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Atmospheric icing of structures

Charges sur les structures dues à la glace

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www. iso. org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso. org/iso/foreword. html.

The committee responsible for this document is ISO/TC 98, *Bases for design of structures*, Subcommittee SC 3, *Loads, forces and other actions*.

This second edition cancels and replaces the first edition (ISO 12494:2001), of which it constitutes a minor revision. The changes made are the following:

— 8.1, line 2, replaced "ISO 4355" by "ISO 4354";

— 8.3, Figure 7, revised the right figure;

— 9.1, line 2 ,9.2, line 2 to 4, replaced "exceedence" by "exceedance";

— 9.2, line 11, replaced "to day's" by "today's";

— Clause 10, line 15, replaced "5.3" by "5.4";

— A.2, Table 3, line 1, replaced "the glaze mass" by "the mass of the ice, glaze or rime";

— A.2, Table 3, line 2, replaced "the glaze thickness" by "the thickness of the ice, glaze or rime";

— A.2, Table 3, line 4, replaced "the glaze density" by "the density of the ice, glaze or rime";

— A.2, Table 3, line 4, replaced "r" by "γ";

— A.2, Table 3, line 1 to 4, moved before Table 3,

— B.3.2, c), replaced "see Table 2 and 2.3" by "see Table 1 in 6.2.1";

— B.3.3, line 5, replaced "definitions 3.1 and 3.2" by "definitions B.3.1 and B.3.2";

— B.3.3, line 6, replaced "Table 4 or 5" by "Table 3 or 4";

— C.3, paragraph 6, line 4, replaced "0,7 cm^{-3}" by "0,7 g cm^{-3}";

— E.4, b), line1, replaced "ICG*x*" by "ICR*x*".

Annexes A to E of this document are for information only.

Introduction

This document describes ice actions and can be used in the design of certain types of structures.

It should be used in conjunction with ISO 2394 and also in conjunction with relevant CEN standards.

This document differs in some aspects from other International Standards, because the topic is poorly known and available information is inadequate. Therefore, it contains more explanations than usual, as well as supplementary descriptions and recommendations in the annexes.

Designers might find that they have better information on some specific topics than those available from this document. This may be true, especially in the future. They should, however, be very careful not to use only parts of this document partly, but only as a whole.

The main purpose of this document is to encourage designers to think about the possibility of ice accretions on a structure and to act thereafter.

As more information about the nature of atmospheric icing becomes available during the coming years, the need for updating this document is expected to be more urgent than usual.

Guidance is given as a NOTE, after the text for which it is a supplement. It is distinguished from the text by being in smaller typeface. This guidance includes some information and values which might be useful during practical design work, and which represents results that are not certain enough for this document, but may be useful in many cases until better information becomes available in the future.

Designers are therefore welcome to use information from the guidance notes, but they should be aware of the intention of the use and also forthcoming results of new investigations and/or measurements.

Atmospheric icing of structures

1 Scope

This document describes the general principles of determining ice load on structures of the types listed in this clause.

In cases where a certain structure is not directly covered by this or another standard or recommendation, designers can use the intentions of this document. However, it is the user's responsibility to carefully consider the applicability of this document to the structure in question.

The practical use of all data in this document is based upon certain knowledge of the site of the structure. Information about the degree of "normal" icing amounts (= ice classes) for the site in question is used. For many areas, however, no information is available.

Even in such cases, this document can be useful because local meteorologists or other experienced persons should be able to, on the safe side, estimate a proper ice class. Using such an estimate in the structural design will result in a much safer structure than designing without any considerations for problems due to ice.

CAUTION — It is extremely important to design for some ice instead of no ice, and then the question of whether the amount of ice was correct is of less importance. In particular, the action of wind can be increased considerably due to both increased exposed area and increased drag coefficient.

This document is intended for use in determining ice mass and wind load on the iced structure for the following types of structure:

— masts;

— towers;

— antennas and antenna structures;

— cables, stays, guy ropes, etc.;

— rope ways (cable railways);

— structures for ski-lifts;

— buildings or parts of them exposed to potential icing;

— towers for special types of construction such as transmission lines, wind turbines, etc.

Atmospheric icing on electrical overhead lines is covered by IEC (International Electrotechnical Commission) standards.

This document is intended to be used in conjunction with ISO 2394.

NOTE Some typical types of structure are mentioned, but other types can also be considered by designers by thinking in terms of which type of structure is sensitive to unforeseen ice, and act thereafter.

Also, in many cases, only parts of structures are to be designed for ice loads because they are more vulnerable to unforeseen ice than is the whole structure.

Even if electrical overhead lines are covered by IEC standards, designers can use this document for the mast structures to overhead lines (which are not covered by IEC standards) if they so wish.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 2394:2015, *General principles on reliability for structures*

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
accretion
process of building up ice on the surface of an object, resulting in the different types of icing on structures

3.2
drag coefficient
shape factor for an object to be used for the calculation of wind forces in the along-wind direction

3.3
glaze
clear, high-density ice

3.4
ice action
effect of accreted ice on a structure, both as gravity load (= self-weight of ice) and as wind action on the iced structure

3.5
ice class
IC
classification of the characteristic ice load that is expected to occur within a mean return period of 50 years on a reference ice collector situated in a particular location

3.6
in-cloud icing
icing due to super-cooled water droplets in a cloud or fog

3.7
precipitation icing
icing due to either

a) freezing rain or drizzle, or

b) accumulation of wet snow

3.8
return period
average number of years in which a stated action statistically is exceeded once

Note 1 to entry: A long return period means low transgression intensity (occurring rarely) and a short return period means high transgression intensity (occurring often).

3.9
rime
white ice with in-trapped air

4 Symbols

C_i	drag coefficient of an iced object	1
$C_{0,3}$	drag coefficient for large objects (width >0,3 m)	1
C_0	drag coefficient of an object without ice	1
D	diameter of accreted ice or total width of object including ice	mm
F_W	wind force	N/m
H	height above terrain	m
k	factor for velocity pressure from wind action	1
K_h	height factor	1
L	length of ice vane measured in windward direction	mm
m	mass of accreted ice per meter unit length	kg/m
m_W	ice mass for ice on large objects	kg
T	return period	year
t	ice thickness	mm
t_a	air temperature	°C
W	width of object (excluding ice) perpendicular to wind direction	mm
α	angle of incidence between wind direction and the objects longitudinal axis	°
γ	density of ice	kg/m^3
θ	angle of wind incidence in a vertical plane	°
τ	solidity ratio: $\dfrac{\text{exposed panel area}}{\text{total panel area within outside boundaries}}$	1
τ'	increased value of τ caused by icing to be used in calculations	1
ϕ	factor of combination	1

5 Effects of icing

5.1 General

The general effects of icing are the increased vertical loads on the iced structure and increased wind drag caused by the increased wind-exposed area. The latter can lead to more severe wind loads than without icing.

NOTE Clause 5 describes the way the ice loads act on a structure, and this can enable designers to understand the background and to use this document, even in cases which are not mentioned here.

5.2 Static ice loads

Different types of structure are more or less sensitive to varying aspects concerning ice action, and some examples on this are as follows.

a) Tensioned steel ropes, cables and guys, etc., are generally very sensitive to ice action, consequently tension forces in such elements can increase considerably in an iced condition.

b) Slender lattice structures, especially guyed masts, are sensitive to the increased axial compression forces from accreted ice on the structure.

c) Antennas and antenna structures can easily be overloaded by accreted ice, if this has not been foreseen. In particular, small fastening details are weak when increased load is added on top of other actions, because the ice may easily double the normal load.

d) “Sagging of ice” on non-structural elements can be harmful. Non-structural elements such as antennas and cables, may be exposed to unexpected ice load because the ice sags downwards and covers or presses on the elements. The ice action on these elements can then be substantially greater than the ice load normally accreted on them.

e) The load of accreted ice can easily deform or damage envelope elements (claddings, etc.), and damage also might occur if the ice has not fallen off before forces have grown too great.

5.3 Wind action on iced structures

Structures such as masts and towers, together with tensioned steel ropes, cables, mast guys, etc., are sensitive to increased wind drag caused by icing.

Wind action on iced structures may be calculated based on the same principles as the action on the ice-free structure. However, both the dimensions of the structural members and their drag coefficients are subject to changes. Therefore, the main purpose of this document is to specify proper values for

— dimensions and weight of accreted ice,

— shapes of accreted ice, and

— drag coefficients of accreted ice.

5.4 Dynamic effects

A significant factor influencing the dynamic behaviour of a structure is its natural frequencies.

Normally, the natural frequencies of a structure are decreased considerably if the structure is heavily iced. This is important in connection with dynamic investigations because the lower frequencies normally are the critical ones.

In addition, the change in cross-sectional shape due to the accreted ice may require dynamic investigations to be made. For example, the eccentric cross-sectional shape of ice on a cable or guy can cause aerodynamic instability resulting in heavy oscillations (e.g. galloping). Also, fully iced mast or tower sections can introduce vortex shedding, resulting in cross wind vibrations.

Shedding of ice from a structure can cause severe dynamic effects and stresses in the structure, depending on the type of structure and the amount and properties of the ice. Such dynamic effects should be investigated if the structure in question is sensitive to those actions. For a guyed mast, the shedding of ice from heavily iced guys may introduce severe dynamic vibrations and should be considered (see Clause 10).

NOTE This phenomenon has caused total collapses of very tall, guyed masts.

5.5 Damage caused by falling ice

When a structure is iced, this ice will sooner or later fall from the structure. The shedding of ice can be total or (most often) partial.

Experience shows that ice shedding typically occurs during increasing temperatures. Normally, accreted ice does not melt from the structure, but breaks because of small deflections, vibrations, etc. and falls off in fragments.

It is extremely difficult to avoid such falling ice, so this should be considered during design and when choosing the site for the structure.

Damage can occur to structural or non-structural elements (antennas, etc.) when ice from higher parts fall and hit lower elements in the structure. The height of falling ice is an important factor when evaluating risks of damage, because a greater height means greater dynamic forces from the ice. A method of avoiding or reducing damage from falling ice is the use of shielding structures.

NOTE See also 5.2 d) about "sagging of ice" and Clause 10 about unbalanced ice on guys, and Clause 11 on considerations on ice falling from a structure.

6 Fundamentals of atmospheric icing

6.1 General

The expression "atmospheric icing" comprises all processes where drifting or falling water droplets, rain, drizzle or wet snow in the atmosphere freeze or stick to any object exposed to the weather.

The accretion processes and resulting types of ice are described in this clause. The more theoretical explanation of the processes is given in Annexes C and D.

NOTE Unlike other meteorological parameters such as temperature, precipitation, wind and snow depths, there is generally very limited data available about ice accretions.

The wide variety of local topography, climate and icing conditions make it difficult to standardize actions from ice accretions.

Therefore, local (national) work has to be done, and such work should be based upon this document (see Annex B). It is urgent to be able to undertake comparisons between collected data and to exchange experiences, because this will be a way to improve knowledge and data necessary for a future comprehensive International Standard for atmospheric icing.

Detailed information about icing frequency, intensity, etc. should be collected.

The following methods may do this.

— A: collecting existing experiences.

— B: icing modelling based on known meteorological data.

— C: direct measurements of ice for many years.

Method A is a good starting one, because it makes it possible to obtain quickly information of considerable value. However, it will be necessary to have different types of structures established on proper areas, to be able to collect sufficiently broad information on ice frequencies and intensities. Therefore, experienced people in those fields should be consulted, e.g. telecommunication and power transmission companies, meteorological services and the like with in-service experience. The method can be recommended as the first thing to do, while awaiting results from Method C.

Method B usually demands some additional information or assumptions about the parameters.

The principles of icing modelling are presented in Annexes C and D.

For Method C, standardized measuring devices shall be operating in the areas representative of the planned site or at the actual construction site.

It is important that measurements follow standardized procedure, and such a procedure is described in Annex B.

Measurements should be taken for a sufficient long period to form a reliable basis for extreme value analysis. The length of the period could be from a few years to several decades, depending on the conditions.

However, shorter series can be of valuable help and can also be connected to longer records of meteorological data, either statistically or (better) physically, in combination with theoretical models.

6.2 Icing types

6.2.1 General

Atmospheric icing is traditionally classified according to two different formation processes:

a) precipitation icing;

b) in-cloud icing.

However, a classification may be based on other parameters, see Tables 1 and 2.

The physical properties and the appearance of the accreted ice will vary widely according to the variation in meteorological conditions during the ice growth.

Besides the properties mentioned in Table 1, other parameters, such as compressive strength (yield and crushing), shear strength, etc., may be used to describe the nature of accreted ice.

The maximum amount of accreted ice will depend on several factors, the most important being humidity, temperature and the duration of the ice accretion.

A main preconditions for significant ice accretion are the dimensions of the object exposed and its orientation to the direction of the icing wind. This is explained in more detail in Clause 7.

Table 1 — Typical properties of accreted atmospheric ice

Type of ice	Density kg/m^3	Adhesion and cohesion	General appearance	
			Colour	Shape
Glaze	900	strong	transparent	evenly distributed/icicles
Wet snow	300 to 600	weak (forming) strong (frozen)	white	evenly distributed/eccentric
Hard rime	600 to 900	strong	opaque	eccentric, pointing windward
Soft rime	200 to 600	low to medium	white	eccentric, pointing windward

NOTE 1 In practice, accretions formed of layers of different types of ice (mentioned in Table 1) can also occur, but from an engineering point of view the types of ice do not need to be described in more detail. Table 2 gives a schematic outline of the major meteorological parameters controlling ice accretion.

A cloud or fog consists of small water droplets or ice crystals. Even if the temperature is below the freezing point of water, the water droplets may remain in the water state. Such super-cooled droplets freeze immediately on impact with objects in the airflow.

Table 2 — Meteorological parameters controlling atmospheric ice accretion

Type of ice	Air temperature °C	Wind speed m/s	Droplet size	Water content in air	Typical storm duration
Precipitation icing					
Glaze (freezing rain or drizzle)	$-10 < t_a < 0$	any	large	medium	hours
Wet snow	$0 < t_a < +3$	any	flakes	very high	hours
In-cloud icing					
Glaze	see Figure 1	see Figure 1	medium	high	hours
Hard rime	see Figure 1	see Figure 1	medium	medium	days
Soft rime	see Figure 1	see Figure 1	small	low	days

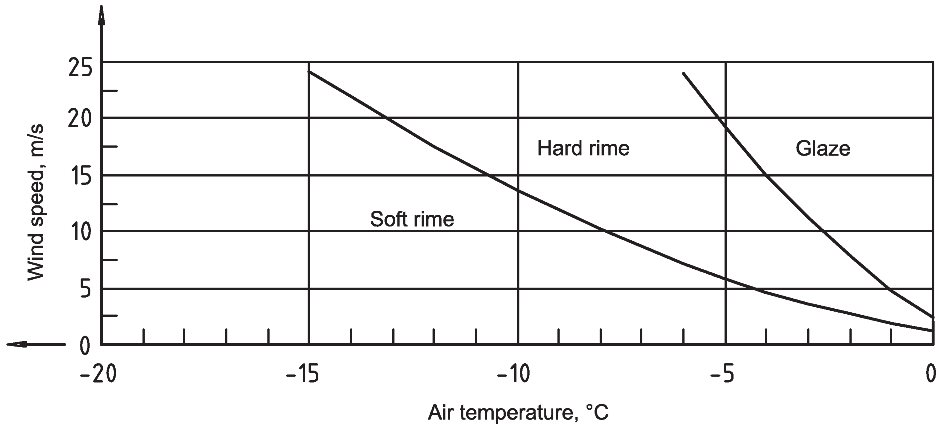
NOTE 2 When the flux of water droplets towards the object is less than the freezing rate, each droplet freezes before the next droplet impinges on the same spot, and the ice growth is said to be dry.

When the water flux increases, the ice growth will tend to be wet, because the droplets do not have the necessary time to freeze, before the next one impinges.

In general, dry icing results in different types of rime (containing air bubbles), while wet icing always forms glaze (solid and clear).

Figure 1 gives an indication of the parameters controlling the major types of ice formation.

The density of accreted ice varies widely from low (soft rime) over medium (hard rime) to high (glaze).



NOTE The curves shift to the left with increasing liquid water content and with decreasing object size.

Figure 1 — Type of accreted ice as a function of wind speed and air temperature

6.2.2 Glaze

Glaze is the type of precipitation ice having the highest density. Glaze is caused by freezing rain, freezing drizzle or wet in-cloud icing, and normally causes smooth evenly distributed ice accretion.

Glaze may result also in formation of icicles; in this case, the resulting shape can be rather asymmetric.

Glaze can be accreted on objects anywhere when rain or drizzle occurs at temperatures below freezing point.

NOTE Freezing rain or drizzle occurs when warm air aloft melts snow crystals and forms rain drops, which afterwards fall through a freezing air layer near the ground. Such temperature inversions can occur in connection with warm fronts, or in valleys where cold air can be trapped below warmer air aloft.

The surface temperature of accreting ice is near freezing point, and therefore liquid water, due to wind and gravity, can flow around the object and freeze also on the leeward side.

The accretion rate for glaze mainly varies with the following:

— rate of precipitation;

— wind speed;

— air temperature.

6.2.3 Wet snow

Wet snow is able to adhere to the surface of an object because of the occurrence of free water in the partly melted snow crystals. Wet snow accretion therefore occurs when the air temperature is just above the freezing point.

If decreasing temperature follows wet snow accretion, the snow will freeze. The density and adhesive strength vary widely with, among other things, the fraction of melted water and the wind speed.

6.2.4 Rime

Rime is the most common type of in-cloud icing and often forms vanes on the windward side of linear, non-rotatable objects, i.e. objects which will not rotate around the longitudinal axis due to eccentrical loading by ice.

During significant icing on small, linear objects, the cross section of the rime vane is nearby triangular with the top angle pointing windward but, as the width (diameter) of the object increases, the ice vane changes its form (see Clause 7).

Evenly distributed ice can also be formed by in-cloud icing when the object is a (nearly) horizontal "string" (linear shape) which is rotatable around its axis. The accreted ice on the windward side of the "string" will force it to rotate when the weight of ice is sufficient. This mechanism may continue as long as the ice accretion is going on. It results in an ice accretion more or less cylindrical around the string.

NOTE The liquid water content of the air becomes so small at temperatures below about −20 °C that practically no in-cloud icing occurs.

The most severe rime icing occurs on freely exposed mountains (coastal or inland), or where mountain valleys force moist air through passes, and consequently both lifts the air and increases the wind speed over the pass.

The accretion rate for rime mainly varies with the following:

— dimensions of the object exposed;

— wind speed;

— liquid water content in the air;

— drop size distribution;

— air temperature.

6.2.5 Other types of ice

Hoar frost, which is due to direct phase transition from water vapour into ice, is common at low temperatures. Hoar frost is of low density and strength, and normally does not result in significant load on structures.

6.3 Topographic influences

Regional and local topography modifies the vertical motions of the air masses and hence also the cloud structures precipitation intensity and, by these, the icing conditions.

The influence of terrain is generally different for in-cloud icing than for precipitation icing. In general, topography may be the basis for defining icing zones. Most often a detailed description is necessary concerning the following:

— distance from the coast (to windward/leeward);

— elevation above sea level;

— local topography (plains, valleys);

— mountain sides facing maritime climates (to windward);

— high level areas sheltered by higher mountains;

— high mountains situated on high level areas.

The most severe icing often occurs in mountain areas, where conditions can result in a combination of in-cloud and precipitation icing, where precipitation icing will normally be of the wet snow type.

NOTE When the wind is blowing from the sea, the mountains force the moist air upwards. This leads to condensation of water vapour and droplet growth on the windward side of the mountains due to cooling of the lifted, moist air.

On the leeward side of the mountains, the cloudy air will descend and the water droplets (or ice crystals) will evaporate, resulting in dissolution of the clouds.

In a mountain area, a local face of a cliff only about 50 m in height can give a significant reduction of in-cloud icing on the leeward vicinity of the cliff.

Additional lifting of the air by higher mountains, situated further inland, will cause new condensation and formation of clouds. But in this case, the passing of the coastal mountains has already reduced the liquid water content into the air. Therefore, the resulting icing at inland heights usually is less severe than the icing at the coastal heights.

In valleys, where cold air can be "trapped", severe icing due to precipitation is more frequent in the valley bottoms than on the surrounding hillsides.

6.4 Variation with height above terrain

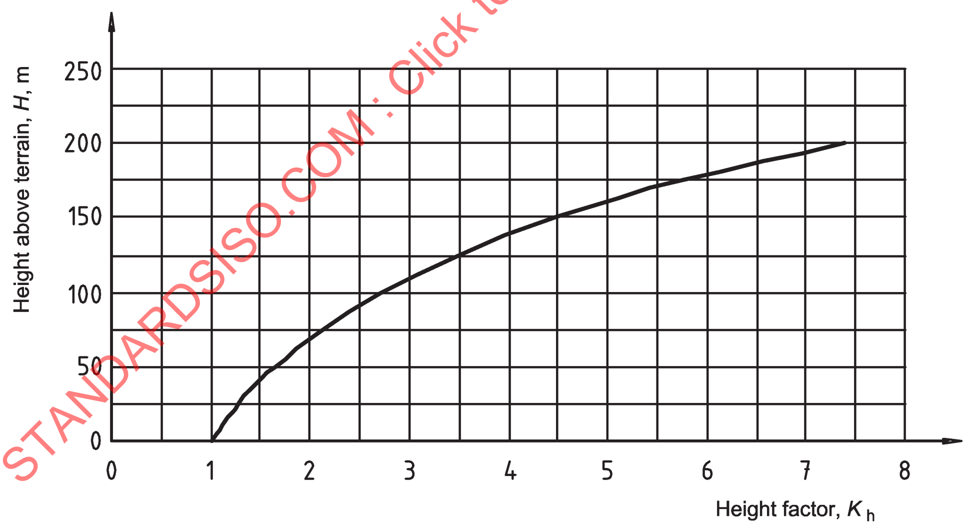
Ice mass on a structure may vary strongly with height of the element above terrain, but so far a simple model for the distribution of ice with height has not been found.

In some cases, ice may not be observed close to ground level, but at higher levels the ice load can be significant, and also the reverse situation may be found.

If heavy ice accretions appear probable, further meteorological studies on the particular site are recommended.

NOTE Figure 2 shows a typical multiplying factor for ice masses at higher levels above terrain (not above sea level). The factor can be applied for all types of ice, if site-specific data are not available, but reality can in some cases be more complicated than Figure 2 shows.

The height effect can be expressed also by specifying different ice classes for different levels of a high structure, e.g. mast, towers, ski-lifts, etc.



NOTE Height factor: $K_h = e^{0,01H}$. See Formula (A.3).

Figure 2 — Typical variation of ice masses with the height above terrain

7 Icing on structures

7.1 General

This clause contains principles of the procedure for determining characteristic ice actions and their effects on structures.

It is necessary to have accreted ice dimensions and masses to be able to determine ice actions.

The meteorological parameters, together with the physical properties of ice and icing duration, determine the size and weight of accreted ice on a given object.

Shapes of the accreted ice are primarily controlled by the amount and type of ice accreted and the size, shape and orientation of the exposed object.

Icing types specified below are separated into "glaze" (G) and "rime" (R). Wet snow should be treated as rime.

NOTE Under the same meteorological conditions, the ice accretion rate will vary with the dimensions, shape and orientation of the exposed object to the wind.

The most severe ice accretion will occur on an object which is placed in a plane, perpendicular to the wind direction, and with small cross-sectional dimensions. For example, ice accretes more rapidly on a thin wire than on a thick one. However, if the icing duration is long enough, the accreted ice dimensions of the two objects will be almost similar.

Therefore, specific objects such as cables, mast guys, antenna elements, lattice structures and the like can be exposed to much higher ice accretion rates than objects of greater diameter and of a solid structural type.

For the same reasons, on bigger objects the accreted ice normally will be concentrated on rims, sharp edges, etc.

There will be almost no ice accreted on a "one-dimensional" object (e.g. a wire) orientated parallel to the wind direction.

7.2 Ice classes

To be able to express the expected amount of accreted ice at a certain site, the term "ice class" (IC) is introduced.

IC is the parameter to be used by designers to determine how severe the ice accretion is expected to be at a particular site.

Meteorologists may provide information about the IC, and for a certain site, icing severity is defined by a certain ice class, which in general terms tells how much ice can be expected as defined for dimensioning purposes.

Data for ice classes in this clause are used as recommendations, based on which all ice actions may be determined for engineering use. These ice classes cover the possible variation of accreted ice for most sites, but not all sites (ref. IC G6 and R10 in Tables 3 and 4 should be used for extreme ice accretions).

NOTE Measurements and/or model studies are necessary to obtain the information needed for a specific site, unless experience can supply the same information.

The ice class may vary within rather short distances in a specific area. Measuring should be carried out where ice accretion is expected to be most severe, or at the precise building site (see Annex B).

7.3 Definition of ice class, IC

ICs are defined by a characteristic value, the 50 years return period of the ice accretion on the reference collector. This reference collector is a 30 mm diameter cylinder of a length not less than 0,5 m, placed 10 m above terrain and slowly rotating around its own axis (see Annex B and B.3).

ICs can be determined based upon

— meteorological and/or topographical data together with use of an ice accretion model, or

— ice masses (weight) per metre structural length, measured on site.

This means that a proper IC can be stipulated for certain sites, if one of the above-mentioned sets of information is available.

ICs are defined for both glaze and rime, because the characteristics for these differ. ICG is for glaze deposits and ICR for rime deposits (wet snow is here treated as rime).

The mass of ice is always calculated as the cross-sectional area of accreted ice (outside the cross-sectional area of the object inside the ice), multiplied by the density of the accreted ice.

7.4 Glaze

7.4.1 General

ICGs are defined as a certain ice thickness on the reference ice collector. Table 3 shows the ice thickness and mass for each ice class for glaze, ICG, while Figure 3 shows the stipulated accretion model for glaze.

Table 3 — Ice classes for glaze (ICG) (density of ice = 900 kg/m^3)

Ice class (IC)	Ice thickness t mm	Masses for glaze, m, kg/m Cylinder diameter, mm 10	30	100	300
G1	10	0,6	1,1	3,1	8,8
G2	20	1,7	2,8	6,8	18,1
G3	30	3,4	5,1	11,0	28,0
G4	40	5,7	7,9	15,8	38,5
G5	50	8,5	11,3	21,2	49,5
G6	To be used for extreme ice accretions				

7.4.2 Glaze on lattice structures

The masses and dimensions from Figure 3 and Table 3 may be used directly, and it is not normally necessary to consider adjustments because of icing overlaps at member intersections. If experience says so, allowance for severe formation of icicles may be made. This applies especially to ICG3 and greater, and may result in greater wind action and ice load than stated here.

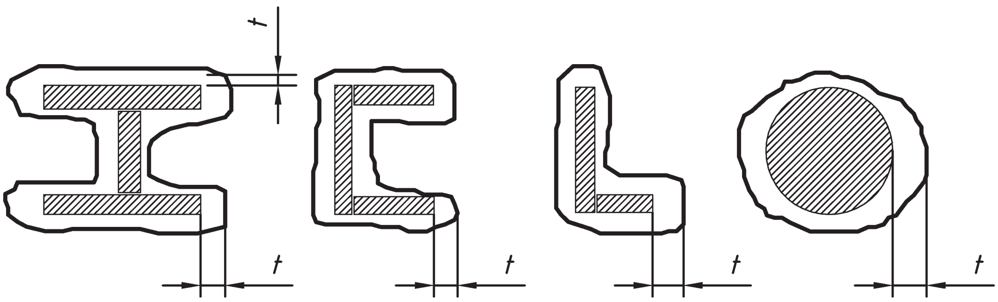


Figure 3 — Ice accretion model for glaze

The specified ice thickness is valid also for sloping elements. The thickness is measured perpendicular to the length axis of the bar and is always the same in all directions around the bar/object.

7.5 Rime

7.5.1 General

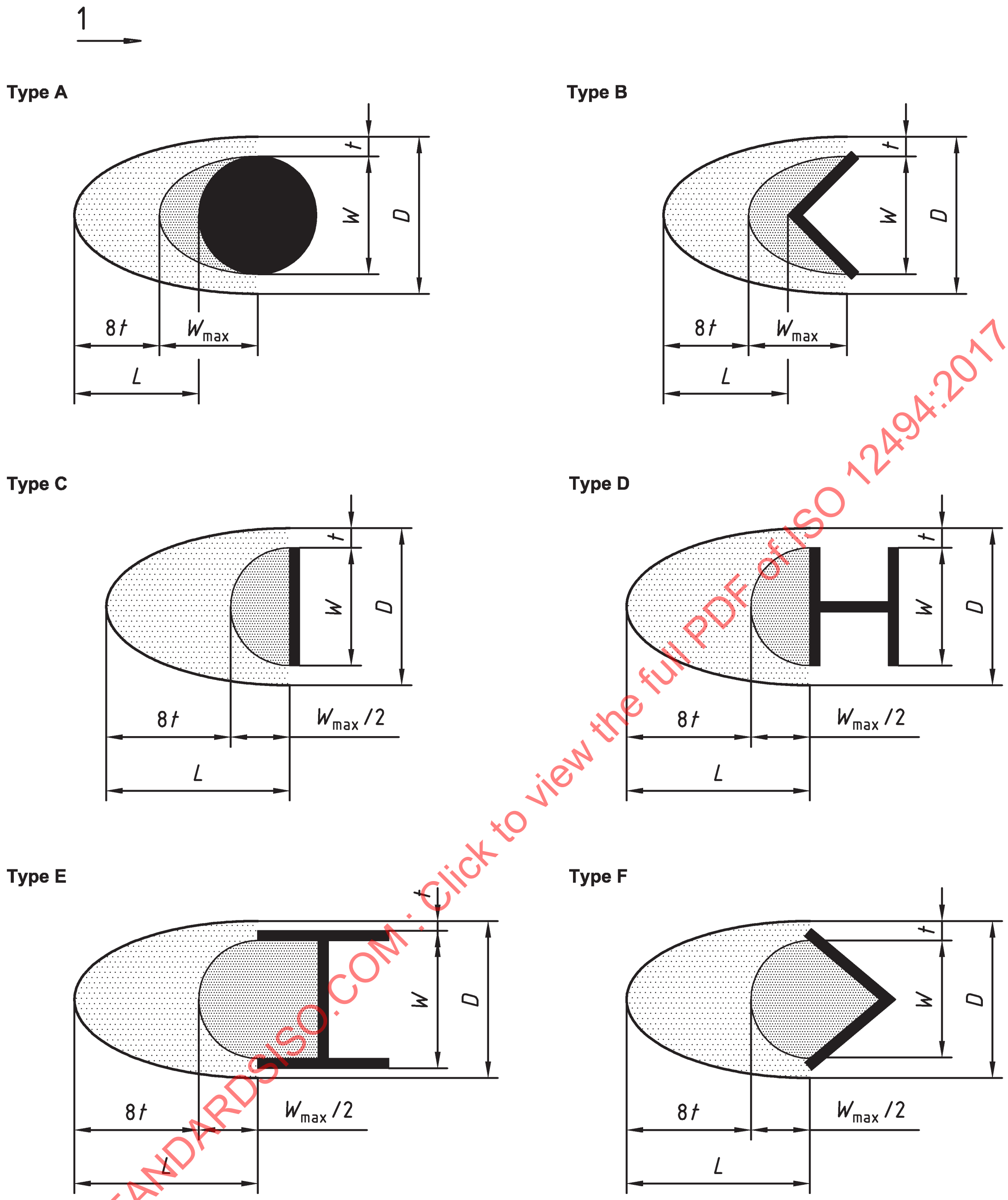
ICRs are defined as a certain ice mass on the reference ice collector. The tables below show the connection between ice masses and ice dimensions, depending on object shapes and dimensions and on ice density.

Unless otherwise specified, all rime shall be considered vane-shaped (see Figure 4) on profiles up to a width of 300 mm.

Table 4 shows the ice mass and dimensions for each ice class for rime, ICR.

Table 4 — Ice classes for rime (ICR)

Ice class (IC)	Ice mass *m* kg/m	**Rime diameter** (mm) **for object diameter of 30 mm**			
		Density of rime (kg/m^3)			
		300	**500**	**700**	**900**
R1	0,5	55	47	43	40
R2	0,9	69	56	50	47
R3	1,6	88	71	62	56
R4	2,8	113	90	77	70
R5	5,0	149	117	100	89
R6	8,9	197	154	131	116
R7	16,0	262	204	173	153
R8	28,0	346	269	228	201
R9	50,0	462	358	303	268
R10	To be used for extreme ice accretions				



Key

1 wind direction

Figure 4 — Ice accretion model for rime

The model for rime in Figure 4 is based on the precondition that the ice collector is non-rotatable and nearly horizontal.

In general, ICRs and density of ice define ice masses accreted on profiles, but the iced dimensions have to be calculated.

7.5.2 Rime on single members

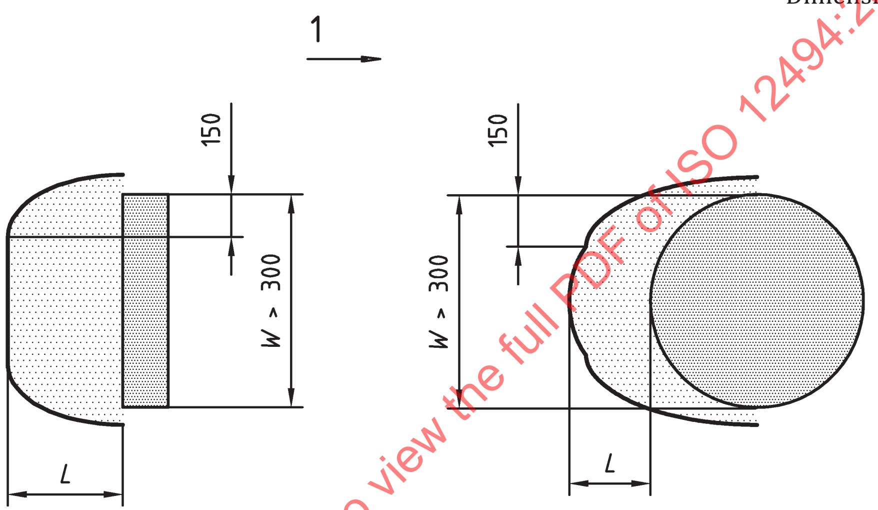
7.5.2.1 General

Information similar to those shown in Tables 5 to 9 is necessary for the practical use of this document. As soon as the ICR has been found, the corresponding ice vane dimensions can be calculated. Ice vane dimensions will slightly change with the type of (steel) section used.

7.5.2.2 Slender structural members with object width u 300 mm

The icing models in Figures 4 and 5 explain how the ice deposits are presumed to be shaped and consequently how the formulae are constructed.

Dimensions in millimetres



Key

1 wind direction

Figure 5 — Ice accretion model for rime, large objects

If better information from, for example, measurements are available, this should be used. If this is not the case, Tables 5 to 7 should be used for calculation of loads and actions.

NOTE 1 Figure 4 shows the stipulated accretion model for rime on bars of dimension up to 300 mm. The model shows that ice accretion is built up against the wind direction (on the windward side of the object).

The shaded area indicated as W (width of object) or ½W shows the first ice accretion without any increase in object width. The indication 8t shows the way further accretion occurs, where t (thickness of ice) is the increase measured perpendicular to the wind direction.

Ice accretion on profile shapes E and F starts without increasing the dimensions of the cross sections.

The measure L is the increase of the original profiles exposed width and is therefore added to W (without ice) for wind load calculations.

Tables 5 to 7 show ice vane dimensions for typical profile dimensions and cross-sectional shapes, all calculated for an ice density of 500 kg/m^3. If values required cannot be found in the tables, they should be calculated by using the formulae in Annex A, e.g. dimensions and densities not given in the tables.

Even if the values in Tables 5 to 7 appear to be almost alike, it has been found to be rational to separate between the few major types of cross sections, also because the future might show increased difference.

Table 5 — Ice dimensions for vane shaped accreted ice on bars, types A and B (valid only for in-cloud icing; density of ice = 500 kg/m³)

Cross sectional shape of bars: Types A and B									
Object width, mm		10		30		100		300	
IC	**Ice mass**	**Ice vane dimensions,** mm							
	m, kg/m	*L*	*D*	*L*	*D*	*L*	*D*	*L*	*D*
R1	0,5	54	22	34	35	13	100	4	300
R2	0,9	78	28	54	40	23	100	8	300
R3	1,6	109	36	82	47	41	100	14	300
R4	2,8	150	46	120	56	67	104	24	300
R5	5,0	207	60	174	70	106	114	42	300
R6	8,9	282	79	247	88	165	129	76	300
R7	16,0	384	105	348	113	253	151	136	300
R8	28,0	514	137	478	146	372	181	217	317
R9	50,0	694	182	656	190	543	223	344	349
R10	To be used for extreme ice accretions								

Table 6 — Ice dimensions for vane shaped accreted ice on bars, types C and D (valid only for in-cloud icing; density of ice = 500 kg/m³)

Cross sectional shape of bars: Types C and D									
Object width, mm		10		30		100		300	
IC	**Ice mass**	**Ice vane dimensions,** mm							
	m, kg/m	*L*	*D*	*L*	*D*	*L*	*D*	*L*	*D*
R1	0,5	56	23	36	35	13	100	4	300
R2	0,9	80	29	57	40	23	100	8	300
R3	1,6	111	37	86	48	41	100	14	300
R4	2,8	152	47	124	57	68	105	24	300
R5	5,0	209	61	179	71	111	115	42	300
R6	8,9	284	80	253	90	173	131	76	300
R7	16,0	387	105	355	115	265	154	136	300
R8	28,0	517	138	484	147	387	184	224	318
R9	50,0	696	183	663	192	560	227	361	353
R10	To be used for extreme ice accretions								

NOTE 2 Cylindrical accreted ice is only valid for slender elements of low torsional stiffness and sloping not more than about 45° to a horizontal plane (e.g. cables, steel ropes, etc.). In such cases, ice dimensions can be calculated from ice masses, defined as ICRs (see Table 4).

Table 7 — Ice dimensions for vane-shaped accreted ice on bars, types E and F (valid only for in-cloud icing; density of ice = 500 kg/m^3)

Cross-sectional shape of bars: Types E and F									
Object width, mm		10		30		100		300	
IC	**Ice mass**	**Ice vane dimensions,** mm							
	m, kg/m	*L*	*D*	*L*	*D*	*L*	*D*	*L*	*D*
R1	0,5	55	23	29	34	0	100	0	300
R2	0,9	79	29	51	39	0	100	0	300
R3	1,6	111	36	81	47	9	100	0	300
R4	2,8	152	47	121	57	39	100	0	300
R5	5,0	209	61	177	70	87	109	0	300
R6	8,9	284	80	251	89	154	126	0	300
R7	16,0	387	105	353	115	250	150	40	300
R8	28,0	517	138	483	147	376	181	142	300
R9	50,0	696	183	662	192	551	225	294	336
R10	To be used for extreme ice accretions								

The values in the tables shall be changed in accordance with other profile dimensions and densities of ice; see Annex A for formulae used.

7.5.2.3 Single members with object width (W) > 300 mm

When profile dimensions increase and gradually change shape towards other types of cross sections, another accretion model is expedient, and when object dimensions increase, the ice accretion will change in amount and shape.

It is therefore necessary regarding large objects to change the accretion model in order to come as close to nature as possible.

Figure 5 shows the stipulated accretion model for rime on big objects, which have been defined as dimensions (W) above 300 mm up to 5 m. Tables 8 and 9 show dimensions and masses for large objects.

NOTE Within each ICR, the length (L) of the ice vane for W = 300 mm (in accordance with Figures 5 and 6) is kept constant for all object widths, but the ice mass is gradually increased with increasing object width. The shape of large objects follows the types in Figure 4.

Profiles with W > 300 mm and non-lattice structures, such as concrete towers, claddings or other structures with solidity ratio near to or equal to 1,0, should be handled in accordance with this clause, and there is no upper limit for W.

The change of icing model will for larger object dimensions result in proportionally less wind load with ice compared to that without ice, than the model for smaller dimensions, but with a slight increase in ice masses, so masses will now be greater than those according to the ICR definitions.

Figure 5 shows the used icing model for objects with W greater than 300 mm. Ice masses are increased but not at the same rate as for smaller objects.

For the most common object shapes of large dimensions, Table 8 (flat objects) and Table 9 (circular-shaped objects) show ice dimensions and masses for object widths 300 mm, 500 mm, 1 000 mm, 3 000 mm and 5 000 mm.

As for smaller dimensions, ice density is 500 kg/m^3 and all values shall be adjusted for other densities and/or other dimensions, see Annex A for formulae used.

Table 8 — Accreted ice dimensions and masses for large, flat objects (valid only for in-cloud icing; density of ice = 500 kg/m^3)

Cross-sectional shape of object: Large, flat objects							
Object width, mm			300	500	1 000	3 000	5 000
IC	**Ice mass**	**Ice length,** *L* (mm), **and mass,** *m* (kg/m)					
	m, kg/m	*L*, all dim.	*m*	*m*	*m*	*m*	*m*
R1	0,5	4	0,5	0,9	2,0	6,2	10,5
R2	0,9	8	0,9	1,7	3,6	11,2	18,9
R3	1,6	14	1,6	3,0	6,4	19,9	33,5
R4	2,8	24	2,8	5,2	11,1	34,9	58,7
R5	5,0	42	5,0	9,2	19,9	62,3	105
R6	8,9	76	8,9	16,5	35,3	111	186
R7	16,0	136	16,0	29,6	63,5	199	335
R8	28,0	224	28,0	50,4	106	330	554
R9	50,0	361	50,0	86,1	176	537	898
R10	To be used for extreme ice accretions						

Table 9 — Accreted ice dimensions and masses for large, rounded objects (valid only for in-cloud icing; density of ice = 500 kg/m^3)

Cross-sectional shape of object: Large, rounded objects							
Object width, mm			300	500	1 000	3 000	5 000
IC	**Ice mass**	**Ice length,** *L* (mm), **and mass,** *m* (kg/m)					
	m, kg/m	*L*, all dim.	*m*	*m*	*m*	*m*	*m*
R1	0,5	4	0,5	0,9	2,0	6,2	10,5
R2	0,9	8	0,9	1,7	3,6	11,2	18,9
R3	1,6	14	1,6	3,0	6,4	19,9	33,5
R4	2,8	24	2,8	5,2	11,1	34,9	58,7
R5	5,0	42	5,0	9,2	19,9	62,3	105
R6	8,9	76	8,9	16,5	35,3	111	186
R7	16,0	136	16,0	29,6	63,5	199	335
R8	28,0	217	28,0	49,7	104	321	538
R9	50,0	344	50,0	84,4	171	515	859
R10	To be used for extreme ice accretions						

7.6 Rime on lattice structures

7.6.1 General

In the case of structures built of interconnected, slender elements (such as lattice masts), the ice vanes can grow together and result in much larger ice formations than is possible for the solid, unperforated profile.

The basic specification of ice loads for calculations is normally specification of an amount of ice on single members (bars) of the structure. The amount of ice can now be expressed as an ICR, because ICR defines both the ice mass and the profile dimension with ice.

A specification of ICR could include “a total iced structure” instead of a specific member ICR, and in this case, the iced structure will appear like an iced concrete tower.

If the basic specification is just a certain ICR, the ice mass on any profile dimension is defined and all ice dimensions on any profile dimension can be found by using the tables or the formulae in Annex A.

NOTE When ICRs have been found from Table 4, this information is used in connection with Tables 5 to 7 for determining ice dimensions and masses for other (normal) types of profile.

In principle, accreted ice is assumed to be vane-shaped, and the density shall have been determined, see Table 1.

For high ICRs, icing dimensions (Tables 5 to 7) can develop considerable icing overlaps at intersections of structural members, because of the ice thickness. Ice masses may be reduced to take into account overlaps (the iced length of a member is shorter than the structural length of the same member). As mentioned above, it is also possible that icing will grow into a solid structure.

It is therefore important to be aware of the icing mechanisms when estimating the total ice load on such a type of structure.

The total ice mass (self-weight of ice) should be found as the sum of ice masses per metre unit length, where the specific mass per metre is taken from the tables (or calculated from Annex A). Adjustments for overlapping of ice at intersections of structural members may be made.

7.6.2 Direction of ice vanes on the structure

The optimum situation for determining ice load is when information about the icing wind direction is known. For such a case the ice vanes accrete in this known, fixed wind direction regardless of the wind directions used for the design of the uniced structure.

This situation, however, might not occur, and in those cases the calculation of wind forces shall be determined under the most unfavourable assumption. This is that the ice vanes should be placed on the structure as if the icing wind direction is perpendicular on the direction of the wind used for the design of the uniced structure. Because many structures need to be investigated for several wind directions, this procedure should be carried out for each wind direction.

Because many structural cross sections have different dimensions (e.g. profile width) when seen from different directions in the horizontal plane, the ice vanes’ dimensions will change as well. Therefore, new calculations of amounts of ice shall be carried out for each wind direction.

A more simple (“on the safe side”) calculation may be used: Find the icing direction which produces the greatest wind action on the structure in question. Use this wind action and ice load for the same situation for all wind directions to be investigated.

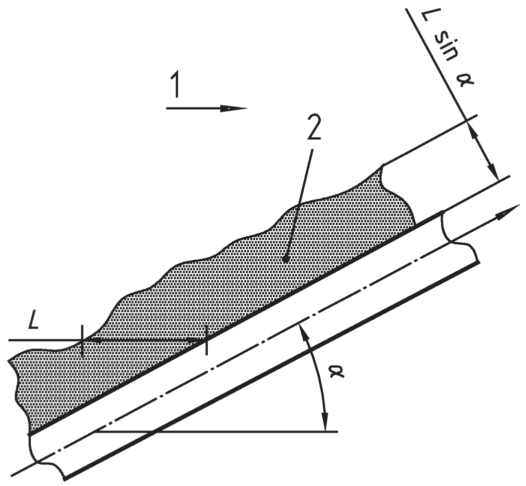
7.6.3 Icing on members inclined to the wind direction

The length axis of ice vanes shall always be horizontal, so all dimensions of ice are measured in the horizontal plane.

The inclination to the wind is measured in the horizontal plane, see Figure 6, so ice mass along the axis of a member is $m \sin \alpha$, where m is found from the tables.

In order always to obtain some ice also on horizontal members with length axis in the wind direction, the angle α shall not be considered smaller than 10° corresponding to a change of wind direction (in all planes) of ±10° during ice accretion.

NOTE This means that a bar theoretically situated parallel to the icing wind direction will at least get ice from an angle of incidence of 10°, resulting in ice thickness of $L \sin 10°$, where L is the ice vane length from the tables. The ice masses measured along the bar length will be $m \sin 10°$ as well, where m is found from the tables (or calculated based on the formulae in Annex A).



Key

1 wind direction

2 ice mass, *m*, per unit length

Figure 6 — Calculations for inclined members (round bar shown in horizontal plane)

8 Wind actions on iced structures

8.1 General

Wind actions are in principle calculated in accordance with standard procedures for wind-load calculations (see ISO 4354). However, dimensions and drag coefficients with ice are changed compared to "without ice" in accordance with this document.

To be able to calculate wind actions for a structure in an iced condition, values of the drag coefficient for the iced structure, C_i are necessary. In most cases, C_i values are different from the drag coefficients for the uniced structure, C_0. The C_i values however, can to some extent be connected to the C_0 values, which can be made use of in stipulating C_i values.

For almost any shape and dimension, it is possible to find information about C_0 values and this, combined with the knowledge of the surface condition of rime, has been used to stipulate the C_i values given below.

All C_i values shall be used on the iced dimensions, which are greater than without ice.

The drag coefficient is always valid for wind direction perpendicular to the plane containing the length axis of the object (profile). Other angles of incidence to this plane should be adjusted for, for example, by using the formulae given in 8.3.

8.2 Single members

8.2.1 General

Such elements are normally profiles of different cross-sectional shapes and sizes. Existing standards give C_0 values (perpendicular to length, without ice) for all types of profiles used.

The drag coefficient of an iced member depends on the type of profile, its C_0 value, the ice class, the type of ice, the width of the member and the wind direction compared to the axis of ice accretion.

8.2.2 Drag coefficients for glaze

It is important to use reasonable values for drag coefficient on iced members, and they normally will differ from values for the same members without ice.

The values in Tables 10 to 15 have been chosen based on typical natural shapes of ice accretions and normally used values for sections of approximately same shapes and dimensions as the iced members.

It might be possible to find more reliable values, and if so this should be done. However, if this is not possible, the coefficients below should be used.

NOTE Glaze is considered to be deposited as a uniform layer of ice on the whole surface of an object (see 7.4). This accretion model tends to smooth out the differences in the cross section of the member, leading towards a more or less uniform shape. The main effect concerning drag coefficients is that C_i values are expected to increase on circular cross sections and to decrease on edged cross sections compared to values without ice, and the effect is stronger the higher is the IC.

The final C_i value is for the highest IC estimated to be about 1,4 as for a circular cross section with a rough surface.

Table 10 contains recommended values of C_i for different values of C_0, and for all ICGs. It should be noted that at high ICGs icicles can occur and can cause increased C_i values. This model may be assumed for members up to a width without ice of about 0,3 m.

Large, solid objects are less influenced by ice accretion. It is therefore considered that the effect of glaze may be neglected on members with a width of 5 m and above.

Table 10 — C_i coefficients for glaze on bars

Ice class (IC)	Ice thickness	C_i coefficients for glaze on bars						
		Drag coefficients without ice, C_0						
	mm	0,50	0,75	1,00	1,25	1,50	1,75	2,00
G1	10	0,68	0,88	1,08	1,28	1,48	1,68	1,88
G2	20	0,86	1,01	1,16	1,31	1,46	1,61	1,76
G3	30	1,04	1,14	1,24	1,34	1,44	1,54	1,64
G4	40	1,22	1,27	1,32	1,37	1,42	1,47	1,52
G5	50	1,40	1,40	1,40	1,40	1,40	1,40	1,40
G6	To be used for extreme ice accretions							

The following C_i values are recommended used for object width between 0,3 m and 5,0 m, and have been calculated using linear interpolation on the important parameters: glaze thickness, C_0 values and member width.

For object width >5,0 m, C_i values can be assumed equal to C_0 (without ice accretion).

Tables 11 to 15 show C_i values for large objects and ICG1-G5.

Table 11 — C_i coefficients for glaze, ICG1, large objects

Object width	C_i coefficients for glaze, large objects						
	Drag coefficients without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,68	0,88	1,08	1,28	1,48	1,68	1,88
1,0	0,65	0,86	1,07	1,28	1,48	1,69	1,90
2,0	0,61	0,83	1,05	1,27	1,49	1,71	1,92
3,0	0,58	0,81	1,03	1,26	1,49	1,72	1,95
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 12 — C_i coefficients for glaze, ICG2, large objects

Object width	C_i coefficients for glaze, large objects						
	Drag coefficients without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,86	1,01	1,16	1,31	1,46	1,61	1,76
1,0	0,81	0,97	1,14	1,30	1,47	1,63	1,80
2,0	0,73	0,92	1,10	1,29	1,47	1,66	1,85
3,0	0,65	0,86	1,07	1,28	1,48	1,69	1,90
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 13 — C_i coefficients for glaze, ICG3, large objects

Object width	C_i coefficients for glaze, large objects						
	Drag coefficients without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,04	1,14	1,24	1,34	1,44	1,54	1,64
1,0	0,96	1,08	1,20	1,33	1,45	1,57	1,69
2,0	0,84	1,00	1,15	1,31	1,46	1,62	1,77
3,0	0,73	0,92	1,10	1,29	1,47	1,66	1,85
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 14 — C_i coefficients for glaze, ICG4, large objects

Object width	C_i coefficients for glaze, large objects						
	Drag coefficients without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,22	1,27	1,32	1,37	1,42	1,47	1,52
1,0	1,11	1,19	1,27	1,35	1,43	1,51	1,59
2,0	0,96	1,08	1,20	1,33	1,45	1,57	1,69
3,0	0,81	0,97	1,14	1,30	1,47	1,63	1,80
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 15 — C_i coefficients for glaze, ICG5, large objects

Object width	C_i coefficients for glaze, large objects						
	Drag coefficients without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,40	1,40	1,40	1,40	1,40	1,40	1,40
1,0	1,27	1,30	1,34	1,38	1,41	1,45	1,49
2,0	1,07	1,16	1,26	1,35	1,44	1,53	1,62
3,0	0,88	1,03	1,17	1,31	1,46	1,60	1,74
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

8.2.3 Drag coefficients for rime

It is important to use reasonable values for drag coefficients on iced members, and they normally will differ from values for the same members without ice.

The values below have been chosen based on typical natural shapes of ice accretions and normally used values for sections of approximately same shapes and dimensions as the iced members.

It might be possible to find more reliable values, and if so this should be done. However, if this is not possible, the coefficients below should be used.

NOTE 1 The assumed model for accretion of rime is described in 7.6.

As for glaze, rime accretion also diminishes the differences of drag coefficients for profiles with different cross-sectional shapes.

For the most severe ICRs all slender members are expected to have the same C_i values, no matter what initial profile shapes.

The C value for the particular cross section without ice is C_0. In ICR9 the C_i value is estimated to be 1,6 for all object widths (without ice) up to 300 mm.

All the following C_i values are valid for a wind direction perpendicular to the ice vane and the length axis of and the member.

For ICRs between R1 and R9, C values shall be found by linear interpolation with respect to the important parameters.

Table 16 shows recommended values of C_i for different values of C_0 and for slender objects.

Table 16 — C_i coefficients for rime on bars

IC	Ice mass m kg/m	C_i coefficients for rime on bars Drag coefficient without ice, C_0						
		0,50	0,75	1,00	1,25	1,50	1,75	2,00
R1	0,5	0,62	0,84	1,07	1,29	1,51	1,73	1,96
R2	0,9	0,74	0,94	1,13	1,33	1,52	1,72	1,91
R3	1,6	0,87	1,03	1,20	1,37	1,53	1,70	1,87
R4	2,8	0,99	1,13	1,27	1,41	1,54	1,68	1,82
R5	5,0	1,11	1,22	1,33	1,44	1,56	1,67	1,78
R6	8,9	1,23	1,32	1,40	1,48	1,57	1,65	1,73
R7	16,0	1,36	1,41	1,47	1,52	1,58	1,63	1,69
R8	28,0	1,48	1,51	1,53	1,56	1,59	1,62	1,64
R9	50,0	1,60	1,60	1,60	1,60	1,60	1,60	1,60
R10	To be used for extreme ice accretions							

NOTE 2 As for glaze, the model for rime is assumed valid up to a member width of 0,3 m. For wider members, the drag coefficients are less influenced by ice accretion, and the effect can be neglected for object widths above 5,0 m.

Tables 17 to 25 show C_i values for large objects and ICR1 to ICR9.

Table 17 — C_i coefficients for rime, ICR1, large objects

Object width m	C_i coefficients for rime, large objects Drag coefficient without ice, C_0						
	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,62	0,84	1,07	1,29	1,51	1,73	1,96
0,5	0,62	0,84	1,06	1,29	1,51	1,73	1,96
1,0	0,60	0,83	1,06	1,28	1,51	1,74	1,96
1,5	0,59	0,82	1,05	1,28	1,51	1,74	1,97
2,0	0,58	0,81	1,04	1,27	1,51	1,74	1,97
2,5	0,57	0,80	1,04	1,27	1,51	1,74	1,98
3,0	0,55	0,79	1,03	1,27	1,50	1,74	1,98
4,0	0,53	0,77	1,01	1,26	1,50	1,75	1,99
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 18 — C_i coefficients for rime, ICR2, large objects

Object width m	C_i coefficients for rime, large objects Drag coefficient without ice, C_0						
	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,74	0,94	1,13	1,33	1,52	1,72	1,91
0,5	0,73	0,93	1,13	1,32	1,52	1,72	1,91
1,0	0,71	0,91	1,11	1,32	1,52	1,72	1,92
1,5	0,68	0,89	1,10	1,31	1,52	1,73	1,93
2,0	0,66	0,87	1,09	1,30	1,51	1,73	1,94
2,5	0,63	0,85	1,07	1,29	1,51	1,73	1,95
3,0	0,60	0,83	1,06	1,28	1,51	1,74	1,96
4,0	0,55	0,79	1,03	1,27	1,50	1,74	1,98
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 19 — C_i coefficients for rime, ICR3, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,87	1,03	1,20	1,37	1,53	1,70	1,87
0,5	0,85	1,02	1,19	1,36	1,53	1,70	1,87
1,0	0,81	0,99	1,17	1,35	1,53	1,71	1,89
1,5	0,77	0,96	1,15	1,34	1,52	1,71	1,90
2,0	0,73	0,93	1,13	1,32	1,52	1,72	1,91
2,5	0,70	0,90	1,11	1,31	1,52	1,72	1,93
3,0	0,66	0,87	1,09	1,30	1,51	1,73	1,94
4,0	0,58	0,81	1,04	1,27	1,51	1,74	1,97
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 20 — C_i coefficients for rime, ICR4, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	0,99	1,13	1,27	1,41	1,54	1,68	1,82
0,5	0,97	1,11	1,26	1,40	1,54	1,69	1,83
1,0	0,92	1,07	1,23	1,38	1,54	1,69	1,85
1,5	0,86	1,03	1,20	1,37	1,53	1,70	1,87
2,0	0,81	0,99	1,17	1,35	1,53	1,71	1,89
2,5	0,76	0,95	1,14	1,33	1,52	1,71	1,91
3,0	0,71	0,91	1,11	1,32	1,52	1,72	1,92
4,0	0,60	0,83	1,06	1,28	1,51	1,74	1,96
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 21 — C_i coefficients for rime, ICR5, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,11	1,22	1,33	1,44	1,56	1,67	1,78
0,5	1,09	1,20	1,32	1,44	1,55	1,67	1,79
1,0	1,02	1,15	1,28	1,42	1,55	1,68	1,81
1,5	0,96	1,10	1,25	1,39	1,54	1,69	1,83
2,0	0,89	1,05	1,21	1,37	1,54	1,70	1,86
2,5	0,83	1,00	1,18	1,35	1,53	1,71	1,88
3,0	0,76	0,95	1,14	1,33	1,52	1,71	1,91
4,0	0,63	0,85	1,07	1,29	1,51	1,73	1,95
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 22 — C_i coefficients for rime, ICR6, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,23	1,32	1,40	1,48	1,57	1,65	1,73
0,5	1,20	1,29	1,38	1,47	1,56	1,65	1,74
1,0	1,12	1,23	1,34	1,45	1,56	1,66	1,77
1,5	1,05	1,17	1,30	1,42	1,55	1,68	1,80
2,0	0,97	1,11	1,26	1,40	1,54	1,69	1,83
2,5	0,89	1,05	1,21	1,37	1,54	1,70	1,86
3,0	0,81	0,99	1,17	1,35	1,53	1,71	1,89
4,0	0,66	0,87	1,09	1,30	1,51	1,73	1,94
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 23 — C_i coefficients for rime, ICR7, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,36	1,41	1,47	1,52	1,58	1,63	1,69
0,5	1,32	1,38	1,45	1,51	1,57	1,64	1,70
1,0	1,23	1,31	1,40	1,48	1,57	1,65	1,74
1,5	1,14	1,24	1,35	1,45	1,56	1,66	1,77
2,0	1,05	1,17	1,30	1,42	1,55	1,68	1,80
2,5	0,96	1,10	1,25	1,39	1,54	1,69	1,83
3,0	0,86	1,03	1,20	1,37	1,53	1,70	1,87
4,0	0,68	0,89	1,10	1,31	1,52	1,73	1,93
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 24 — C_i coefficients for rime, ICR8, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,48	1,51	1,53	1,56	1,59	1,62	1,64
0,5	1,44	1,47	1,51	1,55	1,59	1,62	1,66
1,0	1,33	1,39	1,45	1,51	1,58	1,64	1,70
1,5	1,23	1,31	1,40	1,48	1,57	1,65	1,74
2,0	1,12	1,23	1,34	1,45	1,56	1,66	1,77
2,5	1,02	1,15	1,28	1,42	1,55	1,68	1,81
3,0	0,92	1,07	1,23	1,38	1,54	1,69	1,85
4,0	0,71	0,91	1,11	1,32	1,52	1,72	1,92
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

Table 25 — C_i coefficients for rime, ICR9, large objects

Object width	C_i coefficients for rime, large objects						
	Drag coefficient without ice, C_0						
m	0,50	0,75	1,00	1,25	1,50	1,75	2,00
≤0,3	1,60	1,60	1,60	1,60	1,60	1,60	1,60
0,5	1,55	1,56	1,57	1,59	1,60	1,61	1,62
1,0	1,44	1,47	1,51	1,55	1,59	1,62	1,66
1,5	1,32	1,38	1,45	1,51	1,57	1,64	1,70
2,0	1,20	1,29	1,38	1,47	1,56	1,65	1,74
2,5	1,09	1,20	1,32	1,44	1,55	1,67	1,79
3,0	0,97	1,11	1,26	1,40	1,54	1,69	1,83
4,0	0,73	0,93	1,13	1,32	1,52	1,72	1,91
≥5,0	0,50	0,75	1,00	1,25	1,50	1,75	2,00

8.3 Angle of incidence

Drag coefficients refer to a wind direction perpendicular to the length axis of the member and to the width of the (iced) member.

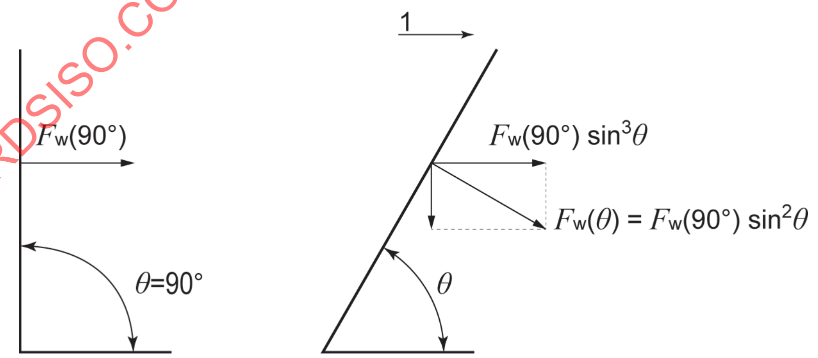
If the angle between the wind direction and the plane containing the length axis of the member differs from 90°, the wind forces F_w (θ) may be reduced.

NOTE F_w is wind force perpendicular on a member. If the member is situated at a sloping angle to the wind direction, the wind forces on this member change. Figure 7 shows the different components usually needed:

$$F_w(\theta) = F_w(90°)\sin^2\theta$$

where θ is the angle of incidence measured in the plane of wind direction and the member's length axis.

F_w (θ) is acting perpendicular to the length axis of the object. Therefore, the component of the wind force on the object in the wind direction is F_w (90°) $\sin^3 \theta$.



Key

1 wind direction

Figure 7 — Forces on an inclined member

8.4 Lattice structures

Wind load on an iced lattice structure shall in principle be found as if there were no ice. Therefore, the calculating model for wind load is not part of this document, but should be the same as normally used.

The only differences compared to values without ice are the values of: dimensions, drag coefficients and the results of these changes. Normally, it therefore is necessary to use a wind load model which include these parameters.

Structural dimensions shall be increased with the thickness of ice as seen from the direction of the wind, and drag coefficients shall be changed to fit the iced elements. The wind load model is often based on some kind of solidity ratio calculations and, in that case, this ratio is the parameter influenced by the structural dimensions in the iced condition.

NOTE Wind load on a lattice structure is a function of the solidity ratio, τ.

If the structural width, the bracing system or service equipment, etc. vary along height, τ may be calculated for different levels of the structure, but always as seen from the wind direction.

The exposed shadow area should include the windward part of the structure as well as the inside middle of the structure (ladders, elevators, cables, etc.).

The calculated value of $\tau = \tau'$ should be used on the total panel area with ice to find the exposed shadow area, used for calculations of wind action, and then calculations can be executed (concerning exposed area) as for without ice.

The change of C value compared to C_0 may be taken care of by using a factor C_i/C_0 on the area in question, and rime vanes are supposed to be perpendicular to the wind direction.

For low ICs (both Gs and Rs) a lattice structure could be treated as a sum of one-dimensional objects concerning the weight of ice. The same principle could be used concerning wind action calculations, in which case the rules for an ice-free structure should be followed, just using drag coefficients and ice dimensions for iced members in accordance with this document.

However, for higher ICs (especially R), where amount of accreted ice is increasing, the exposed wind area is substantially higher and if the ICR is high enough compared to the structural dimensions, ice deposits will grow together and result in a solid, iced structure.

For lattice structures, the leeward parts of the structure can have reduced ice accretion.

If nothing else is specified, the leeward parts of the structure may have an ICR which is one level lower than the specified ICR for the (windward) structure.

If such effects are included in the calculations, more advanced wind load calculation models are needed.

However, ICR1 cannot be reduced, and neither can ICGs.

9 Combination of ice loads and wind actions

9.1 General

Ice loads, described here, are characteristic loads and are estimated as actions with a return period of 50 years or an annual exceedance probability of 0,02.

This means that ice load can be used together with other variable loads within the normal partial coefficient system for combined loads.

All basic actions are characteristic values.

Principles for the use of partial coefficient, loads and their combinations are given in ISO 2394:2015, Clause 1, 6.2 and Clause 9.

9.2 Combined loads

Two combined load cases of wind and ice shall be considered.

In one load case, the wind action with a low exceedance probability is normally combined with an ice load of high exceedance probability.

In the other load case, the wind action has a high exceedance probability and the ice load has a low one.

Also, the IC has some influence on the combined load case because heavy ice accretion (i.e. high ICs) is more likely to be followed by high wind speeds than low ICs. For glaze, however, such accretions are seldom followed by high wind speeds before the ice is melted again.

NOTE This leads to the recommendations for combination of actions from wind and ice given in Table 26.

Table 26 — Principles for combination of wind actions and ice loads

Combination	Wind action		Ice loads	
	Wind pressure	T (years)	Ice mass	T (years)
I	$k \cdot q_{50}$	50	$\phi_{ice} \cdot m$	3
II	$\phi_W \cdot k \cdot q_{50}$	3	m	50

Wind and ice are variable characteristic actions.

ϕ_{ice} and ϕ_W are used to change actions and load from 50-year to 3-year occurrence. The factor ϕ_{ice} is used to reduce 50-year ice to 3-year ice, and from today's experience a value close to 0,3 could be recommended. ϕ_W shall be taken from relevant wind codes.

Factor k has values as shown in Table 27.

NOTE The factor ϕ_W is taken from national codes for the possible decrease of wind action for simultaneous variable actions. The factor k is used to decrease wind pressure because of reduced probability for simultaneous 50 years wind action combined with heavy icing condition.

Table 27 — Factor for reduction of wind pressure

ICG	k	ICR	k
G1	0,40	**R1**	0,40
G2	0,45	**R2**	0,45
G3	0,50	**R3**	0,50
G4	0,55	**R4**	0,55
G5	0,60	**R5**	0,60
		R6	0,70
		R7	0,80
		R8	0,90
		R9	1,00

Basic actions used together with combinations of wind and ice action shall be the following:

— self-weight of structure (without ice);

— wind action on iced structure;

— ice action on structure [mass (self-weight) of ice].

Partial coefficients are to be taken from relevant codes and standards.

10 Unbalanced ice load on guys

Asymmetric or unbalanced ice on structures or structural elements may result in situations which are not covered by the previous clauses.

In 8.4, the normal situation is mentioned, where the leeward side of a structure has reduced ice deposits compared to the windward part.

However, this effect may be much more predominant and therefore in such cases may need closer attention.

Typical structures where this effect is known often to cause problems are guyed masts where some of the guy ropes may be heavily iced, while the other guys have less or no ice. This can be due to the accretion of ice or due to shedding of ice.

Therefore, guyed masts might need additional investigation for load cases with asymmetric ice load on guys and perhaps also on the mast structure itself.

NOTE There are different ways that asymmetrical ice load can occur, and the typical situations which result in asymmetrical load cases to be investigated are outlined in the list below.

— Accreted ice on guys start falling off. This may result in situations where ice from upper guys hit lower guys and by this cause ice on (one or all) guys in the same direction to fall off. The event itself causes dynamic forces, mentioned in 5.4, but the situation after the fall can remain for a long time and is an example of an asymmetrical ice load case to be investigated. In one direction, one or all guys may be without ice, while the rest may be fully iced.

— On certain sites, ice accretion can be of different ICs in different heights above terrain. This has been mentioned in 6.4, and may result in a situation where the ice load on upper guys are essentially different from the ice load on lower guys. This can cause variations in the stiffness of the different sets of guys. Such cases may also need closer investigation.

— On some sites, a prevailing icing direction is very common. This may result in different ice accretions on the windward side of the structures (heavy icing) compared to the leeward side. This can cause different ice accretions on guys in different directions, but also result in asymmetrical ice load on the mast structure itself. Especially if for example radio-link antennas or other large antennas are placed in or near to the windward direction, they can give quite a contribution to asymmetrical load on the structures.

11 Falling ice considerations

When a structure from which ice shedding may be expected is to be placed near public traffic, buildings, etc., the risk of damage from the impact of falling ice should be taken into account.

If a structure is guyed and the IC is R4, G2 or higher (see Clause 7), there should not be public admittance to the areas located directly under the guy wires, e.g. roads, pathways and the like.

Falling ice can cause personal injury and excessive damage to objects below. This includes not only the lower parts of the tall structure itself, but also other facilities nearby. Thus, when planning sites for tall structures or other facilities near such structures, the risk of falling ice shall be considered. Consulting an icing expert or a meteorologist is the best way to do this. However, if this cannot be done due to lack of data, for example, Table 28 may be used as a guideline.

NOTE There is very little information about the area of a site which can be hit by shedding ice. It depends strongly on the structure of the ice in question and the actual wind speeds occurring during shedding events, and the actual wind direction decides the direction of the falling ice.

When a piece of ice is released from a structure, gravity and wind drag determine its trajectory. Exact trajectories are difficult to predict because ice pieces are of different sizes, densities and shapes. Generally, the higher the wind speed and the smaller the ice dimensions, the longer is the distance between the structure and the impact location on the ground.

Table 28 — Recommended maximum distance for falling ice

IC		Maximum distance for falling ice
R0 to R3	G0 to G1	normally not considered[a]
R4 to R6	G2 to G3	2/3 of structure height
R7 to R8	G4 to G5	Equal to structure height
R9 to R10		1½ times structure height

[a] Even in IC R2, R3 and G1, some ice on the structure can be a risk for people moving about near the structure. The area should then be closed in the rare events of risk due to falling ice.

Annex A
(informative)

Formulae used in this document

NOTE Annex A lists all used formulae for figures and tables, so it is possible to calculate all values not shown in the tables.

A.1 Formulae connected to figures

Figure 1:

y is the wind speed [m/s]; x is the air temperature [°C]

a) Separation between glaze and hard rime [see Formula (A.1)]:

$$y = \left(-x + 1,75\right)^{1,55} \quad \text{(A.1)}$$

b) Separation between hard and soft rime [see Formula (A.2)]:

$$y = \left[\left(-x\right) \cdot 0,3 + 1,1\right]^{1,85} \quad \text{(A.2)}$$

Figure 2:

x is the height factor [1/1]; H is the height above terrain [m]

$$x = \mathrm{e}^{0,01 \cdot H} \quad \text{(A.3)}$$

A.2 Formulae connected to tables

m is the mass of the ice, glaze or rime [kg/m]

t is the thickness of the ice, glaze or rime [mm]

d is the cylinder diameter [mm]

γ is the density of the ice, glaze or rime [kg/m³]

Table 3:

$$m = \pi \cdot \gamma \cdot t \left(d + t\right) \times 10^{-6} \left[\mathrm{kg/m}\right] \quad \text{(A.4)}$$

Table 4:

D is the rime diameter [mm]

$$D = \left(\frac{m \cdot 4 \times 10^{6}}{\gamma \cdot \pi} + d^{2}\right)^{1/2} \left[\mathrm{mm}\right] \quad \text{(A.5)}$$

Table 5:

See Figure 4.

For $L \leq \frac{W}{2}$:

$$L = \frac{m \cdot 4 \times 10^6}{\pi \cdot \gamma \cdot W} \, [\text{mm}] \tag{A.6}$$

For $L > \frac{W}{2}$:

$$L = \frac{W}{2} + 8 \cdot t \, [\text{mm}], \text{ and} \tag{A.7}$$

$$t = \frac{1}{32} \left\{ -10W + \left(68W^2 + \frac{m}{\gamma} \times 8,149 \times 10^7 \right)^{1/2} \right\} [\text{mm}] \tag{A.8}$$

Table 6:

As Table 5, but:

$$t = \frac{1}{32} \left\{ -9W + \left(49W^2 + \frac{m}{\gamma} \times 8,149 \times 10^7 \right)^{1/2} \right\} [\text{mm}] \tag{A.9}$$

Table 7:

Formulae for Table 7 have been based upon type F cross section, because this gives the biggest length for a given mass.

$$L = 0 \, [\text{mm}] \text{ for } m \leq \frac{W^2}{4} \cdot \gamma \times 10^{-6} \, [\text{kg/m}] \tag{A.10}$$

For $L \leq \frac{W}{2}$:

$$L = \frac{m \cdot 4 \times 10^3}{\pi \cdot \gamma \cdot W} - \frac{W}{\pi} \, [\text{mm}] \tag{A.11}$$

For $L > \frac{W}{2}$:

$$L = \frac{W}{2} + 8 \cdot t \, [\text{mm}], \text{ and} \tag{A.12}$$

$$t = 0,039\,8 \left\{ -7,07W + \left(17,68W^2 + \frac{m}{\gamma} \times 5,027 \times 10^7 \right)^{1/2} \right\} [\text{mm}] \tag{A.13}$$

Table 8:

L is the ice vane length for object with >300 mm and type C and D, Table 6.

m is the ice mass for ICRs

m_W is the ice mass for $W > 300$ mm

$$m_w = m + (W - 300) \cdot L \cdot \gamma \times 10^{-6} \, [\text{kg/m}] \quad (A.14)$$

L shall be found from Formula (A.6) and used together with the correct value of γ.

Table 9:

L is the ice vane length for an object width >300 mm and type A (Table 5).

m is the ice mass for ICRs

m_W is the ice mass for $W > 300$ mm

$$m_w = m + (W - 300) \cdot L \cdot \gamma \times 10^{-6} \, [\text{kg/m}] \quad (A.15)$$

Table 10:

X is the value of ICG, e.g. ICGX

$$C_i = C_0 - \left(\frac{C_0 - 1,4}{5} \right) \cdot X \, [1/1] \quad (A.16)$$

Tables 11 to 15:

$C_{0,3} = C_i$ from Table 10 for $W \leq 0,3$ m

$$C_i = C_{0,3} - \left(\frac{C_{0,3} - C_0}{4,7} \right) \cdot (W - 0,3) \quad [1/1] \quad (A.17)$$

$C_{0,3}$ is the value for $W = 0,3$ m and shall be taken for the appropriate IC.

Table 16:

X is the value of ICR, e.g. ICRX

$$C_i = C_0 - \left(\frac{C_0 - 1,6}{9} \right) \cdot X \, [1/1] \quad (A.18)$$

Tables 17 to 25:

$C_{0,3} = C_i$ from Table 16 for $W \leq 0,3$ m

$$C_i = C_{0,3} - \left(\frac{C_{0,3} - C_0}{4,7} \right) \cdot (W - 0,3) \, [1/1] \quad (A.19)$$

$C_{0,3}$ is the value for $W = 0,3$ m and shall be taken for the appropriate IC.

Annex B
(informative)

Standard measurements for ice actions

B.1 General

Engineering work needs specification of the climatic actions.

This document deals with ice actions, but ice accretions are not today included in meteorological data and services provided by the National Meteorological Institute (NMI) or the World Meteorological Organization (WMO).

Because of this, it is important to agree on a common basis for the collection of information about ice accretions to be used for engineering estimation of ice actions.

Annex B gives recommendations which make it possible to start the collection of data. However, the procedure may be subject to adjustments, as experience tell us to do so. Some coordination of this and of work on the collected data might be necessary, and could be carried out in cooperation with NMI and WMO. Collaboration with other interested parties (e.g. electrical utilities) should be encouraged.

There are practical difficulties in the implementation of the recommended collection of data, but the proposed method for doing so should be adopted as far as possible.

Because of these practical difficulties, other methods for collecting data are also of interest, if the proposed method cannot be carried out to a full extent.

If other collecting methods are used, the results from these should be calibrated to the method described below.

B.2 General considerations

Ice accretions are not only a function of environmental parameters, but are also dependent on the properties of the accreting object itself, for example:

— size (diameter, width, etc.);

— shape (flat, sharp edges, cylindrical, spherical, etc.);

— flexibility (rigid/flexible member in bending/torsion, etc.);

— orientation relative to wind direction (angel of incidence);

and to some extent

— surface structure (paint, steel, concrete, etc.);

— material (wood, steel, plastics, etc.).

Measurements of ice accretions therefore have to be specified with respect to devices, procedures, arrangements on site, etc.

The arrangements should be designed in a way that causes the lowest possible influence on the accretion process itself.

At least one part of measuring devices should always be the standard reference device, giving standard measurements of ice accretion.

Other parts of the arrangement may give the connections between "standard accretions" and the most important structural parameters as exemplified above (size, shape, etc.). These extended measurements should only be executed on special selected sites, and collected data should be worked up and used generally together with the standard measurements.

The poles (towers) could be used for such investigations when found appropriate or necessary, for instance installation of other ice-collecting parts, such as ropes of smaller diameter (than 30 mm), profile, planes, etc.

Frequency of observations may be adjusted to the local conditions.

On sites where melting or shedding are likely to occur shortly after the accretion period, observations should be carried out before this happens (within hours or a few days after icing).

In stable, cold areas (high mountains, etc.) weekly or even monthly observations may be sufficient.

At least the maximum value for one season (winter) should be recorded.

It is important, when automatic recordings are performed, also to do manual observations during and/or after the accretion period, because only these types of observation can give maximum information on such complex load situations.

Also recordings with remote readings make it possible to get immediate information about an icing situation and the site may be visited in due time.

B.3 Recommended measurements

B.3.1 Standard reference measurements

The overall design of the standard measurement device should be in principle as follows.

a) A cylinder with a diameter of 30 mm is placed with the axis vertical and slowly rotating around the axis. The cylinder length should be a minimum of 0,5 m, but if heavy ice accretion is expected, length should be 1 m.

b) The cylinder is placed 10 m above terrain[1)].

c) Recordings of ice mass are done as a minimum.

B.3.2 Other observations

When practical, observations should also include the following.

a) Overall dimensions of accreted ice; i.e. diameter or max. and min. measurements of cross section. There might be variations along the length of the cylinder, which also should be registered.

b) Sketches with shape or cross section combined with the above-mentioned measurements.

c) Type of ice (see Table 1 in 6.2.1).

d) Wind direction during the accretion period.

e) Collection of ice samples for determination of density.

f) Photographs (overall views and close-ups).

1) Consideration should be given to the maximum snow depth during the winter. The cylinder should preferably be placed in an area where snow is blown away. For practical reasons, different erection heights above terrain are accepted, as long as the results correspond to those for 10-m height.

B.3.3 Output of measurements

The length of the measurement series should be sufficiently long to form a reliable basis for extreme value analysis. This length could be from a few years to several decades depending on the conditions.

However, shorter series can be of valuable help and can also be connected to longer records of meteorological data, either statistically or (better) physically in combination with theoretical models.

The result of measurements in accordance with definitions B.3.1 and B.3.2 should be expressed as follows.

a) The ice class (IC) should be stated in accordance with Table 3 or 4.

b) The average dimension (diameter) of ice measured on a vertical projection: diameter or L or D (m).

c) The average density of ice: γ (kg/m^3). (Measuring method should be discussed.)

If, in addition to the rotating cylinder, other measurements have been done such as wind measurements and detailed load recordings [reactions in all directions, vertical and transverse (horizontal)], it might be possible to estimate the drag coefficient, C_D by calculations.

This is very useful, because the proposed values of C_D are rather uncertain and might need adjustments, especially from field measurements.

Therefore, it is recommended that further measurements are performed in such a way that the above-mentioned additional information can be found.

B.3.4 Additional meteorological measurements

In areas with only a few or no meteorological observations, some meteorological recordings are recommended in connection with the standard reference measurements.

Temperature and humidity should be recorded as minimum, but also wind speed and direction are very useful information, especially regarding calculation of actions.

However, special arrangements shall be made to ensure the quality of data. Ice accretions on instruments and/or instrument shields can lead to both misreading of parameters as well as destruction of sensors.

B.4 Measurements on other objects

In this document, areas exposed for ice accretion are defined as having a certain “ice class”. The higher the number, the more accreted ice should be expected.

In accordance with Tables 4 and 5, the specific ice class of a certain site or area can be found by using results from the standard reference measurements.

In other tables, accreted ice from standard reference measurements are converted into accreted ice on other objects for the same ice class. This conversion should be done mainly by means of experience, which means that recordings of accreted ice on other objects, placed together with the standard ice collector (⌀ 30 mm cylinder), are very useful.

Also observations of accreted ice on already existing objects in icing regions should be done. Such objects could typically be antenna structures, structures for overhead transmission lines, skilifts, etc.

However, to get maximum values of such observations, the same meteorologists who operate the standard reference measurements should work up all data.

B.5 Responsibility

Measurements of atmospheric ice are not included in the existing meteorological standard observation programmes, so the involved owners (e.g. electric power utilities and telecommunication companies, etc.), should themselves take the responsibility of performing the necessary data recording programmes.

In particular, systematic observations of ice should be performed in connection with regular inspection and maintenance of existing structures.

However, the National Meteorological Institutions should be strongly encouraged to take over themselves the overall responsibility for collecting and analyzing these data. In due time, the Meteorological Institutions should be able to present all recorded data as background material for their clients/customers. The NMI is usually responsible for drawing up the necessary climatic information used for the national codes and standards, which typically are worked out by a national society of engineers.

Annex C
(informative)

Theoretical modelling of icing

C.1 Fundamentals

The source of natural ice that forms on structures may be either cloud droplets, rain drops, snow or water vapour. In this classification, the term “cloud droplets” includes droplets in clouds that are locally observed as can be shown (see Reference [15]) that condensation of water vapour (hoarfrost) is usually negligible compared to typical growth rates of ice due to impingement of liquid water droplets and snow particles.

Thus, significant ice loads form due to particles in the air colliding with the object. These particles can be liquid (usually super-cooled), solid or a mixture of water and ice. In any case, the maximum rate of icing per unit projection area of the object is determined by the flux density of these particles. The flux density, F, is a product of the mass concentration of the particles, w, and the velocity, v, of the particles with respect to the object. Consequently, the rate of icing is obtained using Formula (C.1).

$$\frac{dm}{dt} = \eta_1 \eta_2 \eta_3 \cdot w \cdot A \cdot v \qquad \text{(C.1)}$$

where

A is the cross-sectional area of the object (with respect to the direction of the particle velocity vector v);

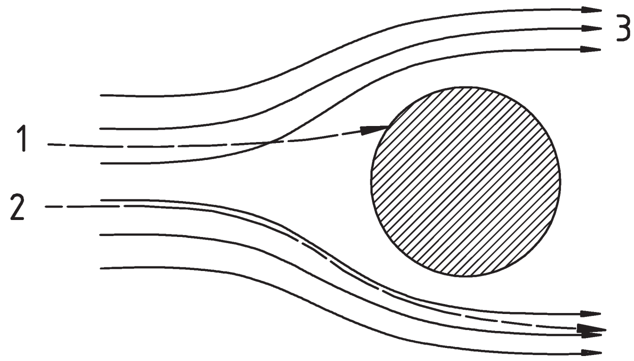
η_1 is the collision efficiency;

η_2 is the sticking efficiency;

η_3 is the accretion efficiency.

The correction factors η_1, η_2 and η_3, represent different processes that may reduce dm/dt from its maximum value $w\ A\ v$. These correction factors vary between 0 and 1.

Factor η represents the efficiency of a collision of the particles, i.e. is the ratio of the flux density of the particles that hit the object to the maximum flux density. The collision efficiency η_1 is reduced from one, because small particles tend to follow the air streamlines and may be deflected from their path towards the object, as shown in Figure C.1.



Key

1 large droplet

2 small droplet

3 air

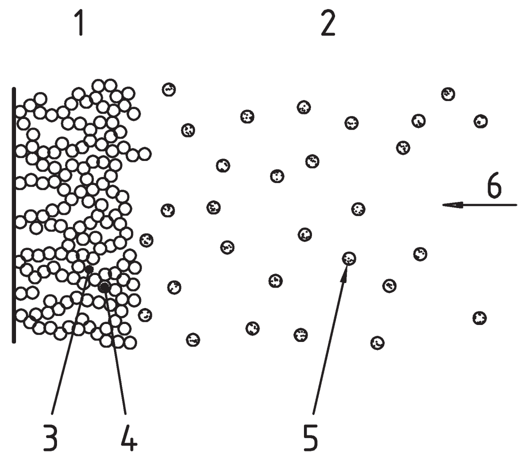
Figure C.1 — Air streamlines droplet trajectories around a cylindrical object

Factor η_2 represents the efficiency of collection of those particles that hit the object, i.e. η_2 is the ratio of the flux density of the particles that stick to the object to the flux density of the particles that hit the object. The sticking efficiency η_2 is reduced from one when the particles bounce from the surface. The particles are considered to stick when they are permanently collected, or their residence time on the surface is sufficient to affect the icing rate due for example to exchange of heat with the surface.

Factor η_3 represents the efficiency of accretion, i.e. η_3 is the ratio of the rate of icing to the flux density of the particles that stick to a surface. The accretion efficiency η_3 from one when the heat flux from the accretions too small to cause sufficient freezing to incorporate all sticking particles into the accretion. In such a case, part of the mass flux of the particles is lost from the surface water by run-off. The situation is schematically shown in Figure C.3.

When the situation in Figure C.3 develops ($\eta_3 < 1$), there is a liquid layer on the surface of the accretion and freezing takes place beneath this layer. This is called “wet growth”. The ice resulting from this process is customarily called “glaze”. When there is no liquid layer and no run-off ($\eta_3 = 1$), the process is called “dry growth”. This situation is schematically shown in Figure C.2. The ice resulting from dry growth is called “rime”. Finally, it should be noted that the term “collection efficiency” for η_1 and the term “freezing fraction” for η_3 are sometimes used in the literature.

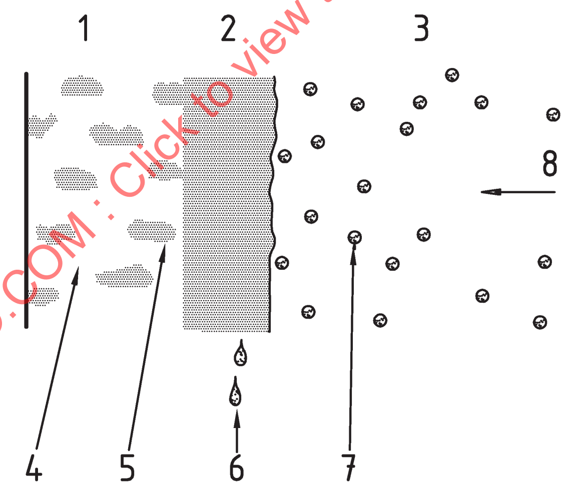
One should note that, although we speak of “icing” and “icing rate” dm/dt, the accretion that forms may be a mixture of ice and liquid water. In fact, when a liquid film forms at the accretion surface (Figure C.3), the growing ice always initially entraps a considerable amount of liquid water[18]. Accretion of wet snow also results in a deposit that includes liquid water. Liquid water is seldom detected, because the deposits usually completely freeze soon after the icing storm is over.



Key

1 rime
2 cold air
3 air
4 ice
5 droplets
6 wind direction

Figure C.2 — Growth of rime ice (dry growth)



Key

1 ice
2 water film
3 cold air
4 ice
5 liquid water
6 runoff water
7 droplets
8 wind direction

Figure C.3 — Growth of glaze ice (wet growth)

C.2 Rate of icing

C.2.1 General

Formula (C.1) reveals some of the basic problems of estimating ice loads on structures. Three factors, η_1, η_2 and η_3 that all may vary between 0 and 1, shall be determined. In addition, the mass concentration of particles in air, w, the particle velocity, v, and the cross-sectional area of the object, A, shall be known. Determination of the atmospheric parameters is more a practical problem than a theoretical one, and we will not discuss it in this annex. It may be noted here, however, that the mass concentration w is not a routinely measured parameter and its estimation is a difficult problem of its own, and that the velocity v is a vector sum of the wind speed and the, often unknown, terminal velocity of the particles.

In the following, theoretical means to determine the factors η_1, η_2, η_3 and A are discussed.

C.2.2 Collision efficiency

When a droplet moves within the air stream toward the icing object, the forces of aerodynamic drag and inertia determine its trajectory. If inertial forces are small, then drag will dominate and the droplets will closely follow the streamlines of air (Figure C.1). Since air must go around the object, the droplets will in this case also tend to do so. The actual impingement rate will then be smaller than the flux density of the spray. For large droplets, on the other hand, inertia will dominate and the droplets will tend to hit the object, without being deflected (Figure C.1).

The relative magnitude of the inertia and drag on the droplets depends on the droplet size, the velocity of the air stream and the dimensions of the icing object. When these are known, the collision efficiency, η_1 can be theoretically determined by numerically solving the formulae of droplet motion in the airflow. This approach, pioneered in 1946[9] involves numerical solution of the airflow and of the droplet trajectories. The trajectories shall be determined for a number of particle sizes and impact positions in order to finally derive the overall collision efficiency η_1. These calculations are complicated and computationally costly. Fortunately, there are several means to simplify the calculation of η_1 for practical applications.

Firstly, if it is assumed that the icing object is cylindrical, there exists an analytical solution for the airflow around the object, and the collision efficiency can be parameterized by two-dimensionless parameters as show in Formulae (C.2) and (C.3):

$$K = \rho_w d^2 / 9\,\mu D \tag{C.2}$$

and

$$\phi = Re^2 \big/ K \tag{C.3}$$

with the droplet Reynolds number based on the free stream velocity v:

$$Re = \rho_a d v / \mu \tag{C.4}$$

where

d is the droplet diameter;

D is the cylinder diameter;

ρ_w is the water density;

μ is the absolute viscosity of air;

ρ_a is the air density.

The following empirical fit to the numerically calculated data [see Formula (C.5)] has been developed[5]:

$$\eta_1 = A - 0{,}028 - C\left(B - 0{,}045\ 4\right) \tag{C.5}$$

where

$$A = 1{,}066 K^{-0{,}006\ 16} \exp\left(-1{,}103 K^{-0{,}688}\right)$$

$$B = 3{,}641 K^{-0{,}498} \exp\left(-1{,}497 K^{-0{,}694}\right)$$

$$C = 0{,}006\ 37\left(\phi - 100\right)^{0{,}381}$$

Secondly, it has been shown[6] that with a good accuracy, a single parameter, the median volume diameter (MVD) can be used in the calculations [as d in Formulae (C.2) and (C.4)] without having to calculate η_1 separately for each droplet size category.

The collision efficiency η_1 depends strongly on the particle size, and for sufficiently large MVD one can put $\eta_1 = 1$ in practical applications, unless the structure is extremely large. Therefore, η_1 usually needs to be calculated only when cloud droplets cause icing. In precipitation (both rain and snow), the collision efficiency is close to one.

C.2.3 Sticking efficiency

When a super-cooled water drop hits an ice surface, it rapidly freezes and does not bounce (Figure C.2). If there is a liquid layer on the surface, the droplet spreads on the surface and again there is no bouncing (Figure C.3). Small droplets that leave the surface can be created in these processes due to splintering. Their relative volume is, however, mostly so small that their effect on icing is insignificant. Therefore, liquid water droplets can generally be considered not to bounce, i.e. for water droplets $\eta_2 \approx 1$.

Snow particles, however, bounce very effectively. For completely solid particles (dry snow), the sticking efficiency, η_2, is basically 0, but when there is a liquid layer on the surface of the snow particles, they stick more effectively. At small impact speeds and favourable temperature and humidity conditions, η_2 is close to the unity for wet snow.

Presently there is no theory for the sticking efficiency of wet snow. The available approximation methods of η_2 are empirical formulae based on laboratory simulations and some field observations. The best first approximation for η_2 is probably as shown in Formula (C.6)[1]:

$$\eta_2 = 1/v \tag{C.6}$$

where the wind speed v is in metres per second; when $v < 1\ \mathrm{ms^{-1}}$, $\eta_2 = 1$.

Air temperature and humidity also affect η_2, but there are presently not enough data to take them into account. However, it should be noted that $\eta_2 > 0$ only when the snow particle surface is wet, so that for snow, $\eta_2 = 0$ when the wet-bulb temperature is below 0 °C[20].

C.2.4 Accretion efficiency

In dry growth icing, all impinging water droplets freeze and the accretion efficiency, $\eta_3 = 1$ (Figure C.2). In wet growth icing, the freezing rate is controlled by the rate at which the latent heat released in the freezing process can be transferred away from the freezing surface. The portion of the impinging water that cannot be frozen by the limited heat transfer, runs off the surface due to gravity or wind drag (Figure C.3).

The heat balance on the icing surface can, for wet growth icing, be written as:

$$Q_f + Q_v = Q_c + Q_e + Q_l + Q_s \tag{C.7}$$

where

Q_f is the latent heat released during freezing;

Q_v is the frictional heating of air;

Q_c is the loss of sensible heat to air;

Q_e is the heat loss due to evaporation;

Q_l is the heat loss (gain) in warming (cooling) impinging water to the freezing temperature;

Q_s is the heat loss due to radiation.

The terms of the heat balance Formula (C.7) can be parameterized using the meteorological and structural variables.

The heat released in freezing is transferred from the ice-water interface through the liquid water into the air, and consequently there is a negative temperature gradient through the liquid film. This kind of super-cooling results in dendritic growth morphology, and consequently some liquid water is trapped within the spray ice matrix. Since the unfrozen water can be entrapped without releasing any latent heat, the term Q_f in Formula (C.3) is

$$Q_f = (1 - \lambda)\eta_3 F L_f \tag{C.8}$$

where

λ is the liquid fraction of the accretion;

F is the flux density of water to surface ($F = \eta_1 \eta_2 w v$).

Attempts to determine the liquid fraction, λ have been made both theoretically[18] and experimentally[7]. These studies suggest that λ is rather insensitive to the growth conditions, and that the value of $\lambda = 0{,}26$ is a reasonable first approximation.

The kinetic heating of air, Q_w, is relatively small term, but since it is easily parameterized by

$$Q_w = h r v^2 / (2C_p) \tag{C.9}$$

it is usually included in the heat balance. Kinetic heating of the droplets is insignificant and is ignored. Here, h is the convective heat transfer coefficient, r is the recovery factor for viscous heating ($r = 0{,}79$ for a cylinder), v is the wind speed and C_p is the specific heat of air.

The convective heat transfer is

$$Q_c = h(t_s - t_a) \tag{C.10}$$

where t_s is the temperature of the icing surface ($t_s = 0$ °C in wet growth) and t_a is the air temperature.

The evaporative heat transfer is parameterized as

$$Q_e = h\varepsilon L_e (e_s - e_a) / (C_p p) \tag{C.11}$$

where

ε is the ratio of the molecular masses of dry air and water vapour (ε = 0,622);

L_e is the latent heat of vaporization;

e_s is the saturation water vapour pressure over the accretion surface;

e_a is the ambient vapour pressure in the air stream;

p is the air pressure.

Here e_s is a constant (617 Pa) and e_a is a function of the temperature and relative humidity of ambient air. It is usually assumed that relative humidity is 100 % in a cloud.

The term Q_l is caused by the temperature difference between the impinging spray droplets and the surface of the icing object.

$$Q_l = F C_w (t_s - t_d) \tag{C.12}$$

where

C_w is the specific heat of water;

t_d is the temperature of the droplets at impact.

For cloud droplets t_d = t_a may be assumed, and this assumption should usually be made also for supercooled raindrops.

The heat loss due to long-wave radiation may be parameterized as

$$Q_s = \sigma a (t_s - t_a) \tag{C.13}$$

Where σ is the Stefan-Boltzmann constant (5,67 × 10^{-8} $Wm^{-2}K^{-4}$) and a is radiation linearization constant (8,1 × 10^7K^3). This formula takes into account only long-wave radiation and assumes emissivities of unity for both the icing surface and the environment.

Using the parameterizations of Formulae (C.8) to (C.13) in the heat balance Formula (C.7) and solving the accretion fraction, results in the following formula

$$\eta_3 = \frac{h}{F(1-\lambda)L_f}\left[(t_s - t_a) + \frac{\varepsilon L_e}{C_p p}(e_s - e_a) - \frac{r v^2}{2C_p}\right] + \frac{C_w (t_s - t_d)}{(1-\lambda)L_f} + \frac{\sigma a (t_s - t_a)}{F(1-\lambda)L_f} \tag{C.14}$$

So far, nothing has been said about determining the convective heat transfer coefficient h in Formula (C.14). There are standard methods to estimate both local and overall values for h on smooth objects with various sizes and shapes. In most icing models, it has been assumed that the heat transfer coefficients of cylinders represent the icing objects well enough. Even assuming this simple shape, roughness of the ice surface makes the problem rather complicated. The effect of roughness of the surface on has been studied theoretically in detail[17] and this theory can be used as a part of an icing model.

With an estimate of h, Formula (C.14) can now be used in determining the accretion efficiency η_3, and thereby the rate of icing Formula (C.1). It should be noted that although Formula (C.14) has been written in terms of the spray water flux density F, it is basically valid also locally on the surface of an icing object. In that case, F represents the direct mass flux plus the run-back water from the other sectors of the surface. Then, also the mean temperature of the net flux will be different from the temperature of the droplets. In order to predict not only the overall mass of the accretion, but also its shape and vertical distribution, these aspects of formulation the local heat balance have been included in some of the recent icing models (see, for example, References [11] and [31]).

C.3 Numerical modelling

Solving the icing rate analytically using Formula (C.14) is not practical, because empirical formulae for the dependence of saturation water vapour pressure, and specific heats on temperature, as well as the procedure in determining h are involved. Numerical methods shall be used also because icing is a time-dependent process, and the changes in the dimensions of the accretion affect h the heat transfer coefficient A in Formula (C.1) and, as examples. All this makes the process of icing a rather complicated one. A schematic presentation of the many relationships involved is shown in Figure C.4. Modern computers provide means to readily obtain results of the complex icing models. The problem of accretion shape changing with time is usually avoided by assuming that the ice deposit maintains its cylindrical geometry. The growth of icicles may complicate the problem. A separate model that simulates icicle growth[19] may be included in the simulations when icing due to freezing rain is modelled. Such a comprehensive model for simulations of ice loads due to freezing rain has been proposed[21].

Time-dependent numerical models of icing also require modelling of the density of the accreted ice. This is because the icing rate for the next time-step depends on the dimensions of the object A in Formula (C.1) and the relationship between the modelled ice load and dimensions of the iced structures is, therefore, required. For rime ice, the density may be simulated numerically by a separate ballistic model[30]. For most applications, the following best-fit formula [Formula (C.15)] [23] may be used for the density ρ of rime ice (dry growth) on a cylinder:

$$\rho = 0{,}378 + 0{,}425\,(\log R) - 0{,}082\,3\,(\log R)^2 \quad \text{(C.15)}$$

Here, R is Macklin's parameter[12] [see Formula (C.16)]:

$$R = -\,(V_0 d_m)/2t_s \quad \text{(C.16)}$$

where

V_0 is the droplet impact speed based on the median volume droplet size d_m;

t_s is the surface temperature of the accretion.

Formulae to calculate V_o can be found in Reference [5]. The surface temperature t_s shall be solved numerically from the heat balance formula. However, in most cases of atmospheric rime, the air temperature can approximate icing t_a.

For glaze ice (wet growth), the density variations are small and the value of 0,9 g cm^{-3} may be assumed.