

EFFECTS OF TEMPERATURE UPON REINFORCED CONCRETE COOLING TOWERS

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1. Introduction

No detailed investigation of temperature effects upon civil engineering structures were made before the recent decades, partly because the resulting stresses were underestimated, and partly because of the neglect of details in engineering education. Temperature effects were taken into consideration primarily if the structure was exposed to special heat effects (e.g. storage of hot materials).

KILIÁN and BALÁZS [1] investigated in detail the effect of heat upon reinforced concrete circular symmetric tanks. KORDINA and EIBL [2] published a useful process for calculating the uneven warming of a singular cylinder due to one-sided insolation. Elongation and bending stiffnesses of the reinforced concrete tank wall were pointed out to drop upon cracking, affecting also thermal stresses, without, however, supplying numerical data. SEBŐK [3] pointed to the softening of structures holding hot matter. Insolation of a prestressed concrete liquid tank was found by PRIESTLEY [4] to heat the concrete surface over the atmosphere and the temperature difference across the wall to be higher than supposed earlier, maybe as high as 40 °C.

In detailed analyses of inherent shrinkage and thermal stresses in reinforced concrete members PALOTÁS [5] proved short-time temperature drops of about 15 °C to be likely to cause exhaustion of concrete extensibility, i.e. cracking without external loads.

The first comprehensive theoretical and experimental analysis of temperature effects on reinforced concrete cooling towers by LARRABEE et al. [6] has led to the conclusion that circumferential variation of radial temperature differences due either to uniform internal heating up or to one-sided insolation may be omitted, stresses depending only on local temperature differences. The shell edges, however, exhibit edge disturbances. Deflection due to one-sided insolation is small enough to be neglected.

In summer 1977, HOLÉCZY [7] made precision measurements on shell deformations of the cooling tower of the Gagarin Power Station due to one-sided insolation.

Shell cross section was found to become elliptic, deformations to be small (of a few cm order), but the stiffening effect of edge beams to prevail.

No detailed thermometry data for cooling tower walls are available, measurements are informative for the lower shell part alone, without indicating e.g. the vertical temperature distribution, justifying a deeper analysis of the problem.

2. The nature of thermal effects

Thermal effects on structures may have three basic cases, such as:

- change of mean temperature of the structure (warming up or cooling);
- temperature difference between members of the structure;
- temperature gradient inside the structural unit.

Temperature effects are generally time-dependent processes, rather difficult to mathematically formulate especially as concerns forces, reactions and deformations. Therefore practical calculations involve approximate assumptions, the most important being:

- temperature change in the material of a structural unit is independent of stresses and strains;
- deformations are small enough to permit analysis of the original form;
- the principle of superposition is valid, the material follows Hooke's law;
- thermal stresses are unaffected by shrinkage or creep.

These assumptions are but partly met, thus even mathematically exact methods remain approximations.

Rather than to exactly follow time-dependent processes, we are satisfied to take only the extreme values of their thermal effect into consideration, supposing an intermediate state not to be critical.

2.1 Permanent heat flow

In practical calculations, heat flow is supposed to be constant in time at a linear temperature distribution across the wall.

2.11 Temperature decrease in a multilayer cylindrical wall

Temperature difference between two faces of a multilayer cylindrical wall exposed to a heat flow of at least 6 to 8 hours is given by [8]:

$$\Delta T_i = \frac{h_i R (T_b - T_k)}{\lambda_i r_i \frac{1}{k}}$$

where heat transmission coefficient

$$\frac{1}{k} = \frac{1}{\alpha_k} + \sum_{i=1}^m \frac{h'_i}{\lambda_i} \frac{R}{r_i} + \frac{1}{\alpha_b}$$

here

- h_i — layer thickness [m];
- h'_i — the substituting thickness [m];
- T_k — outer face temperature [$^{\circ}\text{C}$], or always the lower temperature;
- T_b — inner face temperature, or always the higher temperature [$^{\circ}\text{C}$];
- λ_i — conductivity coefficient [W/mK];
- α_k — outer heat transmission coefficient [W/m² K];
- α_b — inner heat transmission coefficient [W/m² K];
- R — radius belonging to the outer face [m];
- r_i — radius belonging to the outer face of each layer [m].

The substituting thickness $h'_i = \nu h_i$, where ν can be determined from the diagram in Fig. 1c.

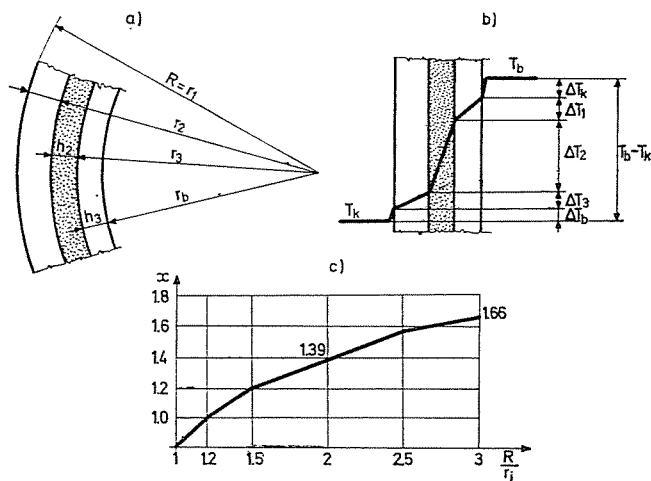


Fig. 1

For a radius belonging to the inner wall face $r_i > 3$ m, the wall curvature may be neglected, and substitution $R/r_i = 1$ simplifies the formula.

2.12 Temperature change in a flat plate

In case of a single flat plate or wall:

$$\Delta T = \frac{h}{\lambda} \cdot \frac{T_k - T_b}{\frac{1}{k}}$$

where

$$\frac{1}{k} = \frac{1}{\alpha_k} + \frac{h}{\lambda} + \frac{1}{\alpha_b} = c + \frac{h}{\lambda} = \frac{c\lambda + h}{\lambda}.$$

With air on both faces of the unit, substitution $\alpha_k = \alpha_b$ and $c\lambda \approx 0.2$ leads to the approximate formula for the temperature drop:

$$\Delta T = \frac{h}{0.2 + h} (T_k - T_b).$$

2.2 Warming up of the structural unit

In the general case, exact calculation of the heating up of a hot-faced structural unit, temperature flow, is rather difficult, inducing to apply the simplifying assumption of constant temperatures of both insulated and shaded

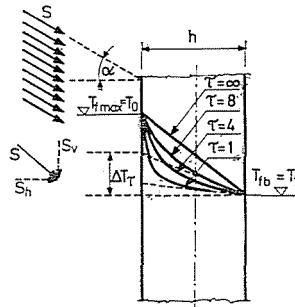


Fig. 2

faces during the full insolation time. Radiation, e.g. solar heat may rise the surface temperature over that of the ambient air, and for this case PRIESTLEY suggests the temperature gradient seen in Fig. 2. Distribution of the surface temperature within the structural unit will be investigated below, using the partial differential equation

$$\frac{\partial T}{\partial \tau} = a \frac{\partial^2 T}{\partial x^2}$$

where

- T — temperature,
- τ — exposure time,
- x — distance of the test spot from the surface

$$a = \frac{\lambda}{c\rho} = \frac{\text{heat conductivity coefficient}}{\text{specific heat} + \text{solid density}} = \frac{\text{temperature conductivity coefficient}}{\text{coefficient}}.$$

Boundary conditions:

- at $x = 0$, on the hot face $T = T_0$,
- at $x = h$, on the shaded face $T = T_b$,

where h is the unit thickness.

Solution of the partial differential equation meeting also the boundary conditions is given by:

$$T(x, \tau) = T_0 - (T_0 - T_b) \left[\frac{x}{h} - \frac{2}{\pi} \sum_{n=1}^{\infty} (-1)^n \frac{1}{n} e^{-\left(\frac{\alpha n}{h}\right)^2 \tau} \cdot \sin \frac{n\pi x}{h} \right].$$

The series is convergent for practical values of τ , so it is enough to take 2 or 3 members into consideration. Temperature gradient at different times τ is seen in Fig. 3.

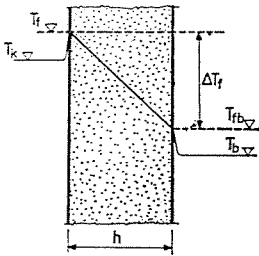


Fig. 3

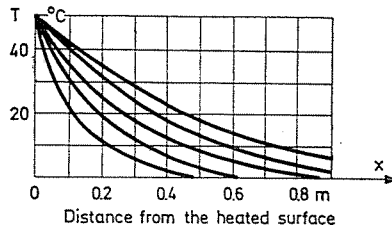


Fig. 4. Temperature gradients

The temperature gradient is seen to be about linear after an exposure of 8 hours.

Temperature gradients measured across different wall thicknesses are seen in Figs 4 and 5 [9, 10].

Both theoretical calculations and measurement results permit to consider the temperature gradient across a wall 20 cm thick exposed to solar heat (radiation) for 6 to 8 hours as linear.

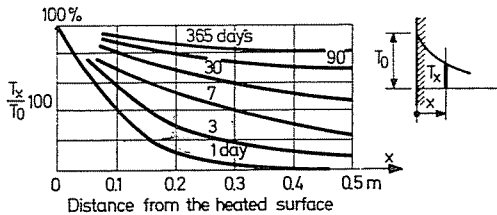


Fig. 5. Temperature gradients

2.3 Heat flow changing with time

Technical and meteorological heat effects on structures are changing with time. They may be short-time or permanent heat loads, e.g. daily or seasonal fluctuation, direct sunshine, sudden chill (e.g. a summer shower), etc.

Change in time of the outside and the surface temperatures are shown in Fig. 6. Inside the unit, the heat lag shifts the peak appearance, at the same time the amplitude of the surface temperature T_0 is reduced by heat damping to a value T_x . Thus the surface temperature variation appears inside the unit with a time lag and less conspicuously.

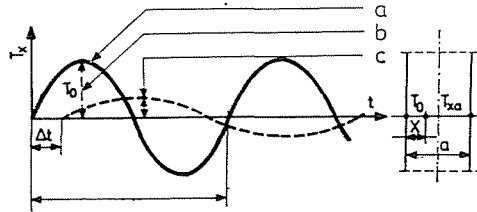


Fig. 6 a — surface temperature change; b — amplitude; c — inner amplitude

Examination of timely variation of thermal stresses in the structural unit leads to conclusions schematically illustrated in Fig. 7. Stresses due to a short-time thermal effect follow essentially the temperature variation. Also temperature at different points of the structure changes differently; thus it is very difficult to point out the instant of stress maxima. Permanent stresses decrease upon creep, further hampering an exact theoretical formulation of the problem.

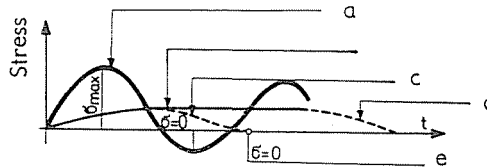


Fig. 7 a — $\sigma(t)/T$ ratio; b — $\sigma_{\min} = \text{const}$; c — $\sigma_{\text{init}} \rightarrow 0$; d — creep; e — statically determined beams, linear temperature gradient

2.31 Insolation effect

Among intermittent, variable meteorological temperature effects, one-sided insolation of the structure has a prominent importance.

2.31.1 Intensity and duration of insolation

At a given point of the earth surface, the intensity of insolation incident on a horizontal or vertical surface seasonally changes as a function of the geographical latitude. Principial rather than factual Fig. 8 shows the highest sunshine intensity (at noon) to be incident on horizontal surfaces in the summer months and on the vertical ones in the winter months. Thus in the summer

months horizontal surfaces, flat roofs, whereas in winter the vertical surfaces become more intensively warmed. Naturally the winter solar heat effect is much lower because of atmospheric damping and the ambient temperature. In the figure — as mentioned — the typical noon sunshine maxima have been plotted. Figures were composed from data for *New Zealand* by M. J. N. PRIESTLEY so as to be valid under Hungarian conditions, taking the geographical latitude into account.

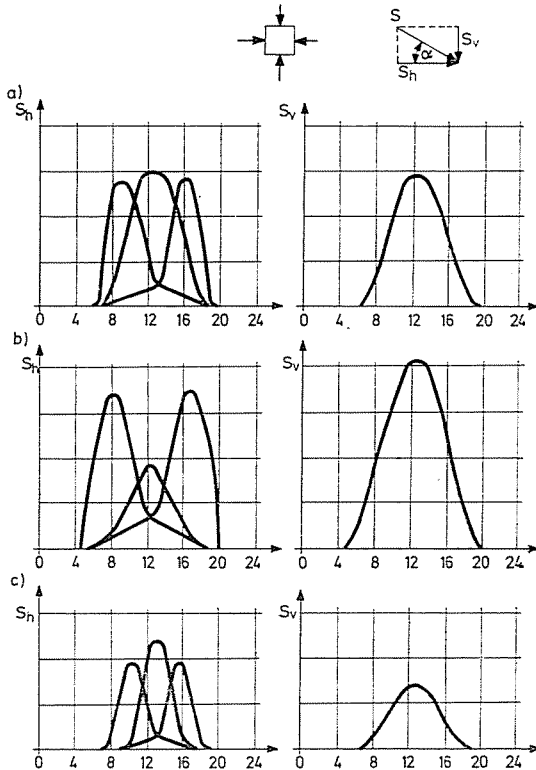


Fig. 8

In the Figures separate curves indicate the variation of the sunshine intensity affecting the vertical surfaces of different orientations. They show that in spring and autumn the sunshine maxima on vertical surfaces facing east, south and west are nearly identical, duration being longer on the south side. Intensity maxima are nearly identical between horizontal and vertical surfaces, but duration is longer on the former. In summer, sunshine intensity affecting vertical surfaces facing east and west exceeds that incident on south sides. At the same time the horizontal surface is hit by very intense and durable solar radiation. In winter the radiation intensity on vertical surfaces facing south is greater than on the east and west sides and a rather low radiation

intensity affects the horizontal surfaces. Heating up of the surfaces is proportional to the domain under the respective curve, thus in summer, higher temperature and stress maxima are expected on the east and west sides than on the south side; the highest heating up may be expected on the horizontal surfaces. The average insolation time of structures can be assessed as 6 to 8 hours for vertical surfaces and 10 to 12 hours for horizontal surfaces.

2.31.2 Heating up of the surface

A few hours of insolation heat the surface of structures.

The rate of heating up is fairly approximated by the Boltzmann radiation formula applied for the insolation-emission balance of a smooth, optically black layer laid on a thermal insulation:

$$S_{eff} - \varepsilon 5.679 \cdot 10^{-12} \cdot T^4 = 0$$

where

S_{eff} — the effective absorbed heat output;

ε — emission coefficient;

T — equilibrium temperature of the radiating surface in absolute temperature degrees [°K].

The effective absorbed heat output is obtained from:

$$S_{eff} = (1 - a_0)S_n = \alpha a S_n$$

α — atmospheric damping factor;

a_0 — reflection factor of the surface (albedo);

S_n — surface normal component of the solar constant.

Values of α and a_0 in the formula depend also on the angle of incidence, since, however, T in the Boltzmann radiation balance formula figures on the fourth power, the equilibrium temperature is little influenced by the small fluctuations of S_{eff} and ε . Rather accurate data for the heating up maximum are obtained by reckoning with S_{eff} for a constant incidence angle in a wide time interval (in Hungary about 6 to 8 hours) of insolation. The equilibrium temperature from the Boltzmann formula:

$$T = \sqrt[4]{\frac{\alpha a S_n}{\varepsilon \cdot 5.679 \cdot 10^{-12}}}$$

The heating up temperature in °C:

$$T_f = T - T_0 = T - 273.$$

Informative warming up temperature values are obtained from the following data:

The atmospheric damping coefficient:

$$\alpha = 0.90,$$

the emission coefficient:

$$\varepsilon = 0.90,$$

the surface reflection factor:

on a black surface: $a_0 = 0.1$,

on a gray surface: $a_0 = 0.3$,

the assumed angle of incidence: $\varphi = 50^\circ$.

The calculated surface temperatures have been tabulated as:

Surface		α_0	Surface temperature °C	
colour	direction		$\varphi = 60^\circ$	$\varphi = 50^\circ$
black	horizontal	0.1	100	87
	vertical	0.1	53	72
gray	horizontal	0.3	76	65
	vertical	0.3	32	51

The method is based on the assumption of constant radiation intensity hence it is an approximation. Also uncertainties in the constants make the numerical values inexact, except for the orders of magnitude.

Different measurement results have been obtained. According to measurements made in Berlin [11], a single-layer gray wall surface temperature changed with the orientation (north 40 °C, south 45 °C, east 52 °C, west 57 °C). PRIESTLEY [4], LARRABEE [6] and HOLÉCZY [7] obtained surface temperatures of about 60 °C, 58 °C and 35 °C, respectively.

The wall surface temperature of a silo in Hódmezővásárhely was 60 °C in calm weather, near the ground, according to our own measurements.

The surface temperature is influenced by air movement, especially for tall buildings.

3. Operational thermal effects in reinforced concrete cooling towers

3.1 General remarks

No measurement data are available for service temperature conditions in reinforced concrete cooling towers. The structure gets warm or cools down after the first openings-up or reinstatements or after standstill, thus resulting in temperature differences between and within structural units.

Specifications and recommendations abroad assume circular symmetric distribution of service temperature effects irrespective of local warming or cooling.

HENNING [12] suggested to reckon with a cooling water temperature rising to 80 °C in case of breakdown in the design of exposed structural parts of wet-process cooling towers as well as temperature differences across the shell wall of 35 °C and 18 °C for the lower wet surface and the upper dry part, respectively. Even in extreme cases of winter breakdowns, temperatures may differ by as much as 60 °C and 20 °C, respectively.

For winter operation the Soviet Standard regulations specify a temperature difference $\Delta T \cong 30$ °C across the lower wet part, and besides, the soaked concrete swelling has to be reckoned with.

Temperature effects are worse on wet than on dry process cooling towers and this has to be taken into account in the specifications.

3.2 Effect of concrete soaking

Concrete swells when soaked or shrinks during drying. Swelling is proportional to the infiltrated water quantity, therefore ALEKSANDROVSKY [13] suggested the following formula for determining the specific deformation:

$$\varepsilon_m = \eta \Delta u$$

where η — linear swelling factor of the concrete, in the mean case

$$\eta = 3 \times 10^{-2} \frac{\text{mm/mm}}{\text{gr/gr}};$$

Δu — absorptivity of concrete, under winter conditions: $\Delta u = 0.35 \times 10^{-2}$ gr/gr; under summer conditions: $\Delta u = 0.5 \times 10^{-2}$ gr/gr.

Accordingly, specific deformation due to moisture absorption is

$$\text{in winter: } \varepsilon_m = 1.05 \times 10^{-4},$$

$$\text{in summer: } \varepsilon_m = 1.5 \times 10^{-4},$$

of the same order as that due to a temperature change $\Delta T = 10$ °C:

$$\varepsilon_t = \alpha \Delta T = 1.10^{-5} \times 10 \text{ °C} = 1.10^{-4}.$$

For wet-process cooling towers equivalent fictitious temperature changes are:

$$\Delta T_n = 10 \text{ °C in winter,}$$

$$\Delta T_n = 15 \text{ °C in summer.}$$

3.3 *Temperature difference between structural parts*

The temperature difference between the ring foundation and the lower edge ring, due to the heating up or cooling down of latter, referred to the median of the rings:

$$\Delta T_a = 20 \text{ }^\circ\text{C in dry process and}$$

$$\Delta T_a = 30 \text{ }^\circ\text{C in wet process.}$$

These temperature differences are partly short and partly long-time effects.

The winter temperature difference between the shell and the lower edge ring may be taken as

$$T_a = 10 \text{ }^\circ\text{C}$$

whereas that between the shell and the horizontal upper edge ring as

$$T_a = 15 \text{ }^\circ\text{C,}$$

summer temperature differences being smaller.

3.4 *Temperature difference across the shell wall*

The temperature difference between two faces of structural parts is greater in winter operation, when the inner temperature is higher. In summer, outside it is hotter but then the temperature difference will be less.

Dry-process cooling towers

in case of winter operation

— near the lower edge ring (at about one fourth
of the shell height) $\Delta T = 30 \text{ }^\circ\text{C}$

— in the upper part of the shell $\Delta T = 25 \text{ }^\circ\text{C,}$

in summer standstill, during overhaul or construction

— temperature difference across the entire
structure $\Delta T = 20 \text{ }^\circ\text{C.}$

Wet-process cooling towers

The effect of swelling due to soaking may be taken into account with the fictitious temperature difference, and in soaked places in the lower shell part up to one fourth of the height, temperature differences to be reckoned with are:

$$\text{in winter: } \Delta T_f = \Delta T + 10 \text{ }^\circ\text{C,}$$

$$\text{in summer: } \Delta T_f = \Delta T + 15 \text{ }^\circ\text{C,}$$

where ΔT is the value for dry-process cooling towers.

4. Effect of one-sided insolation

According to measurements by LARRABEE [6] and HOLÉCZY [7], the cooling tower is heated by sunshine by about 10 °C. The temperature distribution is other than circular symmetric and may be assumed on the sunny side of the structure to follow a cosine function. Also the temperature difference between the sunny and the shaded sides is of the order of 10 °C.

The temperature difference between the two faces of the shell wall is about $\Delta T = 20$ °C. The one-sided solar heat makes the horizontal cross section oval. Towards noon, sunshine is cast on the north wall of the shell causing movements first measured by Holéczy. Thus, the shell makes peculiar time-dependent movements upon insolation rather difficult to follow by computations. On the other hand, measurement results proved unambiguously the reinforcing effect of edge rings because in their vicinity deformations were much smaller. Temperatures due to sunshine being lower than the service ones, in final account, effect of one-sided insolation may be neglected.

5. Bending moment due to temperature difference and approximate calculation of the necessary reinforcement

Annular and meridional bending moment due to temperature difference across the shell wall and to moisture swelling:

$$M_{T+n} = \pm \frac{B}{1-\nu} \frac{\alpha \Delta T + \eta \Delta u}{h} = \pm \frac{B}{1-\nu} \frac{\alpha \Delta T_f}{h}$$

where $B = \Psi E_b I_{bi}$ — stiffness of the cracked cross section;

$\nu \approx 1/6$ — Poisson's ratio;

h — wall thickness;

ΔT_f — fictitious temperature difference taking the wetting into account.

The reinforcement necessary for bearing this bending moment:

$$f_{a,T} = \frac{M_{T+n}}{\sigma_{aH} z}$$

substituting $f_{a,T} = \mu_T h$; $z = \xi h$ and reducing yields the reinforcement percentage:

$$\mu_T = \frac{B}{1-\nu} \frac{\alpha \Delta T_f}{\xi h^3 \sigma_{aH}}.$$

Taking standard material qualities and stiffness drop by cracking into consideration, further supposing that temperature differences are half-way short-

time, half-way permanent, leads for the reinforcement percentage to

$$\mu_T = \frac{\Delta T_f}{200} (\%)$$

in case of concretes B280 or lower grade. Concrete grades B400 or B560 yield for the reinforcement percentage:

$$\mu_T = \frac{\Delta T_f}{150} (\%).$$

These relationships do not include the safety factor.

Summary

Temperature effects on large reinforced concrete cooling towers have been investigated and suggestions made on how and with what numerical values to take service temperature effects into consideration. Examination of one-sided insolation ended with the conclusion that its effect is negligible. An approximate method for determining the reinforcement percentage needed to take bending moments due to temperature differences across reinforced concrete plate structures has been suggested.

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