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THE INFLUENCE OF SOLAR RADIATION ON TEMPERATURE INCREMENT OF SHEET STEEL STRUCTURES

O. I. KORDUN[1]

The paper considers method of determination of solar radiation amount falling on arbitrarily oriented surface of a structure. Provided method allows calculation of influence of structure's geographical coordinates, spatial orientation of structure's surface, day of year and time of day on received amount of solar radiation. The method is intended for determination of thermal stresses and deformations of sheet steel structures caused by action of direct solar radiation. Examples show usage of provided method.

Keywords: shell structures, sun radiation, climatic actions

1. INTRODUCTION

There are many cases in modern engineering when buildings are subjected to direct solar radiation. The list of such buildings includes bridges and overpasses, membrane coverings of public and industrial buildings, tower and mast structures, chimneys, steel sheet structures: blast-furnace production facilities, silos, bunkers, vessels and other structures.

Direct solar radiation provides structure with heat energy, and as a result, sun-lighted parts of structure become warmer and larger. Temperature difference on the lighted part of an object and on its shaded part leads to non-uniform deformations, curving of axes, occurrences of buckling, and in statically indeterminate systems these differences provoke significant inner forces.

[1] V. Shimanovsky Ukrainian Institute of Steel Construction, V. Shimanovsky St. 2/1, 02660 Kiev, Ukraine,
e-mail: kordun@urdisc.com.ua

Solar radiation is the energy flow of electromagnetic waves in infrared, light and ultraviolet spectrum, intensity of which is defined by fundamental physical constant called solar constant.

Solar constant is a compound flow of solar electromagnetic radiation, going through a unit area, which is perpendicular to solar rays' direction and located outside the Earth's atmosphere at the distance of 1 a. u. from the Sun. Solar radiation depends on the distance between the Earth and the Sun in process of the Earth's orbital motion, and also on the Sun's activity. In engineering calculations, solar constant is accepted as 1370 watt/m².

2. LOSSES OF SOLAR ENERGY IN ATMOSPHERE

Before reaching Earth's surface, solar radiation goes through the atmosphere. In the atmosphere, it is partially absorbed and diffused. It is accepted that energy's intensity while going through the atmosphere decreases according to the exponential law in Eq. (2.1):

$$J = J_0 \cdot \exp(-k \cdot x) \tag{2.1}$$

where J_0 – initial amount of energy;

J – – amount of energy left after going through atmospheric depth x;

k – absorption value. Value, which is inverse to this value, is numerically equal to atmospheric depth, which weakens energy e = 2,718 times.

This law was experimentally stated by P. Bouguer (1729) and then theoretically derived by J. H. Lambert (1760) [1].

To measure residual solar energy, it is necessary to know the length of the solar rays' path through the atmosphere. Let us consider a general case of solar rays hitting a surface area perpendicular to them and located on Earth (fig. 1). Rays are directed at the angle λ to vertical. The Earth has radius R and is surrounded by a layer of atmosphere with height d. Length of section x in Eq. (2.2) is the length of path of solar rays in the atmosphere of the Earth.

Path length of solar rays x may be defined on the basis of cosine theorem,

$$x = \sqrt{R^2 \cdot \cos^2\lambda + 2 \cdot R \cdot d + d^2} - R \cdot \cos\lambda \tag{2.2}$$

but dimensionless parameter m is used more often:

$$m = \frac{\sqrt{R^2 \cdot \cos^2\lambda + 2 \cdot R \cdot d + d^2} - R \cdot \cos\lambda}{d} \tag{2.3}$$

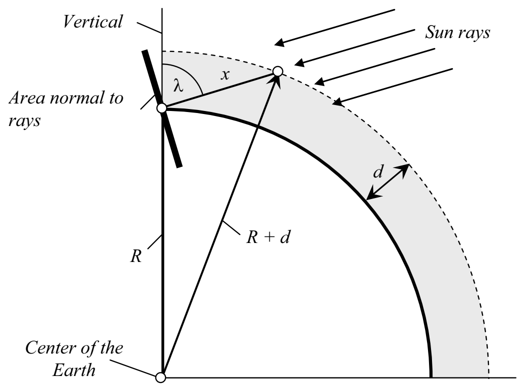

Fig. 1. To determine the length of path ***x*** travelled by the Sun rays in atmosphere

Parameter m defines path length x, measured in heights d of atmosphere layer. In meteorology and actinometry [2] this parameter is called the atmosphere mass.

Dependence of m on λ is defined by Eq. (2.3), graphically it is shown in fig. 2. Here accepted as $R = 6378{,}1$ km, $d = 10$ km.

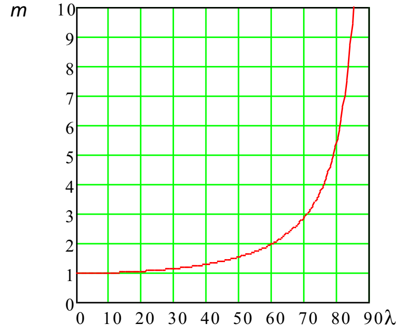

Fig. 2. Dimensionless parameter m as angle function λ Eq. (2.3)

It should be mentioned that dependence of m on λ does not significantly depend on atmosphere height value d accepted for calculation.

The amount of energy, left after light traveling through atmospheric depth, may be expressed by Eq. (2.1). But in meteorology and according to Kondrat`ev [2], other formula is used more often:

(2.4) $$J = J_0 \cdot p^m$$

where J_0 = 1370 watt/m² – solar constant;

J – required intensity of direct solar radiation on the ground level watt/m^2;

m – atmosphere mass expressed by Eq. (2.3);

p – atmosphere transparency coefficient.

Eq. (2.4) is connected with Eq. (2.3). Atmosphere transparency coefficient p in Eq. (2.5) is expressed through absorption value k from Eq. (2.3) and atmosphere layer height h as following:

(2.5) $$p = \exp(-k \cdot d)$$

The atmosphere transparency coefficient is part of solar radiation reaching Earth while the Sun is in zenith. This coefficient is found experimentally. It is not constant (which, of course, would be more convenient), but depends on the length of light wave and atmosphere mass m. If we know spectrum of solar radiation, we may receive integral values of atmosphere transparency coefficient covering the whole spectrum. Table 1 contains integral values of this coefficient for dry and clean atmosphere received experimentally by different scientists.

Table 1. Integral coefficient of transparency p for dry and clean atmosphere according to [2]

m	By Feissner and Dubois (1930)	By Kastrov (1930)	By data of International radiation commission (1956)
1	0,907	0,906	0,906
2	0,915	0,914	0,916
3	0,921	0,921	0,922
4	0,926	0,927	0,928
6	0,935	0,935	0,936

The case of dry and clean atmosphere is convenient in determining of direct solar radiation's impact on buildings and facilities, because in such case maximum temperature of lighted surface is reached.

Results received by different scientists successfully correspond with each other. To calculate, we choose results of International radiation commission. The following approximation dependence expressed by Eq. (2.6) was derived in order to provide comfortable automation of calculation:

$$p(m) = \frac{4,616 + 0,972 \cdot m}{5,166 + m} \tag{2.6}$$

Approximation coefficients, given in this formula, are received by minimization of sum of squares of curve deviations (Eq. (2.6)) from experimental values given in Table 1. Approximation quality may be assessed by fig. 3.

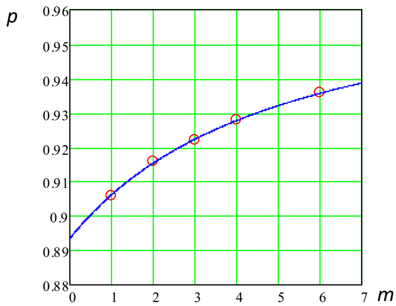

Fig. 3. Comparison of approximation by Eq. (2.6) with experimental data

In such way, intensity of direct solar radiation reaching Earth after traveling through atmosphere with mass *m* may be expressed by formula:

$$J = 1370 \cdot \left(\frac{4,616 + 0,972 \cdot m}{5,166 + m} \right)^m \text{ watt/m}^2.$$

In this formula, mass of atmosphere *m* is an argument. By Eq. (2.3) we may proceed from argument *m* to argument λ – angle of incidence of the Sun rays in relation to vertical (fig. 1). These dependences are expressed graphically in fig. 4.

Given data may be considered as upper bound activity of solar radiation which reaches the Earth's surface. Possibility of such activity is very low. Real level of solar radiation will be smaller. Radiation level, which should be accounted for in calculations, depends on calculations' purpose. The important factor is length of time period needed for averaging data. If we talk about heating of cladding or sheet structures, the averaging time will be estimated in tens of minutes, if it is massive structures – than the averaging time will be estimated in hours.

If we talk about installation of heating systems in buildings, the averaging time may be estimated in days, and in case we talk about solar power engineering, the averaging time may be estimated in years. In calculations of structural reliability, we should consider possibility of excessive temperature during service life of structures.

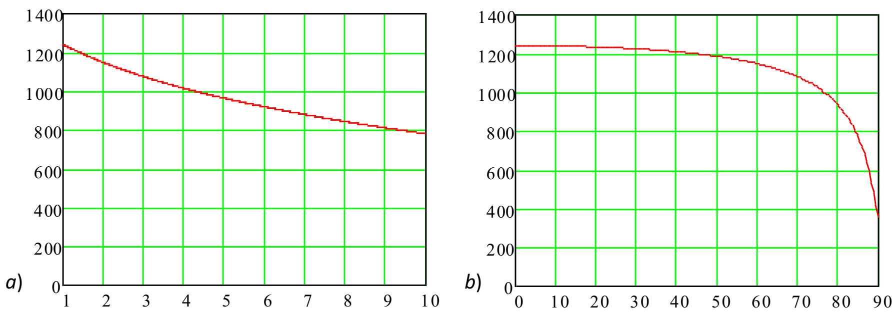

Fig. 4. Intensity of direct solar radiation J on unit of area of normal area watt/m^2 depending on *a*) atmosphere mass m; *b*) angle λ

Dependence of accounted radiation level on averaging time or on possibility of excessive temperature of structure is defined by climatic zone and place of structure's operation. The important factors are presence and intensity of cloudiness, atmospheric humidity and transparency, gas-laden atmosphere, smog etc. Above-mentioned data on intensity of solar radiation may be used in calculating of structure heating in desert climate zones. In conditions of moderate climate, air contains particles of water, gases and dust, which leads to diffusion of light, and thereby radiation level may decrease by 10 – 20%.

3. RADIATION FALLING ON STRUCTURE SURFACE

Three types of solar radiation fall on structure surface: direct, diffused and back. All above-mentioned information concerns direct solar radiation. Diffused solar radiation comes from the sky and clouds. Back solar radiation is the part of radiation reflected from the Earth surface and surrounding objects. The second and the third part of energy are less determinate than the first one, and they are described adequately by J.A. Duffie [3], S.-H. KIM [4] and other.

For studying non-uniform heating of open structures, direct solar radiation is important, since diffused solar radiation influences lighted as well as shaded structure surfaces. Back solar radiation depends on reflection power of surface (albedo) and in most cases is insignificant for sheet structures and facilities. Further we will consider only direct solar radiation.

Radiation, which falls on structure surface, depends on positional relationship of lighted surface area and the direction of solar rays. The location of an area will be characterized by perpendicular to area. This perpendicular is oriented in such way that solar rays subtend an acute angle with it (fig. 5).

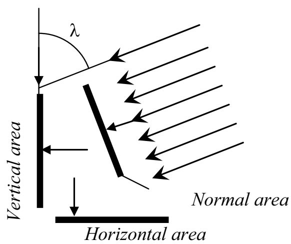

Fig. 5. Direction of solar rays and location of areas

If we know intensity of direct solar radiation *J*, falling on unit area of normal area, we may define intensity of the direct solar radiation falling on unit area of arbitrarily oriented area by multiplying value *J* by cosine of angle between direction of solar rays and direction of normal to considered area.

Let us consider intensity of solar radiation on unit area of horizontal area J_h and intensity of solar radiation on unit area of vertical area J_v, oriented towards solar rays (see fig. 5). These intensities are expressed by Eq. (3.1):

$$J_h = 1370 \cdot \left(\frac{4,616 + 0,972 \cdot m}{5,166 + m} \right)^m \cdot \cos\lambda; \quad J_v = 1370 \cdot \left(\frac{4,616 + 0,972 \cdot m}{5,166 + m} \right)^m \cdot \sin\lambda\,; \tag{3.1}$$

where λ is angle between direction of solar rays and vertical; *m* is mass of atmosphere, see Eq. (2.3). These dependences are shown graphically on fig. 6.

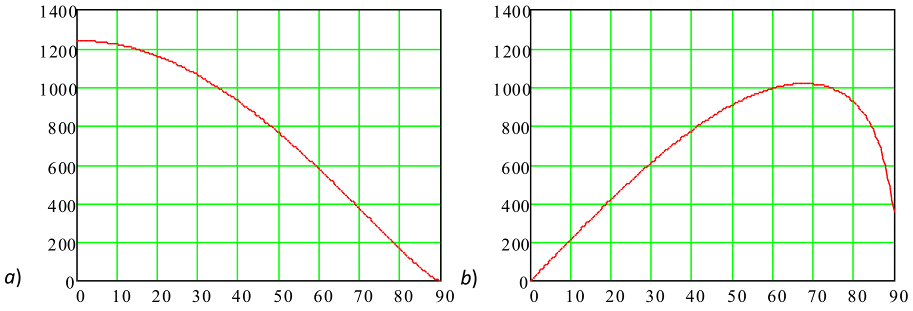

Fig. 6. Intensity of direct solar radiation watt/m², falling on unit area
a) of horizontal area J_h; *b*) of vertical area J_v depending on angle of incidence λ of solar rays

As it appears from Eq. (3.1) and from graph shown on fig. 6 *a*), maximal value of direct solar radiation falling on horizontal area is 1242 watt/m². It may be realized only in tropical countries under conditions of dry and clean atmosphere when the Sun is in zenith. As follows from fig. 6 *b*), maximal value of direct solar radiation falling on vertical surface, oriented towards solar rays, is 1018 watt/m² under conditions of dry and clean atmosphere. This may be realized at any point on the Earth. It is important that in that time the Sun could be observed at the angle $\lambda = 68°$ from vertical.

4. DETERMINATION OF AMOUNT OF SOLAR RADIATION, WHICH FALLS ON AREA OF STRUCTURE IN PARTICULAR DAY AND PARTICULAR TIME

To define amount of solar radiation falling on certain area of arbitrarily oriented structure, we need to know cosines of inclination angles of solar rays to vertical $\cos\lambda$ and to normal to considered area $\cos\theta$ (fig. 7).

Attitude of area is defined by two angles α and β. The first of them is azimuth. It is the angle between projection of normal to surface on horizontal plane and direction to South. The azimuth is counted from South direction to West direction and possesses maximal value $\alpha = 180^{\circ}$ in North direction.

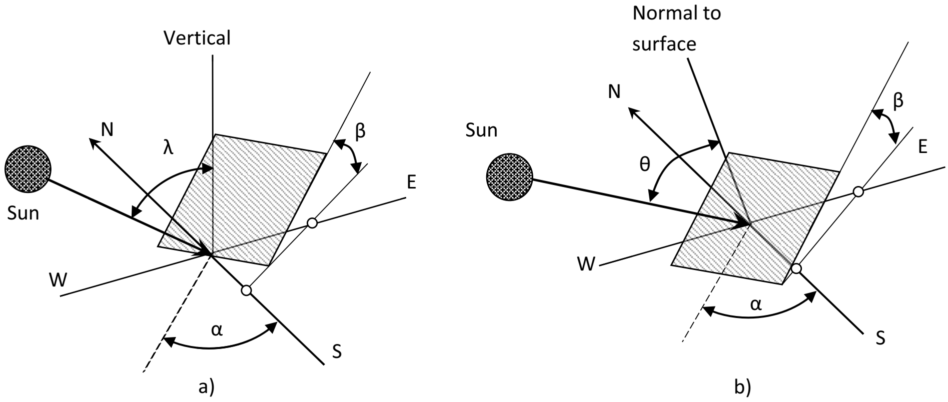

Fig. 7. Angles for determination of solar radiation intensity

a) zenith angle λ; b) angle of incidence of solar rays on arbitrarily oriented area θ.

In East part the azimuth possesses negative values, and in North direction it corresponds to angle $\alpha = -180^{o}$. The second angle β is the inclination angle of considered area to the horizon. This angle may change from 0 to 90º. Figure also shows λ – zenith angle and θ – inclination angle of solar rays to normal of considered area.

Formula of determination of solar radiation amount falling on sun-exposed area will be as following:

(4.1) $$J_o = \gamma_o \cdot 1370 \cdot \left(\frac{4,616 + 0,972 \cdot m}{5,166 + m} \right)^m \cdot \cos\theta \, ;$$

where γ_o – coefficient of light conditions, accepted for countries with moderate climate in range of values 0,8 – 0,9.

For determination of required cosines of angles θ and λ, we need to know position of the Sun in the sky during required time and position of the area on the Earth's surface. Position of the Sun in the sky during the particular moment in time is defined by three main angles: declination angle of the Sun δ, hour angle ω and latitude φ (fig. 8). Declination angle of the Sun δ depends on position of the Earth on the solar orbit. Since rotation axis of the Earth is inclined to the orbit, declination angle δ changes during the year from value 23,45° in summer to – 23,45° in winter. Declination angle equals zero twice a year in days of spring and autumnal equinox.

Declination of the Sun for particularly chosen day is defined by formula:

(4.2) $$\delta = 23,45 \cdot \sin\left(360 \cdot \frac{284+n}{365}\right),$$

where n – order number of day in year. The 1st January is n =1.

Latitude φ is the same as geographical latitude, that changes from φ = – 90° on South Pole to φ = 90° on North Pole, passing through zero on the Equator.

Hour angle ω converts local solar time into number of degrees passed by the Sun in the sky. According to the definition, hour angle equals zero at noon. The Earth rotates 15° during 1 hour. In the morning the hour angle is negative, in the evening it is positive.

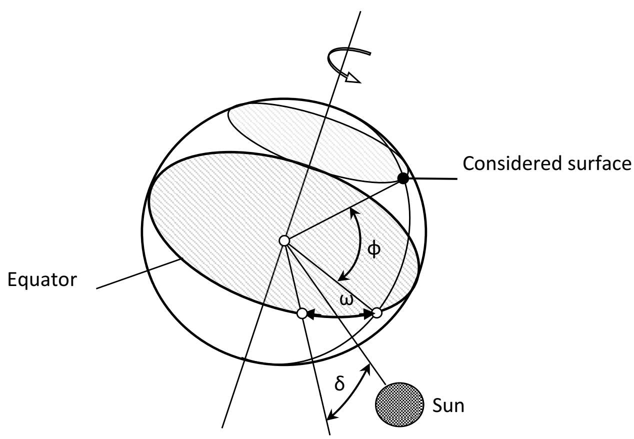

Fig. 8. The main angles, which define position of the Sun in the sky

The incidence angle of solar rays in relation to vertical λ (fig. 5) is often called the zenith angle. The zenith angle may be defined for any day of the year and time of day, using its connection with three main angles:

(4.3) $$\cos\lambda = \cos\omega \cdot \cos\varphi \cdot \cos\delta + \sin\varphi \cdot \sin\delta$$

The cosine of incidence angle of solar rays on arbitrary area is connected with above-mentioned angles by dependence from [3]:

(4.4) $$\cos\theta = \sin\delta \cdot \sin\varphi \cdot \cos\beta - \sin\delta \cdot \cos\varphi \cdot \sin\beta \cdot \cos\alpha + \cos\delta \cdot \cos\varphi \cdot \cos\beta \cdot \cos\omega + \\ + \cos\delta \cdot \sin\varphi \cdot \sin\beta \cdot \cos\alpha \cdot \cos\omega + \cos\delta \cdot \sin\beta \cdot \sin \cdot \alpha \sin\omega$$

For vertical area, angle $\beta = 90^o$, and cumbersome Eq. (4.4) takes the following form:

$$\cos\theta = -\sin\delta\cdot\cos\varphi\cdot\cos\alpha + \cos\delta\cdot\sin\varphi\cdot\cos\alpha\cdot\cos\omega + \cos\delta\cdot\sin\alpha\cdot\sin\omega$$

For horizontal area, angle $\beta = 0^o$ and formula for determination of cosine of incidence angle of solar rays is simplified and takes the following form:

$$\cos\theta = \cos\lambda = \sin\delta\cdot\sin\varphi + \cos\delta\cdot\cos\varphi\cdot\cos\omega .$$

In this formula we see that for considered case angle θ is equal to zenith angle λ. The zenith angle is calculated from vertical to the Sun direction and could be within the limits of 0^o (sunny noon on Equator in equinox days) to 90^o (sunrise or sunset).

As an example, we could consider solar radiation activity on 2nd April (n = 92), at 14-00 (solar time, $\omega = 30^o$), on the roof of a building in the city of Kiev ($\varphi = 50{,}5^o$), with inclination $\beta = 30^o$ and azimuth $\alpha = 15^o$ (South-West direction). For considered case

$$\delta = 23{,}45\cdot\sin\left(360\cdot\frac{284+92}{365}\right) = 4{,}4^\circ .$$

According to Eq, (4.3) cosine of zenith angle λ is:

$$\cos\lambda = \sin 4{,}4^\circ\cdot\sin 50{,}5^\circ + \cos 4{,}4^\circ\cdot\cos 50{,}5^\circ\cdot\cos 30^\circ = 0{,}608.$$

Cosine of incidence angle of solar rays on considered inclined roof in Kiev according to Eq. (4.4) is:

$$\begin{gathered}\cos\theta = \sin 4{,}4^\circ\cdot\sin 50{,}5^\circ\cdot\cos 30^\circ - \sin 4{,}4^\circ\cdot\cos 50{,}5^\circ\cdot\sin 30^\circ\cdot\cos 15^\circ + \\ + \cos 4{,}4^\circ\cdot\cos 50{,}5^\circ\cdot\cos 30^\circ\cdot\cos 30^\circ + \cos 4{,}4^\circ\cdot\sin 50{,}5^\circ\cdot\sin 30^\circ\cdot\cos 15^\circ\cdot\cos 30^\circ + \\ + \cos 4{,}4^\circ\cdot\sin 30^\circ\cdot\sin 15^\circ\cdot\sin 30^\circ = 0{,}890,\end{gathered}$$

which corresponds to angle $\theta = 27^o10'$.

Value of atmospheric mass passed by sun rays on 2nd April at 14-00 in Kiev is:

$$m = \frac{\sqrt{6378{,}1^2\cdot 0{,}608^2 + 2\cdot 6378{,}1\cdot 10 + 10^2} - 6378{,}1\cdot 0{,}608}{10} = 1{,}643 .$$

For this building, amount of direct solar radiation on a sunny cloudless day, which falls on the unit area of the roof, is defined by formula:

$$J_K = 0{,}85\cdot 1370\cdot\left(\frac{4{,}616 + 0{,}972\cdot 1{,}643}{5{,}166 + 1{,}643}\right)^{1{,}643}\cdot 0{,}890 = 891{,}6 \text{ watt/m}^2.$$

5. Sunrise and sunset on inclined areas

It is obvious that lighting of considered area is possible only in daytime, i.e. when $\cos\lambda \geq 0$. Since many surfaces are arbitrarily oriented, they may not receive direct solar radiation even in daytime. For these surfaces, there is a seperate time of "sunrise" and "sunset". The area is lighted by Sun only if $\cos\theta \geq 0$. Task of defininig of "sunrise" and "sunset" times for area comes to the definition of hour angles values ω from Eq. (4.4), at which cosθ changes its sign. Keeping in mind the previous example, consider a roof located in the city of Moscow (φ = 56º), time of "sunset" and "sunrise" ω may be defined by Eq. (5.1), if we accept $\cos\theta = 0$:

$$\begin{gathered} \sin 4,4° \cdot \sin 56° \cdot \cos 30° - \sin 4,4° \cdot \cos 56° \cdot \sin 30° \cdot \cos 15° + \\ + \cos 4,4° \cdot \cos 56° \cdot \cos 30° \cdot \cos\omega + \cos 4,4° \cdot \sin 56° \cdot \sin 30° \cdot \cos 15° \cdot \cos\omega + \\ + \cos 4,4° \cdot \sin 30° \cdot \sin 15° \cdot \sin\omega = 0 \\ or\ 0,8821 \cdot \cos\omega + 0,1290 \cdot \sin\omega + 0,0344 = 0. \end{gathered} \tag{5.1}$$

Since ω may be within the limits from–π to π, then after finding solution of Eq. (5.1) it may be defined that for a considered area "sunrise" will take place at ω= – 83º54′, and "sunset" at ω=100º32′. Also we should account for the beginning and the end of daylight hours, which for Moscow on the 2nd of April will take place at $\omega = \mp 96º34′$. In this case, roof will be lighted during 180º28′, or 12 hours 2 minutes, which is 93,4% of daylight hours. Dependence of cosine value of solar rays incidence angle θ on value of angle ω for considered example may be seen on fig. 9.

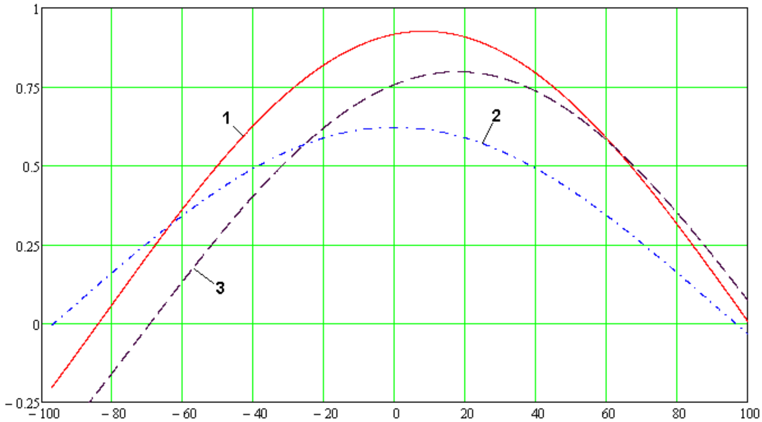

Fig. 9. Dependence of value cosθ (ordinate axis) on hour angle ω (abscissa axis, degrees.):
1 – for considered example, α = 15º; β =30º; 2 – for horizontal area, α = 15º; β =0º;
3 – for vertical area, α = 15º; β =90º.

6. DETERMINATION OF TEMPERATURE OF SHEET STRUCTURE DEPENDING ON HEAT GAIN

Energy coming to structure element will increase its temperature until heat losses are able to balance heat gain. Heat losses occur at the expense of emission, convective transport to the atmosphere and transmission to adjacent areas, caused by heat-conduction. The higher the temperature of the heated element in comparison to surrounding objects, the more significant the heat losses. We could try to calculate them according to physical laws but heat interchange processes are quite complicated and indeterminate. This fact forces engineers to use empirical dependences. One of such dependences is given in Ukrainian norms [5]:

(6.1) $$\Delta T = 0,05 \cdot \rho \cdot J_o \cdot k \cdot k_1$$

where ΔT – excess of element temperature over temperature of environment caused by action of direct solar rays;

ρ – coefficient of solar radiation absorption by material of structure's external surface;

J_o – amount of solar radiation falling on sun-lighted area;

k – coefficient dependent on surface orientation;

k_1 – coefficient dependent on heat output of external surface.

In Russian rules code SP 20.13330.2011 [6] in Eq. (6.1) surface orientation is calculated not by coefficient k, but by tabular values of solar radiation, which take into account building orientation.
Method for determination of direct solar radiation expressed by Eq. (4.1) allows to account arbitrary surface orientation to points of the compass, and in such way Eq. (6.1) takes the following form:

(6.2) $$\Delta T = 0,05 \cdot \rho \cdot J_o \cdot k_1$$

If we take into account that for considered example of roof in Kiev we use green roof steel, then temperature increment in cloudless sunny day will be:

$$\Delta T = 0,05 \cdot 0,6 \cdot 891,6 \cdot 0,7 = 18,72\ ^{\circ}\mathrm{C}.$$

Coefficients ρ and k_1 are accepted according to table 13.3 and 13.6 of [6] correspondingly.
In Eurocode 1991-1-5 [7], in contrast to Ukrainian and Russian building codes, temperature increments caused by climate impacts do not depend on the values of solar radiation and structure material. For example, in summer time for horizontal bright light surface temperature increment will be 18 ºC.

It is important to mention that in normative documents of Europe, Ukraine and Russia for open and non-heated buildings and facilities which are not protected from direct solar radiation, temperature difference by element section in cold season is accepted as zero. Such approach does not account heating of vertical structures by direct solar rays in cold season. For example, values of cosine of incidence angle of solar rays on vertical surface, located in Kiev and South-oriented, at the noon of 1st January is 0,96, and on 1st July – 0,46.

We may conclude from the above mentioned data that for vertical structures, sensitive to temperature deformations, we should take into account also temperature increment during cold season. Information, given in this paragraph, was received with regard to calculations of steel sheet structures on temperature deformations.

REFERENCES

1. I.V. Savel`yev, Course of general physics: v. 2. Electricity and magnetics. Waves. Optics. — 3rd edition, corrected, Science, Moscow 1988.
2. K.Y. Kondrat`ev, Actinometry, Leningrad 1965.
3. J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, John Wiley and Sons, Inc., New York, NY, 1982.
4. S.-H. KIM, K.-I. CHO, J.-H. WON, A study on thermal behaviour of curved steel box girder bridges considering solar radiation, Archives of Civil and Mechanical Engineering, 9, 3,
5. 59-76, 2009.
6. DBN V.1.2-2:2006. The system of ensuring reliability and safety of building objects. Loads and actions. Design norms. Kiev 2006.
7. SP 20.13330.2011 Loads and actions. Actualized revision of SNiP 2.01.07-85*. Moscow 2011.
8. Eurocode 1: Actions on structures – Part 1-5: General actions -Thermal actions. CEN. 2003.

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