text{cw}}) \tag{I.4}$$

where $h_{\text{A,2}}$ is the hot air enthalpy at saturated conditions, that is, according to the simplifying assumption described in the paragraph 9.4.2.2.

$h_{\text{A,1}}$ and the cooling range (T_{hw} - T_{cw}) are provided by test conditions.