Energy method for calculating insolation of residential apartments

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Abstract. The analysis of the current codes for the insolation in apartments has been done by the authors. It is shown that the insolation assessment during exposure is not sufficiently correct. The current codes do not take into account the amount of solar energy, the transmittance of UV radiation with double-glazed windows, the dimensions of light openings and the room parameters. The current codes for insolation do not contain requirements for the essential level of sanitation. The proposed energy method of calculating insolation corrects the shortcomings of the existing Sanitary Codes method considering the climatic and structural factors. It introduces an unambiguous quantitative measure of insolation - the dose of UV radiation as well, which provides a given level of bactericidal efficiency of room sanitation. Additionally a proposal to specify the bactericidal efficacy level of irradiation based on the most common microorganisms in living rooms (Staphylococcus aureus and Escherichia coli) has been made. An example of the UV radiation dose calculation in rooms is given, which provides a necessary level of bactericidal efficiency.

Keywords: UV radiation, intensity, dose, insolation, light transmission of double-glazed windows, solar map, light transmission cartogram, bactericidal radiation efficiency.

1 Introduction

Insolation has a psychophysiological effect on humans and provides the necessary sanitary and hygienic conditions in the rooms, since it causes the death of microorganisms and pathogenic bacteria [1-3]. The main attention is given to the codes and calculation of insolation as an important factor in the design of buildings [4-6]. However no studies have been carried out further than geometric constructions of the sun rays. In the first codes for insolation a continuous 3 hours exposure time for rooms was established [7]. After their introduction in 1963, hygienists noted of microflora decrease in residential rooms, and, consequently, the rehabilitation of the population in new buildings which had been built in compliance with those codes. Later it turned out that the standard duration of exposure became an obstacle to building compaction and, according to investors and developers, the established duration of insolation limited the effective use of land, especially in the centers of large cities. Over the past decades, arguments about the efficient urban land usage have overpowered the requirements for ensuring sanitary and hygienic well-being in residential rooms.

Accordingly, in subsequent versions of the codes about insolation, the duration of exposure is steadily decreasing. Moreover, the regulation on the admissibility of intermittent irradiation has been introduced, although microbiologists argue that interruption of irradiation leads to the growth of bacteria and microorganisms during periods of shading. As a result, by 2001, the duration decreased from 3 to 2 hours of intermittent insolation, and it was allowed to reduce exposure to 1.5 hours with intermittent insolation for centers of large cities [8, 9]. Opinions generally appear about the cancelation of compulsory insolation of residential rooms.
One of the reasons of such attitude to insolation is the incorrectness of the current codes. The fact is that a quantitative measure of insolation - the duration of exposure to direct sunlight in hours is not an unambiguous parameter, because it is not tied to the level of sanitary-hygienic conditions or bactericidal effectiveness of radiation in the rooms. The codes also don’t define the level of bactericidal radiation efficiency itself, by which microbiology refers to the percentage of microorganisms death as a result of insolation. It is known that irradiation of equal duration at different hours of the day in rooms will bring different amounts of solar energy to these rooms. Therefore, the level of bactericidal effectiveness will also be different. Figure 1 shows, that the amount of solar radiation (dose for 2 hours) arriving at the facades of buildings at different hours of the day varies by 1.5-4.0 times [10]. However, the current codes do not operate with the concept of “radiation dose”, which would make the insolation rate an unambiguous quantitative measure.

![Figure 1. The intensity of the total solar radiation, W · h/m² (560 N).](image)

Before introducing the concept of radiation dose in insolation calculations, it is necessary to establish a number of standard indicators:

1. The wavelength range of the solar spectrum, which causes the death of microorganisms, because not all ranges of the solar spectrum carry energy to reorganize microflora.

2. Types of microorganisms that are most common in residential rooms, because it is known that various types of microorganisms die after receiving different energy (dose).

3. The required level of bactericidal effectiveness for residential rooms, because different rooms require a different level of bactericidal effectiveness. (By the level of bactericidal efficiency we mean the reduction of microbial contamination in the air environment of rooms and its surfaces as a result of exposure to solar radiation. It is measured in percent, as the ratio of the number of dead microorganisms to their initial number).

### 2 Justification of the wavelength range of solar radiation

In accordance with the recommendations of the International Commission on Illumination, the range of wavelengths of the solar spectrum from 100 to 400 nm refers to ultraviolet radiation (UV). Within this range, UV radiation is subdivided into the near region A with wavelengths of 320-400 nm (an erythemal, tanning and general stimulating effect), the middle region B with wavelengths of 280-315 nm (a small bactericidal and partially erythemal effect) and the far region C with wavelengths of 100-280 nm (a maximum bactericidal effect).
Thus, to ensure the sanitary and hygienic conditions of the rooms, which are insolated with solar radiation, ranges B and C should be considered as carrying the most destructive energy for pathogenic bacteria and microorganisms.

2.1 Identification of the types of the most common microorganisms in residential rooms

Unfortunately, the well-known studies on the bactericidal effect of solar radiation on microflora [11, 12] are not tied to the dose of UV radiation or the level of bactericidal radiation efficiency.

Microbiological researches have also shown that living quarters are populated by a large number of microorganisms and pathogenic bacteria, the death of which requires different doses of radiation [13]. These doses will also be different for one microorganism to ensure a different level of bactericidal efficacy, as well as if the microorganisms are contained in the air of the room or located on its surfaces. As an example, we give the dose of UV radiation for some microorganisms in Table 1 [14].

| Type of microorganism | On the surface, J/m² | By volume, J/m³ |
|-----------------------|----------------------|-----------------|
|                       | 90 %                 | 99.9 %          |
| 1                     | 2                    | 4               |
| Bacillus Megatherium  | 273                  | 520             |
| (spores)              | 357                  | 718             |
| Escherichia Coli      |                      | 1046            |
|                       | 30                   | 79              |
|                       | 45                   | 132             |
| Legionella bozemanii  | 18                   | 66              |
|                       | 25                   | 79              |
|                       |                      | 385             |
| Micrococcus Candidas  | 60                   | 47              |
|                       | 86                   | 73              |
| Salmonella typhosa    | 22                   | 123             |
|                       | 37                   | 158             |
|                       |                      | 717             |
| Staphylococcus Aureus | 49                   | 60              |
|                       | 57                   | 58              |
|                       |                      | 385             |

Escherichia coli and Staphylococcus aureus are most common in residential areas [13]. The energy required for the death of these microorganisms, is proposed to be taken as a basis in determining of the standard radiation dose. As it follows from Table 1, these doses are different both for indoor air and its surfaces. Their dimensions are also different - J/m³ and J/m².

2.2 Establishment of the required level of bactericidal efficacy

We have not found any scientific work on establishing the standard level of bactericidal effectiveness in residential rooms in the well-known literature. Therefore, the basis for standardizing the level is taken to substantiate the level of bactericidal effectiveness of medical institutions, Table 2 [14].

Having no other justifications, as a first approximation, it is proposed to classify residential rooms into VI categories, i.e. accept the lower limit of bactericidal effectiveness for pathogenic microflora – 70 %.

As it seen from Table 2, this level is even lower than the level for public toilets and stairwells of medical institutions.

| Cat. | Types of rooms | Bact. efficiency, %, not less |
|------|----------------|--------------------------------|
| I    | Surgical, preoperative, maternity, sterile areas, children's wards of maternity hospitals | 99,9 |
|      | Chambers and departments of Chambers and departments of | |
|      | immunocompromised patients, chambers of resuscitation departments | 99 |
III Chambers, cabinets and other premises of medical facilities (not included in categories I and II)

IV Children's playrooms, school classes, domestic premises of industrial and public buildings with a large crowd of people with a long stay

V Smoking rooms. Public toilets and stairwells of the facilities

VI The lower limit of bactericidal efficacy for pathogenic microflora

In [15], it was shown that to ensure a 70 % level of bactericidal efficiency, a required dose of UV radiation was 39 J/m³ for indoor air and 15 J/m² for indoor surfaces. Bactericidal radiation efficiency is ensured while achieving the required dose, both in the room air and on its surfaces.

2.3 Considering the transparency of window structures

The current national codes for insolation calculation do not take into account the light transmission of glasses in the UV range of the solar spectrum. It is assumed that all energy, which comes to the facade of the building, is in the room. It is not so, since any transparent system, in accordance with physical laws, reflects, absorbs and transmits the sun's rays. This problem was especially acute in connection with the development of energy-saving windows [16, 17]. In order to limit heat loss, window panes have low-emission metal or oxide-metal coatings, which highly reduce the penetration of UV radiation through them.

The optical properties of the main manufacturers of glass and double-glazed windows of the companies Pilkington, AGC, Guardian, Saint-Gobain, etc. are in many respects similar. As an example, we cite the light transmission of AGC glasses and double-glazed windows in the UV range of the solar spectrum with low-emission Planibel TOP low-E glasses with a coating in position 3 [18], Table 3.

| Glass type          | Thickness glass mm | UV transmission, % | Formula glass-package | UV transmission, % |
|---------------------|--------------------|--------------------|-----------------------|--------------------|
| Stopsol Classic Clear| 4                  | 19                 | –                     | –                  |
| Stopsol Classic Clear| 6                  | 17                 | 6-15-6                | 6                  |
| Stopsol Classic Grey | 4                  | 8                  | –                     | –                  |
| Stopsol Classic Grey | 6                  | 5                  | 6-15-6                | 2                  |
| Stopsol Classic Green| 4                  | 8                  | –                     | –                  |
| Stopsol Classic Green| 6                  | 5                  | 6-15-6                | 2                  |
| Stopsol Classic Dark blue | 4     | 8                  | –                     | –                  |
| Stopsol Classic Dark blue | 6     | 5                  | 6-15-6                | 3                  |
| Stopsol Supersilver clear| 4     | 38                 | –                     | –                  |
| Stopsol Supersilver clear| 6     | 35                 | 6-15-6                | 14                 |

AGC double-glazed windows with ordinary clear glasses Stopsol Supersilver can have a light transmission of UV radiation of 22-28 %, which is double light transmission of double-glazed windows with low-emission glasses [18].

Own experimental studies performed using the Stella Net Inc. spectrophotometer EPP 2000 showed similar results both with normal incidence of the beam on glass [19] and with different angles of incidence of the rays [20].
From the point of view of the energy of UV radiation entering the room, it becomes obvious that there is the need to take into account the area of the openings (the larger area means more energy penetration into the room) and the size of the room (the larger the size of the room, the smaller the specific energy arriving per unit volume of air premises and unit of its surfaces). These parameters do not take into account the current codes for calculating the insolation in rooms.

Based on the foregoing, the energy method for calculating insolation in residential rooms takes into account the maximum number of factors affecting the bactericidal effectiveness of insolation.

The initial data for the calculation:
1. A solar map for a standardized calendar period of insolation (from 22.04 to 22.08) for given latitude of the area.
2. Parameters of the insulated room (depth L, width B and height H, m) and light opening (width b and height h).
3. Orientation of the light transmission along the horizon (azimuth of the normal to the plane of the window $A_n$).
4. The specifications of the translucent part of the windows, the types of glass and glass.
5. Database of light transmission coefficients of modern glasses and double-glazed windows in the UV range of solar radiation.
6. The UV solar radiation intensity (range <315 nm) of the direct $S_{\text{op}}$ on the surface normal to the rays and the scattered $D_{\text{hor}}$ on the horizontal surface, at every hour of the day of the calendar period of insolation.

Calculation sequence:
1. Determination of the duration of the room insolation using cartograms of light and solar map.
2. Determination of the total intensity ($S_{\text{total}}$) of UV radiation coming to glazing at each hour of exposure formula (1):
   $$ S_{\text{total}} = S_{\text{direct}} + D_{\text{v}} = S_{\perp} \cdot \cos \theta + 0.5 D_{\text{hor}}, \text{mW/m}^2 $$ (1)
3. Determination of the total intensity of UV radiation passing through the window into the room ($S_{\text{room}}$), at each hour of exposure, taking into account the transmittance of UV radiation by the translucent structure ($k_{ts}$) formula (2):
   $$ S_{\text{room}} = S_{\text{total}} \cdot k_{ts}, \text{mW/m}^2 $$ (2)
4. The total amount of UV energy passing through the window area ($f_w = b \cdot h, \text{m}^2$) at each hour of exposure formula (3):
   $$ q = S_{\text{room}} \cdot f_w $$ (3)
5. The amount of UV radiation that has passed into the room for the entire period of exposure $\tau$ formula (4):
   $$ Q = \sum_i q_i $$ (4)

where $\tau$ is the number of hours of exposure to the room.
6. Dose of UV radiation in indoor air $\Delta_{\text{air}}$ formula (5):
   $$ \Delta_{\text{air}} = 3.6 \frac{Q}{V}, \text{J/m}^3 $$ (5)

where: $V$ – room volume ($L \cdot B \cdot H$), m$^3$.
7. The dose of UV radiation on the surfaces of the room $\Delta_v$ formula (6):
   $$ \Delta_v = 3.6 \frac{Q}{F}, \text{J/m}^2 $$ (6)

where $F$ the area of all surfaces of the room minus the area of the window $[(2LB + 2LH + 2BH) - f_w], \text{m}^2$;

3.6 – conversion factor of dimension mW · hour to dimension J.

Example
The task is to determine the bactericidal efficacy of insolation of a southeast orientated room in Kazan (56°N). Normal to the glazing surface $A_n = 45^\circ$ from the direction to the south. The room parameters - width $B = 3.0$ m, depth $L = 4.2$ m, height $H = 2.8$ m. Light transmission parameters - width $b = 1.9$ m, height $h = 1.65$ m. The transparent part of the window is made double-glazed with 6-15-6 Stopsol
Classic Clear, $k_o = 0.06$ (see Table 3). The coordinates of the sun are determined by the solar map (Figure 2) and are presented in calculation Table 5 (lines 1 and 2). By building a cartogram of the light beam, vertical ($45^\circ$) and horizontal ($120^\circ$) insolation angles are determined, which are plotted on the solar map (Figure 2).

![Figure 2. Combination of a solar map of 56 ° N with the trajectory of the sun in April-August with a cartogram of a given light transmission.](image)

A database of direct and scattered UV solar radiation intensities with wavelengths <315 nm is presented in Table 7 of the Construction Climatology Manual [21]. Its sample is based on direct radiation intensity on a surface normal to rays ($S_\bot$) and scattered radiation intensity on a horizontal surface ($D_{\text{hor}}$) are presented in Table 4 for April and August.

| Hours of the day | Radiation intensity, mW / m² |
|-----------------|-----------------------------|
|                 | Direct to the normal to the surface of the rays, $S_\bot$ | Scattered on a horizontal surface, $D_{\text{hor}}$ |
|                 | April | August | April | August |
| 12              | 310   | 380    | 550   | 900    |
| 11/13           | 290   | 360    | 530   | 870    |
| 10/14           | 220   | 280    | 430   | 760    |
| 9/15            | 140   | 170    | 320   | 580    |
| 8/16            | 40    | 70     | 190   | 380    |
| 7/17            | –     | 10     | 70    | 180    |
| 6/18            | –     | –      | –     | 50     |

Table 4 shows that the intensities of UV solar radiation in April and August differ in 1.5 – 2.0 times, although the coordinates of the sun for these months are the same. It follows that the bactericidal effectiveness of insolation in August is 1.5-2.0 times more effective than in April. Apparently, the calculations of energy efficiency should be carried out according to the minimum radiation intensity,
that is, in the month of April, in order to ensure a guaranteed level of bactericidal efficiency of room exposure.

From Table 4 it is also seen that the intensity of the scattered UV radiation is 20-50 % higher than the direct one. This fact confirms the need to take scattered UV radiation into account [22].

The movement of the sun in the celestial sphere is accompanied by the change in the angle between the direction of the sun ray and the glazing plane, which changes the amount of energy that comes to the glazing. The intensity of direct solar radiation coming to the glazing surface at different angles is determined by the law of cosine formula (7):

\[ S_\alpha = S_\perp \cdot \cos \theta \]  

(7)

where \( \theta \) is an angle between the direction of the sun's beam and the normal to the glazing surface, degrees.

Value \( \cos \theta \) is determined by the following formulas (8), (9) [23]:

- for vertical surfaces:

\[ \cos \theta = \cosh \cdot \cos (A_\alpha - A_\circ) \]  

(8)

- for inclined surfaces:

\[ \cos \theta = \sin h_\circ \cdot \cos \beta + \cos h_\circ \cdot \sin \beta \cdot \cos (A_\circ - A_\alpha) \]  

(9)

where \( (A_\alpha - A_\circ) \) – the angle between the azimuth of the sun at a given hour of the day \( (A_\circ) \) and the azimuth of the normal to the window plane \( (A_\alpha) \), degrees. The indicated angle is determined by simple subtracting the smaller azimuth from the larger, depending on the ratios \( A_\circ \) and \( A_\alpha \), i.e. \( (A_\circ - A_\alpha) \) or \( (A_\alpha - A_\circ) \).

In Figure 3 shows a diagram for determining the angle \( \theta \) for vertical surfaces, for which the difference \( (A_\circ - A_\alpha) \) is valid.

![Diagram](image)

**Figure 3.** The scheme for determining the angle \( \theta \): \( N \) is the normal to the glazing plane; \( \beta \) is the angle of inclination of the glazing to the horizon; \( h_\circ \) - the height of the sun; \( A_\circ \) - azimuth of the sun at a given hour of the day; \( A_\alpha \) is the azimuth of the normal to the glazing plane.

According to the recommendation [21], the scattered radiation on a vertical surface \( (D_v) \) is half of the radiation coming to a horizontal surface \( (D_{hor}) \).

\[ D_v = 0,5 \ D_{hor} \]  

(10)

When the sun moves in the celestial sphere during the day, the energy of the sun rays increases and decreases continuously, while in the reference tables, the values of the UV solar radiation intensity are given at fixed hours of the day. These values are the average of the radiation intensity 30 minutes before and 30 minutes after a fixed hour.
Turning to the considered example of the energy calculation of room insolation, it should be noted that the total energy at 6, 7, 8, 9, 10 hours and half the energy at 11 hours come to the light ray, (see Figure 2). With such influx of UV solar energy into the living room, an energy calculation of its insolation was performed, which is presented in Table 5.

| Table 5. Energy calculation of residential insolation. |
|-------------------------------------------------------|
| Design parameters | 6     | 7     | 8     | 9     | 10    | 11*   |
| A_oh, degree (from south) | 97    | 84    | 71    | 56    | 40    | 21    |
| h_oh, degree | 10    | 18    | 26    | 34    | 40    | 44    |
| S_oh, mW/m^2 | –     | –     | 40    | 140   | 220   | 145   |
| D_oh, mW/m^2 | –     | 70    | 190   | 320   | 430   | 265   |
| difference (A_oh – A_v) or (A_oh – A_v) | 52    | 39    | 26    | 11    | 5     | 24    |
| Cosθ | 0.6063 | 0.7391 | 0.8078 | 0.8137 | 0.7631 | 0.6571 |
| S_direc= S_oh · Cosθ, mW/m^2 | 0     | 0     | 35.5  | 113.9 | 167.9 | 95.3  |
| D_v = 0.5 D_hover, mW/m^2 | 0     | 35    | 95    | 160   | 215   | 132.5 |
| S_total = S_direc + D_v, mW/m^2 | 0     | 35    | 130   | 274   | 283   | 228   |
| S_around = S_total · k_oh, mW/m^2 | 0     | 2.1   | 7.8   | 16.4  | 17.0  | 13.7  |
| q = S_around · f_oh, mW | 0     | 6.6   | 24.4  | 51.3  | 53.2  | 42.8  |

\[ Q = \sum_{6}^{10} q_i = 0 + 6.6 + 24.4 + 51.3 + 53.2 + 42.8 = 178.3 \text{ mW} \]

\[ \Delta \text{air} = 3.6Q/V = 3.6 + 178.3/35.3 = 18.2 \text{ J/m}^3 \]

\[ \Delta \sigma = \frac{3.6Q}{\sum_{10}^{6}} = 3.6 + 178.3 \text{ J/m}^3 \]

* half of the tabulated value of UV solar intensity is taken into account radiation in accordance with Figure 2.

From Figure 2 it follows that the duration of insolation of a given room is 5.5 hours, which exceeds 2 hours of exposure according to the requirements of SanPiN [8]. However, the sanitary and hygienic well-being of the room will not be achieved, because the energy dose of UV radiation in the air of the room and on its surfaces does not provide bactericidal radiation efficiency: \( \Delta \text{air} = 18.2 < 39 \text{ J/m}^3 \) и \( \Delta \sigma = 10.3 < 15 \text{ J/m}^2 \).

3 Results and discussion

One of the reasons of this situation is too low transmittance of UV radiation of the selected double-glazed window \( k_oh = 0.06 \) or 6 %. If we replace this double-glazed window with Supersilver clear (line 10 of Table 3) with \( k_oh = 0.14 \), then the indicated living space will receive the necessary dose of UV radiation: \( \Delta \text{air} = 46.1 > 39 \text{ J/m}^3 \) and \( \Delta \sigma = 26.1 > 15 \text{ J/m}^2 \) and bactericidal radiation efficacy will be ensured.

If the trend in the design of residential buildings is shifted from saving energy for heating to protecting human health, it is logical to obtain the required bactericidal radiation efficiency after 2–3 hours of insolation (depending on the orientation and design of the light opening) using double-glazed windows with ordinary Supersilver clear glasses light transmission of UV radiation 22-28 %. So, for the considered example, if we use double-glazed windows 6-15-6 Supersilver clear with \( k_oh = 0.28 \), bactericidal effectiveness of the insolation of the room will be ensured for 2 hours of exposure from 730 to 930 in both the south-west and east orientation light transmission: \( \Delta \text{air} = 40.8 > 39 \text{ J/m}^3 \) and \( \Delta \sigma = 21.6 > 15 \text{ J/m}^2 \).
Thus, the developed energy method for calculating insolation allows providing a given level of bactericidal efficiency of insolation in the designed residential rooms using different double-glazed windows, the size of the rooms and light openings and their orientation.

4 Conclusions
1. Insolation is a prerequisite for ensuring the sanitary and hygienic conditions of residential rooms due to the destruction of pathogenic bacteria and microorganisms when they are irradiated with UV radiation.
2. The current national codes for insolation calculation are based on geometric constructions of the sun ray and do not take into account a number of important climatic and structural factors in the design of buildings, which makes incorrect the assessment of insolation only by the duration of irradiation.
3. In the current codes for the calculation of insolation there are no rules for the required level of bactericidal radiation efficiency.
4. Energy-saving double-glazed windows usage reduces the dose of UV radiation in the rooms and, as a result, it reduces the level of sanitary and hygienic conditions.
5. The proposed energy method application for calculating the dose of UV radiation entering the room with the establishment of the required level of bactericidal radiation efficiency will allow obtaining an unambiguous quantitative assessment of the effectiveness of insolation.

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