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THE INFLUENCE OF DIRECT CAPTURE OF SOLAR RADIATION ON THE HEAT GAIN IN ROOMS

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Abstract. *When designing passive systems for the capture of the sun radiation it is necessary to define USE_{DS} - fraction of the monthly heating load supplied by solar energy. This paper gives a mathematical model, which helps to calculate USE of the direct passive system, in case of a vertical or an oblique , with or without the shade.*

Key words: *USE (fraction of the monthly heating load supplied by solar energy), Direct passive system, mathematical model*

1. INTRODUCTION

When building a block of flats with passive system of the overtake of solar energy it needs such a design to obtain maximum energy saving and the best use of solar radiation. Passive heating is provided through the application of the system for direct and indirect interjection of the solar energy into the heated room.

More intensive interjection of the solar radiation into the rooms with direct passive system is provided by greater window surface in the south facades of the buildings. The use of the direct passive system demand having a shade so as to diminish thermal overload in the summer due to the higher position of the Sun. Shades create shade above the windows. The surface of the shade is changeable throughout the day in relation to the position of the Sun and the given buildings. Through the shaded part of the window there is no penetration of the direct solar radiation thus diminishing the part of the solar energy on the heat wastage in comparison to the rooms with windows with no shades [1, 3, 6].

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2. DEFINITION OF THE USE_{DS} IN ROOMS WITH DIRECT CAPTURE OF SOLAR RADIATION

Monthly heating load for rooms with direct capture of the sun radiation is calculated according to the equation:

$$Q_{DS} = \left[\left(\sum_{p=1}^{f} Q_{t_p} + Q_V\right)(1 - USE_{DS})\right] \quad \left[\frac{\text{W}}{\text{mon.}}\right] \tag{1}$$

where: Q_{DS} represents the average heating load to be supplied for the rooms with the direct capture of the solar radiation [W/mon.]; Q_V – represents ventilation heat wastage of the rooms [W/mon.]; $\sum_{p=1}^{f} Q_{t_p}$ – represents transmission heat wastage of the rooms [W/mon.]; f – represents number of the outdoor facet elements of the rooms where heat is wasted (outer facades walls, windows, front-balcony door, floor, interfloor construction in ratio to the unheated space, roof, etc.); USE_{DS} – fraction of the heating load supplied by solar energy of the interior rooms through south oriented windows.

$$\sum_{p=1}^{f} Q_{t_p} = \sum_{p=1}^{f} (kA)_p (t_u - t_o) 24N \quad \left[\frac{\text{W}}{\text{mon.}}\right] \tag{2}$$

$$\sum_{p=1}^{f} (kA)_p = \sum_{m=1}^{n} (kA)_m + k_{j\_window} A_c + k_{j\_wall} (A_{j\_wall} - A_c) \quad \left[\frac{\text{W}}{\text{K}}\right] \tag{3}$$

where: A_C – is the surface of the windows on the south facade [m^2]; A_{j_wall} – the surface of the south facade wall (including the surface of the windows) [m^2]; k_{j_window} – total coefficient of the heat transmission of windows on the south facade [W/m^{2}K]; k_{j_wall} – total coefficient of the south facade wall [W/m^{2}K]; k – total coefficient of the heat transmission of the building with no south orientation (outer wall, floor, ceiling, window, etc.) [W/m^{2}K]; A – surface of the definite building construction with no south orientation (outer wall, floor, ceiling, window, etc.) [m^2]; f – number of building constructions of the rooms for which transmission heat wastage is calculated; t_o – average monthly temperature of the surroundings [K]; t_u – average monthly temperature in the inner rooms [K]; N – number of days of the observed period (a month or a heating season).

In case termal shades are drawn on the windows during the night the total coefficient of the heat transmission for the windows is calculated according to the equation:

$$\bar{k}_{j\_window} = (1 - f_1)\ k_{j\_window} + f_1 \left[\frac{k_{j\_window}}{1 + R_1 k_{j\_window}}\right] \quad \left[\frac{\text{W}}{\text{m}^2\,\text{K}}\right] \tag{4}$$

where: R_1 – is a heat resistance of the thermal shade [m^{2}K/W], $R_1 = d_1/\lambda$, d_1 – is a thickness of the thermal shade, λ – a coefficient of the heat conductivity of the thermal shade; k_{j_window} – a coefficient of the heat transmission of the window without termal shade (a daily period) [m^{2}K/W]; f_1 – a part of the 24 hours when the termal isolation is installed on the window, $f_1 = n/24$, n – time of the isolation effect of the termal shade within 24 hours [h].

$$USE_{DS} = P_1 X_1 + (1 - P_1)(3{,}082 - 3{,}142\,\bar{\phi})[1 - \exp(-0{,}329\,X_1)] \tag{5}$$

where:

$$\bar{\phi} = \frac{1}{\bar{I}_u N} \sum_{\text{day}} \sum_{\text{hour}} (I_u - I_{uc})^+ \tag{6}$$

where: mark $^+$ designates that only positive values are calculated; $\bar{\phi}$ – *un-utilizability* factor; I_{uc} - critical intensity of the solar radiation within the day time [W/m^2]; $\bar{I}_u$ - monthly average value of the total solar radiation on the vertical window surface [W/m^2].

Klein, Mitchell et al. determinated factor $\bar{\phi}$ according to the equation [4, 5]:

$$\bar{\phi} = \exp\left\{\left[A + B\left(\frac{R_n}{\bar{R}}\right)\right](\bar{X}_C + C\,\bar{X}_C)\right\} \tag{7}$$

$$\bar{X}_C = \frac{I_{uc}}{r_n R_n \bar{I}_{uh}} \tag{8}$$

In equation (7) A, B, C are coefficients calculated according to the following:

$$A = 7{,}10 - 20{,}00\,\bar{K}_t + 12{,}08\,\bar{K}_t \tag{9}$$

$$B = -8{,}02 + 18{,}16\,\bar{K}_t - 10{,}68\,\bar{K}_t \tag{10}$$

$$C = -1{,}02 + 4{,}10\,\bar{K}_t - 1{,}96\,\bar{K}_t \tag{11}$$

where: $\bar{K}_t$ – is a monthly average value of the clarity index

$$\bar{K}_t = \frac{\bar{I}_{uh}}{\bar{I}_o}. \tag{12}$$

The monthly average daily extraterrestrial radiation, from the rise to the sunset applied on the horizontal unit surface for the specific day in a year is calculated according to the equation:

$$\bar{I}_o = \frac{24}{\pi} I_{Sc}\left[1 + 0{,}033\cos\left(\frac{360n}{365}\right)\right] \times \left[\cos L \cos\delta \sin h + \left(\frac{2\pi h}{360}\right)\sin L \sin\delta\right] \tag{13}$$

Monthly average total daily sun radiation falling on the horizontal surface is equal to:

$$\bar{I}_{uh} = \bar{I}_B + \bar{I}_d \tag{14}$$

Value $\bar{R}$ in the equation (7) is calculated according to the equation:

$$\bar{R} = \frac{\bar{I}_u}{\bar{I}_{uh}} = \left(1 - \frac{\bar{I}_u}{\bar{I}_{uh}}\right)\bar{R}_B + \frac{\bar{I}_u}{\bar{I}_{uh}}\left(\frac{1 + \cos s}{2}\right) + \left(\frac{1 - \cos s}{2}\right) \tag{15}$$

$$\overline{R}_B = \left[\frac{1}{\cos L \cos \delta \cos h + \sin L \sin \delta} \right] \times$$
$$\left\{ \begin{array}{l} [\sin L \sin \delta \cos s - \cos L \sin \delta \sin s \cos \varphi] + \\ (\cos L \cos \delta \cosh \cos s + \sin L \cos \delta \cosh \sin s \cos \varphi + \cos \delta \sin h \sin s \sin \varphi) \end{array} \right\} \tag{16}$$

R_n represents the ratio between monthly average value of the solar radiation falling on the oblique surface at noon and the monthly average value of the sun radiation on the horizontal surface. Value R_n is calculated according to the following equation:

$$R_n = \left[1 - \frac{r_{d,n}}{r_n} \frac{\bar{I}_d}{\bar{I}_{uh}} \right] R_{B,n} + \left[\frac{r_{d,n}}{r_n} \frac{\bar{I}_d}{\bar{I}_{uh}} \right] \left[\frac{1 + \cos s}{2} \right] + \rho_o \left[\frac{1 - \cos s}{2} \right] \tag{17}$$

where:

$$r_{dn} = \frac{\pi}{24} \left[\frac{1 - \cos h_s}{\sin h_s - \left(\frac{\pi}{180} \right) h_s \cos h_s} \right] \tag{18}$$

$$r_n = r_{dn} \, [1{,}07 + 0{,}025 \sin (h_s - 60)] \tag{19}$$

$$R_{B_n} = \frac{\cos(L - s) \cos \delta + \sin(L - s) \sin \delta}{\cos L \cos \delta + \sin L \sin \delta} \tag{20}$$

In equation (17) value $\bar{I}_d / \bar{I}_{uh}$ is calculated by the equation:

– For the winter period when the hour angle of the sunset is $h_s = 81{,}4°$

$$\frac{\bar{I}_d}{\bar{I}_{uh}} = 1{,}391 - 3{,}560\, \overline{K}_t + 4{,}189 \overline{K}_t^2 - 2{,}137\, \overline{K}_t^3 \text{ and for } 0{,}3 \le \overline{K}_t \le 0{,}8 \tag{21}$$

– For the spring and summer when the hour angle of the sunset is $h_s > 81{,}4°$

$$\frac{\bar{I}_d}{\bar{I}_{uh}} = 1{,}311 - 3{,}022\, \overline{K}_t + 3{,}427 \overline{K}_t^2 - 1{,}821\, \overline{K}_t^3 \text{ and for } 0{,}3 \le \overline{K}_t \le 0{,}8 \tag{22}$$

Quantity of the heat penetrating the rooms at the critical intensity of the solar radiation meets all the required heating needs. There follows:

$$I_{uc} A_C (\tau\alpha) = \sum_{p=1}^{f} (kA)_p (t_u - t_o) + Q_V \tag{23}$$

$$I_{uc} = \frac{\sum_{p=1}^{f} (kA)_p (t_u - t_o) + Q_V}{A_C (\tau\alpha)} \quad \left[\frac{\text{W}}{\text{m}^2} \right] \tag{24}$$

Values P_1, X_1 and Y_1 are calculated according to the following:

$$P_1 = [1 - \exp(-0{,}294\, Y_1)]^{0{,}652} \tag{25}$$

$$Y_1 = \frac{C_b\ (\Delta T)}{\bar{\phi}\, A_C \bar{I}_u\, (\overline{\tau\alpha})} \tag{26}$$

$$C_b = \Sigma(M\, c_p) = M_{sz}\, c_{p_{sz}} + \frac{1}{2}\Sigma[M_{uz} c_{p_{uz}} + M_p c_{p_p} + M_t c_{p_t}] \quad \left[\frac{\mathrm{J}}{\mathrm{K}}\right] \tag{27}$$

$$M = d\, A\, \rho \ \ [\mathrm{kg}] \tag{28}$$

$$X_1 = \frac{\bar{I}_u\, A_C\, (\overline{\tau\alpha})\, N}{\left[\sum_{p=1}^{f}(kA)_p + \frac{1}{3} n V_R\right](t_u - t_o) 24 N} \tag{29}$$

where: X_1 – is the ratio of the fallen quantity of solar radiation in the rooms and the needed heating load within one month; Y_1 – is the ratio of the accumulated heat in the room and the lost heat within the day; A_c – is the window surface on the south facade (solar windows) [m^2]; $(\overline{\tau\alpha})$ – product of monthly average window transmission and room absorption; ΔT – allowed indoor temperature swing, i. e. difference between the highest and the lowest temperature in the room within a day ($\Delta T \approx 2°C \div 5°C$), $\Delta T = \frac{Q_{DI}}{\sum_{p=1}^{f}(kA)_p + \frac{1}{3} n V_R}$, Q_{DI} – is the quantity of heat gained daily through the passive system of solar radiation capture (window, Trombe wall, etc.) [W]; $\sum_{p=1}^{f}(kA)_p$ – quantity of the lost heat through transmission daily [W/K]; C_b – effective building thermal capacity [J/K]; M – inbuilt mass of the wall [kg]; c_p – specific heat of the building's material [J/kg K]; ρ – density of the building's material [kg/m^3]; A – surface of the building [m^2]; (Index: *sz* – outer wall, *uz* – inner wall, *p* – floor, *T* – ceiling).

In case of the last floor or the ground floor, mass of the roof – ceiling, i. e. floor construction is included with its whole mass. If there is a carpet or any other pled representing an isolation layer it diminishes the accumulation effect and the calculation of the room mass is corrected. For the pled with the heat resistance $R > 0{,}15 - 0{,}3$ [m^{2}K/W], mass of the floor is calculated with 50 %, and for $R > 0{,}3$ [m^{2}K/W] mass of the floor is disregarded [2, 3].

3. Definition of USD$_{DS}$ in Rooms with Shaded Windows

In rooms with shaded windows the size of the shade has a direct effect on the heating overload within the rooms. Horizontal outcome above the window (shades) create shade. Its surface changes throughout the day and depends on the position of the sun in relation to the building. Through the shaded part there is no direct solar radiation and hence the heating overload of the building is less in comparison to the window without shade.

If shade is above window part of solar radiation USE_{DS} in heating load is reduced. The equation (5) is changed to:

$$USE_{DS} = P_1 X_2 + (1-P_1)\,(3{,}082 - 3{,}142\,\overline{\phi})\,[1 - \exp(-0{,}329\, X_2)] \tag{30}$$

where:

$$X_2 = \frac{[(A_C - \overline{A}_S)\,\bar{I}_u + \overline{A}_S\,\bar{I}_d\,]\,(\overline{\tau\alpha})\,N}{\left[\sum_{p=1}^{f}(kA)_p + \frac{1}{3}nV_R\right](t_u - t_o)\,24N} \tag{31}$$

where: A_c – is the total surface of the window [m^2]; $\overline{A}_S$ – average window surface under shade within a month [m^2]; $\bar{I}_u$ – average monthly value of the total solar radiation passing through unshaded part of the window [W/m^2]; $\bar{I}_d$ – average monthly value of the diffuse solar radiation passing through the shaded part of the window [W/m^2].

4. DEFINITION OF VALUE $\overline{A}_S$ OF THE VERTICAL AND OBLIQUE WINDOWS WITH OVERHANG (SHED)

Overhang above vertical windows

Shade with right dimensions enables the afternoon sun up to 1st of February to shine perfectly through the window and to be in the shade from May, 1 on which is shown in figure 1. The width of the shade (*d*) of the vertical windows depends on: gap (*G*) above the top of a vertical window of height (*H*), high of the parapet (*P*), angle of the sun on February 1. (α_1) and the angle of the sun on May 1.(α_2). Height of the gap above the top of a vertical window (*G*), of the window with shed is calculated according to the equation:

$$G = d\ \mathrm{tg}\alpha_1\ [\mathrm{m}] \tag{32}$$

Hight of the parapet:

$$P = D - d\ \mathrm{tg}\alpha_2\ [\mathrm{m}] \tag{33}$$

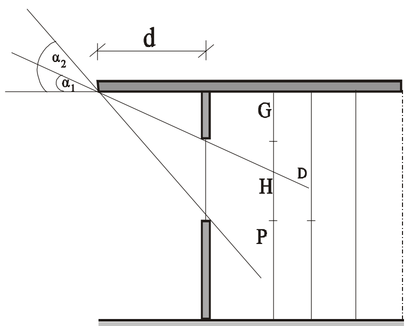

Fig. 1. Vertical window with overhang

If values *d*, *G*, *H* and *B* are known the surface of the shaded window is defined in the following way:

$$F = \left[\frac{d}{H} \times \frac{\sin \alpha}{\cos i}\right] - \frac{G}{H} \qquad [0 \le F \le 1] \tag{34}$$

where: α – solar altitude angle, i – solar incident angle.

Values i, α and δ are calculated in the following way:

$$\sin \alpha = \cos L \cos \delta \cos h + \sin L \sin \delta \tag{35}$$

$$\cos i = \cos \psi \sin L \cos \delta \cosh + \sin \psi \cos \delta \sinh - \cos \psi \cos L \sin \delta \tag{36}$$

$$\delta = 23{,}45 \sin \left[\frac{360}{365} \times (284 + n)\right] \tag{37}$$

where: L – latitude; δ – solar declination; h – hour angle; Ψ – surface azimuth angle; n – day of the year counted from January 1 [3].

Overhang above oblique windows

Solar altitude angle (α) in oblique window (fig. 2.) for surface tilt angle s, is calculated in the following way:

$$\sin \alpha = A_1 \cos h + B_1 \sin h + C_1 \tag{38}$$

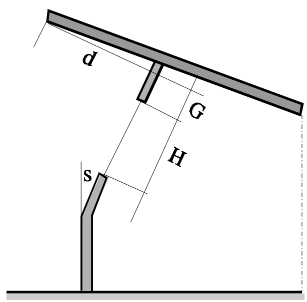

Fig. 2. Tilted window with overhang

Constant values A_1, B_1 and C_1 in definition (36) are calculated with the following formulae:

$$A_1 = \sin s \cos L \cos \delta - \cos s \cos \psi \sin L \cos \delta \tag{39}$$

$$B_1 = -\cos s \sin \psi \cos \delta \tag{40}$$

$$C_1 = \sin s \sin L \sin \delta + \cos s \cos \psi \cos L \sin \delta \tag{41}$$

In this case solar incident angle i is calculated:

$$\cos i = D \cos h + E \sin h + K \tag{42}$$

Constant values D, E and K are calculated:

$$D = \cos s \cos L \cos \delta + \sin s \cos \psi \sin L \cos \delta \tag{43}$$

$$E = \sin s \sin \psi \cos \delta \tag{44}$$

$$K = \cos d \ s \sin L \sin \delta - \sin s \cos \psi \cos L \sin \delta \tag{45}$$

Where: s – surface tilt angle of the window.

By the definition (34) the surface of the shaded window can be (A_S) caused by the changeable position of the sun during the day. In that case the surface of the shaded window for the given orientation is:

$$A_S = A_C \left[\frac{F}{100}\right] \quad [\mathrm{m}^2] \tag{46}$$

The valid size of the shade on the window used in calculation is the one during maximum intensity of total solar radiation within the day for the given orientation of the window. During the heating period (winter), on the south oriented windows maximum intensity of solar radiation is reached at noon (12^h) [3].

Average surface of the window under shade within a month ($\overline{A}_S$) can be obtained with the equation:

$$\overline{A}_S = \frac{1}{N} \sum_{i=1}^{N} [A_S]_i = \frac{1}{N} \sum_{i=1}^{N} \left[\frac{A_c \ F_i}{100}\right] \quad [\mathrm{m}^2] \tag{47}$$

Where: N – is the number of days in a month; F_i – surface of the window under shade during the day at 12^{oo}.

5. CONCLUSION

On the basis of the above mentioned it can be concluded:

1. By the given mathematical model the following can be calculated:
   - USE_{DS} of the direct passive system in the heating load,
   - required absorbing surface of the direct system,
   - optimal dimensions of the shade system for winter and summer.
2. Applied mathematical method can be used:
   - when designing the building with direct passive system of solar radiation transmission, and
   - when reconstructing the existing buildings of the traditional architectural types.

REFERENCES

1. T. Pavlović, B. Čabrić: *Fizika i tehnika solarne energetike*, IRO Građevinska knjiga, Beograd, 1999.
2. J.Radosavljević, A. Đorđević: Defining of the Intensity of Solar Radiation on Horizontal and Oblique Surfaces on Earth, Facta Universitatis, Vol. 2, N° 1, pp.77 – 86, 2001.
3. J. Radosavljević, T. Pavlović: *Uticaj konstrukcije nadstrešnice na termičke karakteristike stambenog objekta,* XXX Kongres o grejanju, hlađenju i klimatizaciji, Zbornik radova, Beograd, 1999.
4. S. A. Klein: *Calculation of Flat-Plate Collector Utilizability*, Solar Energy, Vol. 21, pp. 393, 1978.
5. J. C. Mitchell et al.: Calculation of Monthly Average Collector Operating Time and Parasitic Energy Requirements, Solar Energy, Vol. 26, pp. 555, 1981.
6. J. Radosavljević: *Matematički model energetski samostalnog individualnog stambenog solarnog objekta,* Doktorska disertacija, Univerzitet u Novom Sadu, Tehnički fakultet " M. Pupin ", Zrenjanin, 2001.

UTICAJ DIREKTNOG ZAHVATA SUNČEVOG ZRAČENJA NA TOPLOTNE DOBITKE PROSTORIJE

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Prilikom projektovanja direktnih pasivnih sistema za zahvatanje sunčevog zračenja potrebno je odrediti USE_{DS} *– udeo sunčevog zračennja u zagrevanju prostorije u troku meseca. U radu je dat matematički model pomoću koga se može izračunati* USE_{DS} *direktnog pasivnog sistema, kada je prozor (vertikalan ili kos) sa ili bez nadstrešnice.*