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Bases for design of structures — Temperature climatic actions

Bases du calcul des constructions — Actions climatiques de la température

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The reasons which led to the decision to publish this document in the form of a technical report type 2 are explained in the Introduction.

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0 Introduction

0.1 Work on this subject was undertaken in 1977 and the present document is based largely on the results of work and research carried out in the USSR. The recommendations and proposed formulae are considered to be of undoubted technical value, but they have not yet been recognized internationally. For this reason, it has been decided to publish the document in the form of a type 2 ISO Technical Report and it is strongly believed that, on the basis of experience with the document over a few years, it will be possible to transform it into an International Standard.

It should be noted that is was proposed to enlarge the scope of this document to include bridges or, more precisely, bridge-type structures. This Technical Report does not yet, however, deal to the required extent with the specific features of temperature actions on bridge-type structures that need to be considered.

0.2 In modern construction the necessity of taking proper account of temperature climatic actions in design of buildings and structures is finding wider recognition. This is connected with a number of factors: increase of structure sizes; use of structures with a reduced number of joints; increase of construction of structures of a linear type (pipe-lines, trestles, bridges and viaducts); application of materials with a high coefficient of linear expansion (e.g. aluminium alloys); and development of regions with severe climatic conditions.

When temperature climatic actions for buildings and structures are underestimated, joints may fail, components deform, expansion clearance may be insufficient and cracks may appear.

There is considerable debate among designers from different countries both as to the necessity of taking account of temperature climatic actions and the methods of determination. Development of a unified method of determining temperature climatic actions should contribute to a more correct and unified consideration of temperature effects on structures.

0.3 The first studies of temperature climatic effects on building structures date back to the beginning of this century. In the 1920's a number of significant experimental and theoretical studies were carried out concerning the determination of annual temperature variations in concrete, reinforced concrete and masonry structures (primarily bridges by Prof. H. Krüger in Sweden [1], Eng. W. Lüdtin in Germany [2] and Prof. P.V. Shchusev in the USSR [3]). Each of these authors proposed a method of determining annual temperature variations for structures applicable to the climatic conditions of his country. The method suggested by P.V. Shchusev was adopted as a basis for preparation of a pertinent section in the USSR *Code for the design of bridges and pipes* [4].

Significant investigations into temperature effects have been carried out in the USSR by V.S. Lukyanov and I.I. Denisov (*Prevention of formation of temperature cracks in concrete bridge piers*) [5], S.V. Alexandrovsky (for hydro-technical works) [6], L.I. Goretsky (for airport pavement) [7], A.A. Emelyanov (for large-size panel and masonry buildings) [8] to [10]. Mention should be made of investigations carried out by V. Eichler [11], H. Falkner [12] and [13], M. Emerson [14] to [17], M.R. Jones [18] and [19], and others.

The first proposals concerning the choice of initial temperatures for design of structures based on statistical analysis of the data have been made in the USSR [20] and [21]. These proposals have been further developed and supplemented when the section "Temperature climatic actions" of the chapter of Code of Practice II-6-74 [22] to [26] was prepared.

1 Scope and field of application

This Technical Report is intended to be a guideline for code-writers; it can be applied to the determination of unfavourable characteristic values of temperature difference due to temperature climatic actions which are taken into account in static analysis of structures for which the variation of temperature within the cross-section can be treated as linear.

This Technical Report is not applicable to massive structures (dams, retaining walls, tunnels, bridge piers, etc.). For consideration of such structures it may be necessary to take into account non-linear distribution of temperature through the body of the massive structural elements. It could be important also for multilayered and composite structures (e.g. steel-concrete) as well as for structures in which the existence of cracks is unacceptable. The non-linear distribution of temperature in such cases should be determined by means of thermophysical calculations or from experimental data.

In view of the great variety of types of buildings and structures and their functions, their indoor temperature regime, and their architectural and structural designs, it is useful to classify buildings and structures simply by their indoor temperature regime: open structures and unheated buildings; periodically heated buildings (in the cold season); air-conditioned buildings; buildings with permanent technological sources of heat (or refrigeration). Structures are classified by function and by the extent of protection against solar radiation into externally enveloping structures, and structures located inside a building. It is assumed that structures are not massive and are made from common building materials: metal, reinforced concrete, masonry (including brickwork) or combinations of these materials.

2 General principles

The main climatic factors influencing the temperature of structures are outdoor air temperature and solar radiation. The effect of thermal radiation is not taken into account in this Technical Report. If necessary the effect could be substituted by an equivalent reduction of the outdoor temperature of 2 to 5 K.

The climatic factors are random processes which are characterized by only two regular periodic variations: annual and daily. Due to variations of air temperature and solar radiation intensity, the temperature field of structures changes continuously in time; it is also random and non-stationary. The temperature distribution through the cross-section of a structural element at any time is non-linear.

In static analysis the temperature field is normally considered for the most unfavourable time period. In this case the non-stationary temperature field is often replaced by a equivalent stationary one. It is assumed that within any cross-section the temperature is distributed according to a linear law. In the following, linear variation in only one direction is considered, since a linear variation in the orthogonal direction can be added by superposition.

The linear temperature diagram can be divided into two portions (see figure 1). The first is uniform with a value equal to the temperature along the axis of the bar which causes elongation or shortening of the bar. The second diagram varies linearly with the distance from the axis which causes bending of the axis without changing its length.

In statically determinate systems, temperature variation induces displacements but induces neither bending moments nor transverse or longitudinal forces. In statically indeterminate systems, temperature variations give rise to internal forces. When determining temperature forces and displacements in statically indeterminate structures, the mean temperature is in the cross-section of an element, whereas the temperature gradient over the thickness of the element may be considered separately.

Structures the stressed or deformed state of which, due to climatic actions, is primarily affected by axial temperature deformations (e.g. frame structures of buildings), should be designed for the unfavourable value of the difference ΔT (in time) between the initial temperature T_0 and the mean cross-section temperatures in warm (T_{hk}) and cold (T_{lk}) seasons:

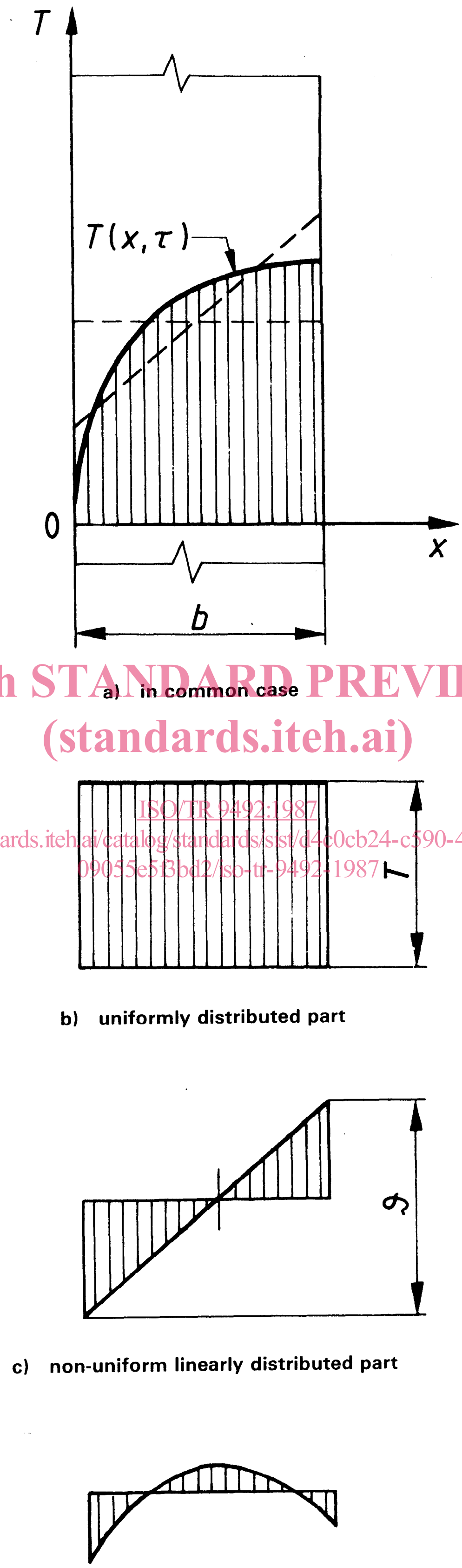
$$\left.\begin{aligned} \Delta T_{hk} &= T_{hk} - T_0 \\ \Delta T_{lk} &= T_{lk} - T_0 \end{aligned}\right\} \quad \ldots \quad (1)$$

The so-called "completion temperature" that corresponds to the stage of completion of the design structural system (or part of it) is assumed to be the initial temperature. Sometimes the completion temperature is also called the temperature of "zero" stresses, bearing in mind that stresses in the structure due to temperature are equal to or close to zero after the completion stage. Completion temperature is assumed in accordance with the erection conditions given (calendar completion dates, sequence of operations, etc.).

However, these conditions are, in general, not known at the design stage. In this instance it is recommended to assume two values of initial temperature for cold, T_{0l}, and warm, T_{0h}, seasons.

The characteristic values ΔT are defined by the formulae:

$$\left.\begin{aligned} \Delta T_{hk} &= T_{hk} - T_{0l} \\ \Delta T_{lk} &= T_{lk} - T_{0h} \end{aligned}\right\} \quad \ldots \quad (2)$$



a) in common case

b) uniformly distributed part

c) non-uniform linearly distributed part

d) non-linearly distributed part

Figure 1 — Temperature distribution through the plate cross-section

Structures for which it is important to estimate stresses and deformations due to non-uniform temperature distribution through the cross-section of an element (e.g. enveloping structure of a building) should be designed for the unfavourable temperature difference (temperature gradient) between the external and internal surfaces of an element for warm (ϑ_{hk}) and cold (ϑ_{lk}) seasons. In this case the distribution of temperature through the cross-section may be regarded as linear.

The most unfavourable characteristic values of the mean cross-section temperature, temperature gradient and non-linear distribution of temperature for warm and cold seasons should be determined by thermophysical methods or on the basis of experimental data.

The characteristic values of the mean cross-section temperature, T_{hk}, T_{lk}, and the temperature gradient in the cross-section of an element, ϑ_{hk}, ϑ_{lk}, for single-layered structures may be evaluated by the approximate formulae of table 3. The basis for these formulae and the determination characteristic values of the parameters are explained in clause 5.

3 Definitions

For the purposes of this Technical Report, the following definitions apply.

3.1 maximum intensity of total solar radiation, S_x: Quantity of heat which falls on the body surface per unit time due to direct and diffused solar radiation in the warmest month under a clear sky, in watts per square metre.

3.2 factor of absorption of solar radiation, k_s: Ratio of solar radiation absorbed by a body surface to the total solar radiation.

3.3 heat exchange factor, α_e: Quantity of heat given (or received) by a unit area of surface when the temperature difference between the body surface and the outdoor air is 1 K, in watts per square metre kelvin.

3.4 heat conduction factor; heat conduction, λ: Quantity of heat passing per unit time through a unit area of surface when the temperature gradient per unit length of a normal to this surface is 1 K, in watts per metre kelvin.

3.5 specific heat capacity, c: Quantity of heat absorbed by a unit mass of body when it is heated by 1 K, in joules per kilogram kelvin.

3.6 thermal resistance, R: Inverse of the heat penetration factor, which is the quantity of heat passing per unit time through a unit area of surface when the temperature difference between the opposite surfaces is 1 K, in square metres kelvin per watt.

4 Main symbols

The main symbols used in this Technical Report are as follows:

a_{ehk}, a_{elk} characteristic values of daily deviation in outdoor air temperature (high and low) in warm and cold seasons, respectively;

T_{ehk}, T_{elk} characteristic values of daily mean outdoor air temperature (high and low) in warm and cold seasons, respectively;

S_{xk} characteristic values of maximum intensity of total (direct and diffused) solar radiation;

T_{sk}, a_{sk} characteristic values of equivalent daily mean temperature and equivalent daily deviation in temperature due to solar radiation;

T_{ihk}, T_{ilk} characteristic values of indoor air temperature in heated buildings (high and low) in warm and cold seasons, respectively;

T_{hk}, T_{lk} characteristic values of mean temperature through the cross-section of the structural element (high and low) in warm and cold seasons, respectively;

ϑ_{hk}, ϑ_{lk} characteristic values of temperature gradient through the cross-section of a structural element (high and low) in warm and cold seasons, respectively;

T_0 initial temperature;

ΔT difference between initial and mean temperature through the cross-section of a structural element;

b thickness of the element, in metres;

λ heat conduction factor of material, in watts per metre kelvin;

c specific heat capacity of material, in joules per kilogram kelvin;

ϱ mass density, in kilograms per cubic metre;

$R = \frac{b}{\lambda}$ thermal resistance, in square metres kelvin per watt;

α_e heat exchange factor of structure surface with outdoor air, in watts per square metre kelvin;

k_s solar radiation absorption factor (for structure surface).

5 Outdoor air temperature

The reference data on outdoor air temperature should be obtained on the basis of measurements at meteorological stations according to recommendations by the World Meteorological Organization.

Air temperature is usually recorded at meteorological stations at definite observation times, e.g. every hour or continuously. Moreover, daily maximum and minimum temperatures are recorded.

Observation data from some stations can be extended to larger regions and modified to account for local features (effect of topography, elevation above sea level, large water reservoirs). In most of these cases space variation of air temperature can be ignored and attention focused on the problem of time variation in the given geographical region.

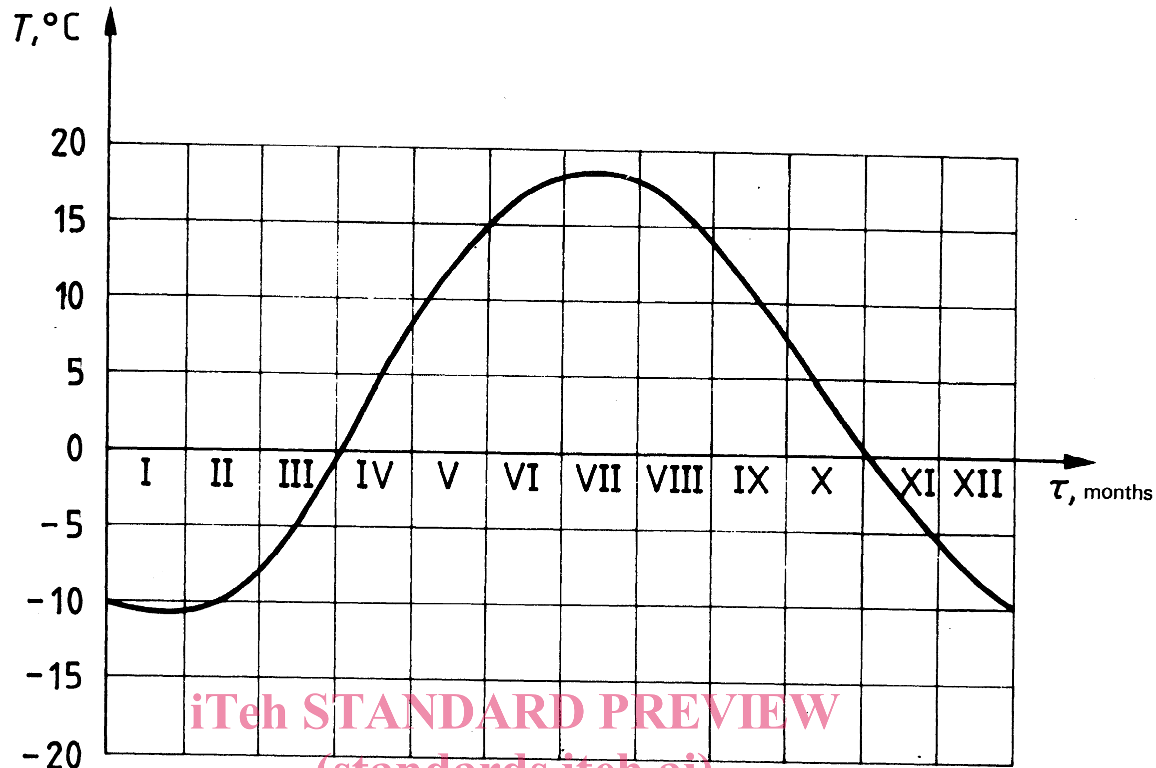
Confidence of statistical evaluation of air temperature parameters is dependent on the duration of observation. For statistical analysis of data on air temperature in connection with design problems of structures, observation data for not less than 25 years should be used, if possible.

The random process of variation of outdoor air temperature has two periodic variations: annual and daily. The "mean function" of temperature variation with annual period, which exhibits non-random dependence of temperature on time, can be represented with sufficient accuracy by a harmonic variation having its minimum in the coldest months of a year and its maximum in the hottest months [see figure 2 a)]. Temperature variation with daily period depends on the season and can be analysed by observations during a definite calendar month. By averaging temperature values for each hour of the day for a great number of examples for the given month and then for a number of years it is possible to obtain the "mean function" of daily variations for all the months of the year. This "mean function" is also close to a harmonic variation with its minimum in early morning hours and its maximum in the daytime [see figure 2 b)].

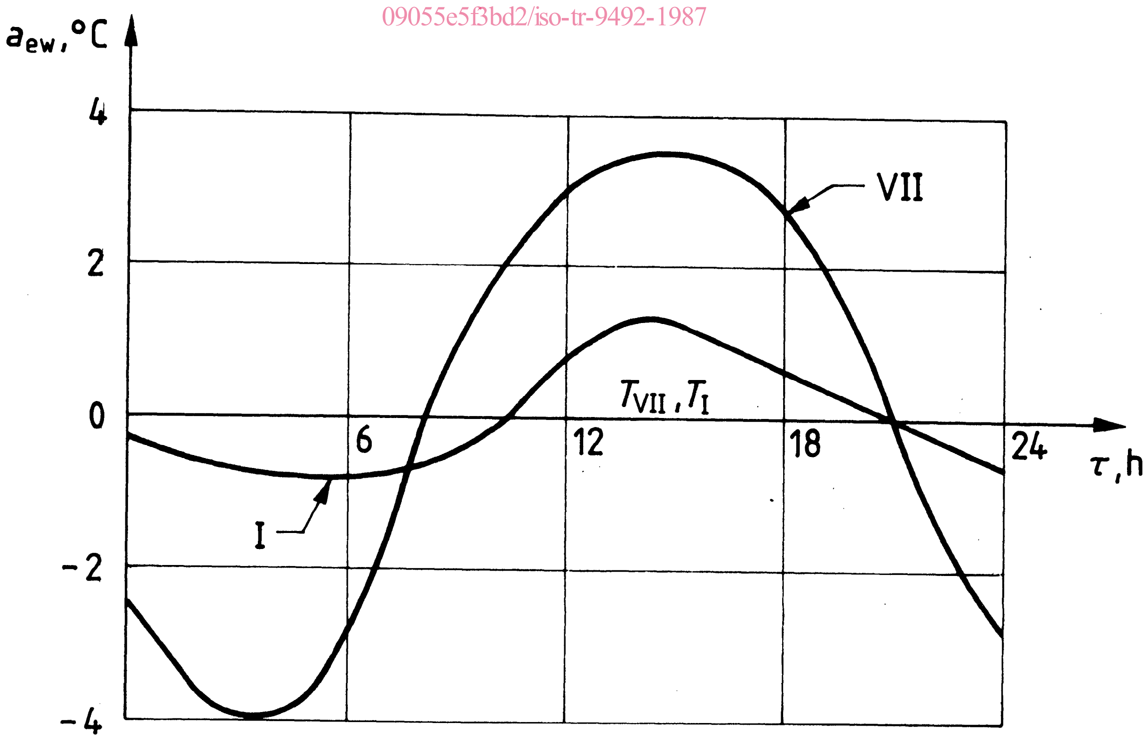
Unfavourable non-periodic temperature variations are related to sudden weather changes occurring in periods with maximum mean temperature for summertime and minimum mean temperature for wintertime. For example, analysis of temperature variations in these periods made it possible to find out some general regularity for the majority of communities in the USSR [20], [21].

The "mean function" of unfavourable temperature variations has a form of "temperature peak" shown in figure 3 with its maximum (minimum) in the middle. The duration of temperature peaks is 7 to 11 days. The temperature peak magnitude varies with and depends on climatic conditions and the season, the winter "peaks", as a rule, being higher than the summer ones.

As observations and calculations show, the mean cross-section temperature of open (unprotected) structures follows variations of mean daily outdoor air temperatures and takes their values. It is, therefore, assumed that annual variations of outdoor air temperature should be characterized by the range of extreme mean daily temperatures. Hence it follows that it is necessary to have extreme values of mean daily temperature for warm (T_{eh}) and cold (T_{el}) seasons.



a) Graph of mean monthly air temperature variations for a year period in Moscow



b) Graph of mean hourly air temperature variations for a day in January (I) and July (VII) in Moscow

Figure 2 — Air temperature variations

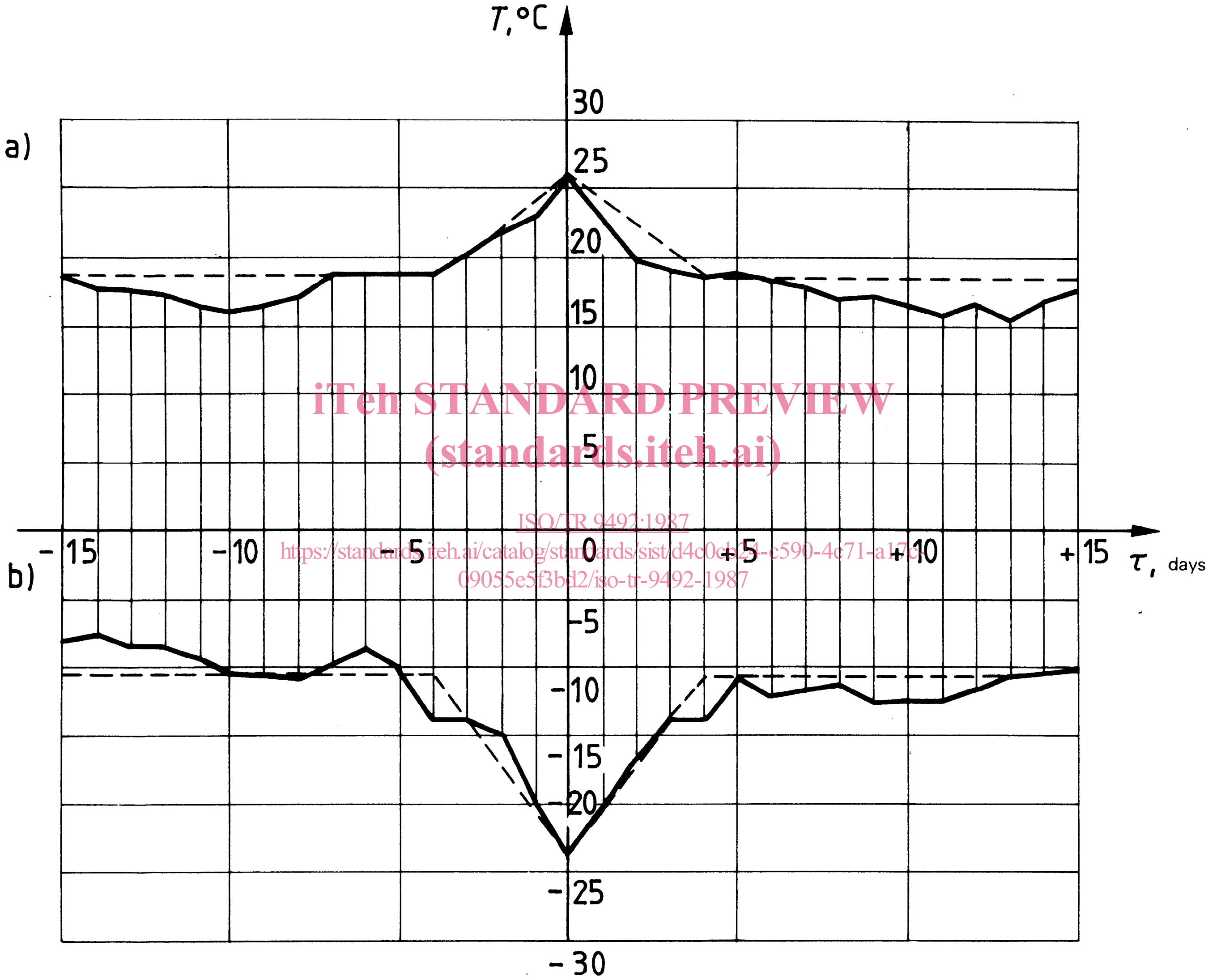


Figure 3 — Graphs of unfavourable mean daily air temperature variations — a) for summer, b) for winter — in Moscow

It is recommended that characteristic values of mean daily temperatures correspond to a return period of their excess (in absolute value) once in N years in accordance with ISO 2394 and national codes:

$$\left.\begin{aligned} T_{ehk} &= \bar{T}_{eh} + k\,\hat{T}_{eh} \\ T_{elk} &= \bar{T}_{el} + k\,\hat{T}_{el} \end{aligned}\right\} \qquad \ldots (3)$$

where

$\bar{T}_{eh}$, $\bar{T}_{el}$ are mean values of extreme mean daily temperature;

$\hat{T}_{eh}$, $\hat{T}_{el}$ are standard deviations of extreme mean daily temperature;

k is the number of standard deviations corresponding to the return period N (see table 1) derived from the formulae:

for normal distribution function F,

$$k = F^{-1}[\varphi(x)]$$

for double exponential distribution,

$$k = \frac{\left[-\ln\ln\frac{1}{\varphi(x)} - \gamma\right]\sqrt{6}}{\pi}$$

where $\varphi(x) = 1 - \frac{1}{N(x)}$ and $\gamma = 0{,}577\,22$ (Euler constant).

Table 1

Return periods, N years	**Values of k** for normal distribution function	for double exponential distribution
2	0,00	− 0,16
5	0,84	0,72
10	1,23	1,30
20	1,65	1,86
50	2,05	2,58

The mean cross-section temperature of massive structures (e.g. reinforced concrete bridge structures) follows the variations of mean daily air temperatures with some delay which increases with the increase of the massiveness (thickness) of elements. For design of such structures it is possible, with some approximation, to use extreme values of mean air temperatures for the averaged periods of 3 to 5 days and longer, instead of employing mean daily values.

Daily variations of outdoor air temperature are defined by daily amplitude, i.e. half the difference between maximum and minimum daily temperature. The highest values of daily amplitude are observed under a clear sky. The following are recommended as characteristic values of daily amplitude:

$$\left.\begin{aligned} a_{ehk} &= \bar{a}_{eh} + k\,\hat{a}_{eh} \\ a_{elk} &= \bar{a}_{el} - k\,\hat{a}_{el} \end{aligned}\right\} \qquad \ldots (4)$$

where

$\bar{a}_{eh}$, $\bar{a}_{el}$ are mean values of daily amplitudes in the hottest and coldest months of the year;

$\hat{a}_{eh}$, $\hat{a}_{el}$ are standard deviations of daily amplitudes in the hottest and coldest months of the year.

6 Solar radiation

Reference data on short-wave solar radiation should be obtained from pyrheliometric observations. The scope of these observations includes measurement of direct radiation on the surface perpendicular to sun rays, S, diffused radiation, D, and total radiation Q (i.e. direct plus diffused) on the horizontal surface. These parameters are recorded at definite observation times or continuously. The values of S, D and Q, averaged for each month or for several years, are given in handbooks.

When observation data are not available, an approximate estimate of direct and diffused radiation can be obtained from a minimum amount of reference data. Investigations have shown [28] that the following empirical formula can be used for determining the intensity, S_m, of direct solar radiation under clear sky and non-varying clearness of atmosphere during the day:

$$S_m = S_0/(1 + C_m) \quad \ldots \quad (5)$$

where

S_0 is the meteorological solar constant equal to 1 256 W/m^2;

C is the coefficient which depends on atmospheric clearness: for normal clearness C = 0,31;

m is the number of optical masses of the atmosphere to be assumed according to the altitude of the sun h (see table 2).

Table 2

Altitude of the sun, h degrees	Number of optical masses, m
90,0	1,0
41,7	1,5
30,0	2,0
23,5	2,5
19,3	3,0
16,4	3,5
14,3	4,0
12,6	4,5
11,3	5,0

Altitude of the sun above the horizon, h, is derived from the formula:

$$\sin h = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\gamma \quad \ldots \quad (6)$$

where

φ is the geographical latitude of the locality,

δ is the angle of the sun declination;

γ is the hour angle of the sun, in degrees, equal to

$\gamma = 15\,\tau$

where

τ is the time, in hours, starting at noon.

The intensity of direct solar radiation on a horizontal surface is:

$$S' = S \sin h \quad \ldots \quad (7)$$

The intensity of diffused solar radiation on the horizontal surface is:

$$D = 0{,}38\,CS \quad \ldots \quad (8)$$

The intensity of total radiation, Q, on the horizontal surface can be obtained as the sum of (7) and (8):

$$Q = S' + D \quad \ldots \text{(8a)}$$

Figure 4 shows curves of intensity of direct radiation, S on the surface normal to the sun rays and S' on a horizontal surface, as well as diffused radiation, D, and total radiation, Q, on a horizontal surface under clear sky and normal clearness of atmosphere.

Data on intensity of direct solar radiation on the surface normal to the sun rays can be used for evaluation of intensity of radiation on vertical, S_v, and inclined surfaces of any orientation, S_α, by the formulae:

$$S_v = S \cos\theta \quad \ldots \text{(9)}$$

$$S_\alpha = S_v \sin\alpha + S' \cos\alpha \quad \ldots \text{(10)}$$

where

θ is the angle between the direction of the sun ray and the normal to the surface at the given point of latitude φ;

α is the angle of inclination between the surface and the horizon.

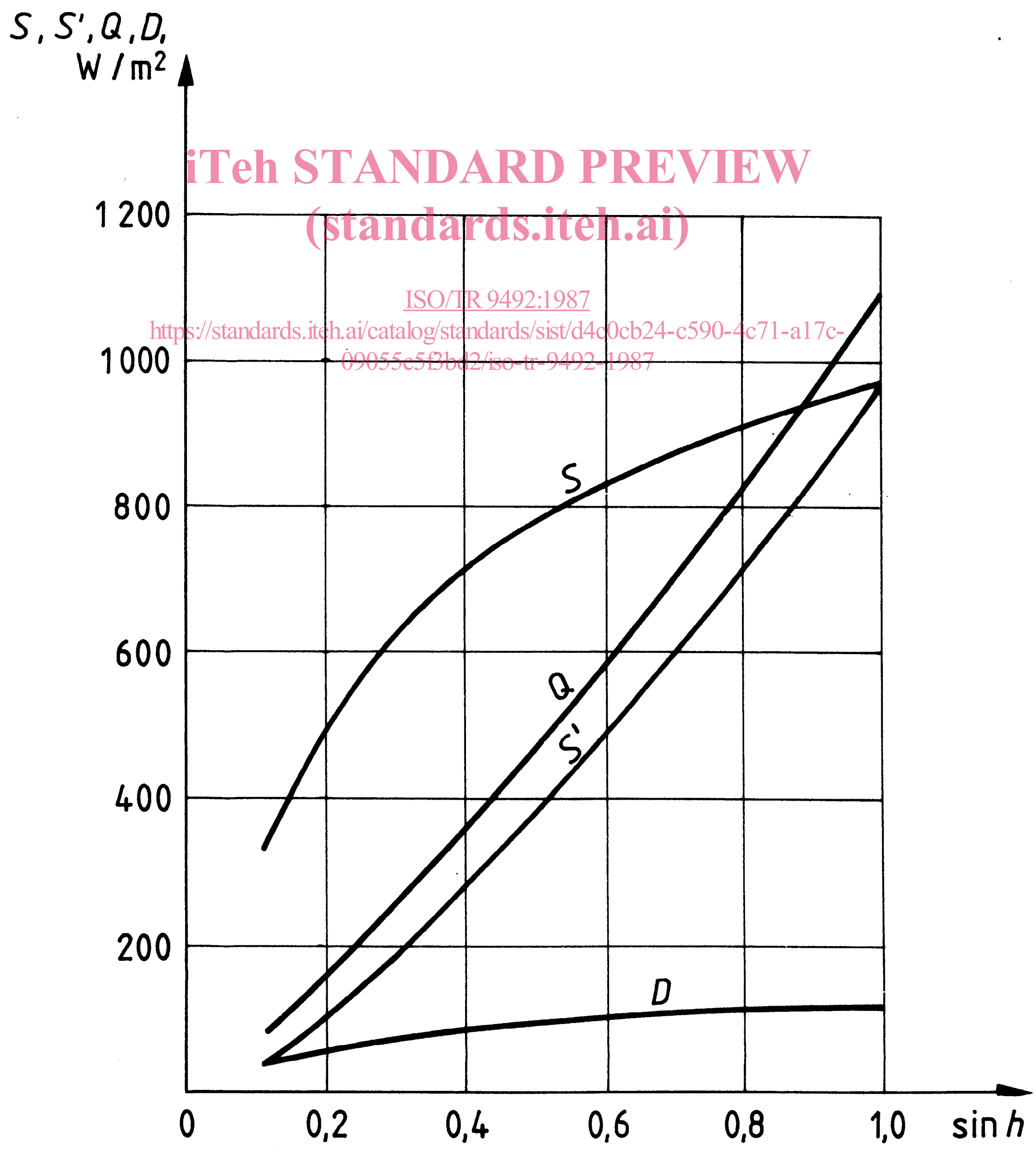


Figure 4 — Graphs of intensity of direct solar radiation