Influence of Solar Radiation Heat Input into Room on Level of Economically-efficient Thermal Protection of Building

Elena Malyavina 1, Anastasia Frolova 1

1 Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

FrolovaAA@mgsu.ru

Abstract. Techniques for choosing an energy and economically feasible thermal protection of buildings in the climatic conditions of Moscow are discussed earlier. An important basis of these techniques is that it was possible to identify the thermal parameters on the basis of which the generalization of the basic energy and economic indicators of the building, depending on its thermal protection, was carried out. The methods were tested for buildings whose working day lasts from 9 am to 6 pm with various internal heat generation. In this case, it was believed that solar radiation is completely obscured. From consideration of the effect of heat gains on energy-efficient thermal protection, it was found that with increasing heat gains, the load on heating systems decreases regardless of the level of heat protection, and the load on the room cooling systems increases more with higher thermal protection than with low thermal protection. However, there are buildings of a number of functional purposes in which solar radiation is partially obscured or not obscured at all. These include some commercial, residential and other buildings. Accounting for heat gains from solar radiation, with variable intensity throughout the year, makes significant adjustments to the choice of the level of thermal protection. This is due to the fact that often cooling of the room is required during periods when the outside air temperature is below the maximum allowable temperature of the room. During these periods, enhanced thermal protection is an obstacle to the natural outflow of heat from the premises. Calculations showed that the higher the heat gain from solar radiation, the smaller the proportion of buildings it is energetically feasible to warm according to the basic standards stipulated in SP 50.13330.2012. And although it is not energetically feasible to carry out thermal insulation for sanitary and hygienic requirements, the conclusions about the benefits of building insulation with reduced heat transfer to the walls and coatings of a building are economically significant. It is also important that when identifying an economically feasible thermal protection of a building, it is necessary to take into account all the components of financial expenses that are affected by the thermal protection of a building. The calculations also showed that an increase in the cost of heat and electricity over time changes the thermal performance of buildings for which this or that thermal protection is economically feasible.

1. Introduction

The choice of economically feasible thermal protection is one of the most important tasks of construction [1-6]. Thermal protection of the building should lead to minimal energy consumption by the systems providing the thermal microclimate of the premises. It should be borne in mind that an increase in heat gains to rooms both from solar radiation and from internal heat sources will reduce the load on the heating system with any heat protection, and the load on the cooling system rather decreases when the outdoor air temperature is below the room temperature with enclosing structures with low heat transfer resistance than with high. Moscow, for the climatic conditions of which the proposed work was
performed, refers to areas with a short period of time when the outdoor air temperature is higher than the required values of the internal air temperature.

Despite the fact that in recent years in the summer hot weather is quite long standing, the work is based on average long-term values of the outdoor temperature.

To study taken building rectangular shape with the same width equal to 20.2 m for the outer measurement. The length of the buildings varied from 13.6 m to 115.6 m. All end walls of the buildings are deaf (without windows). Floors of buildings ranged from 1 to 40 floors. The proportion of glazing of the longitudinal walls is presented in two versions: 0.25; 0.55. The windows are thick enough to disregard infiltration. The heat transfer resistance of windows in all variants is assumed to be 0.54 m²·°C/W.

The individual characteristics of some buildings are listed in table 1.

| Denomination of the value                          | The building option |
|---------------------------------------------------|---------------------|
|                                                   | 1  | 2  | 3  | 4  | 5  | 6  |
| **Building length, m**                            | 13.6| 20.4| 61.2| 88.4| 115.6| 115.6|
| **Number of floors**                              | 2   | 1   | 15  | 24  | 22  | 40  |
| **Building total area, m²**                        | 549 | 412 | 18 544 | 42 856 | 51 373 | 93 405 |
| **Area of exterior enclosing structures, m²**      | 802 | 729 | 10 760 | 22 116 | 25 638 | 44 705 |
| **Building volume, m³**                            | 2 143 | 1 607 | 72 320 | 167 140 | 200 353 | 364 279 |
| **Building compactness coefficient**               | 0.567 | 0.710 | 0.166 | 0.143 | 0.140 | 0.129 |

The buildings consist of rooms of the same size 6.8x10.1x3.9 (h) of four types: ordinary intermediate floors, ordinary upper floors, corner ones on intermediate floors, corner ones on the upper floor.

Three variants of thermal protection of the building were considered, differing from each other in resistance to heat transfer of the outer wall and the covering. For option 1, the heat transfer resistance of the outer wall and coating is close to the normalized formula (5.4) SP 50.13330.2012 "Thermal protection of buildings" for sanitary and hygienic conditions. Option 3 of thermal protection meets the basic standards, based on the energy savings in table. 3 of the same joint venture. For option 2, the heat transfer resistance of external walls and coatings are calculated by the formula (5.1) of the same joint venture using a reduction factor of 0.63 for walls and 0.8 for a coating with respect to option 3. The values of heat transfer resistance, m²·°C / W, for external walling corresponding options 1, 2 and 3 are as follows: for walls: 1.347; 1.704; 2.629; for coatings: 1.490; 2.871; 3.621.

We have previously considered [7, 8] buildings that traditionally shade windows from the sun in order to avoid glare and additional heat to technological inflows. At the same time, there is a mass of other buildings where solar energy is either not completely obscured, or not obscured at all. The specific heat gains to the rooms were taken into account from 9 o'clock to 18 o'clock and were selected at 3 levels: 0 W/m², 40 W/m², and 80 W/m². This value does not include solar radiation penetrating through the windows. Accounting for heat gains from solar radiation was carried out separately, and the daily and annual variations in solar radiation were taken into account [9]. When considering heat gains from solar radiation, the coefficients of total transmittance of solar energy were taken into account with a double-chamber window 0.72, bindings 0.8 and sun-protection devices at two levels: 0.4 and 1. In the latter case, the absence of sun-protection is considered. In addition, an option without solar radiation was considered.

Attention is drawn to the fact that in annual energy consumption, only the need of buildings for heat and cold to maintain a given thermal microclimate of the premises was considered. Losses due to work inefficiencies and additional energy costs for the preparation of the required heat transfer fluids of heating and cooling systems were not considered. When calculating, it was assumed that natural cooling is applied at an outdoor temperature not higher than +5 °C.
The costs of heat and cold for heating and cooling buildings with different resistances to heat transfer of external walling structures are made by direct calculation of the non-stationary thermal conditions of the rooms at different values of the outside air temperature. Non-round-the-clock operation of the premises, and, therefore, non-round-the-clock heat generation, cause non-stationarity of the thermal process. As a research tool, a program for calculating the non-stationary thermal regime of a room has been adopted, based on the calculation in finite differences with the construction of an implicit difference scheme using the heat balance method. The method allows to solve the problem in the most complete setting, taking into account changes in the coefficients of radiant and convective heat transfer on the fencing surfaces without tying the magnitude of the steps in time to the steps along the coordinate with sufficient accuracy for obtaining the result [7].

The calculation investigated the need for heat and cold to maintain a given thermal regime in the premises of buildings during the year. And in the cold season, on certain days, the need for heating at night and cooling during the day was taken into account. The requirement to take into account the year-round maintenance of the specified temperature conditions in the premises is confirmed [10] by the fact that cold is required for an extended period of time when the outdoor air temperature is below the maximum allowable room temperature of 24 °C. At this time, an increase in heat transfer resistance of walls and coatings plays a negative role, since it prevents the natural outflow of heat from the room. In Moscow, the heating period has an average duration of 205 days, that is, most of the year. Even if you do not take into account the economic component of the higher price of cold compared to thermal energy, the amount of cold during the warm period of the year is a significant amount of the amount of heat during the heating period. It is clear that the greater the internal heat dissipation in the room, the greater the load on the cooling system and the more powerful thermal protection is advisable in most of the houses. In this regard, the study of the effect of heat gains from solar radiation is a very timely task.

2. Thermal and economic characteristics of buildings, adopted to summarize results of calculations

To summarize the results of calculations of the specific annual energy consumption (heat or of cold), kW·m²·h/m² per 1 m² of heated area, the main heat transfer coefficient of the building, W/(m²·°C) is taken as the main parameter, in accordance with SP 50.13330.2012:

\[ K_m = \frac{1}{A_{sum}} \sum_i A_i R_{r,i}, \]  

where \( A_{sum} \) – the sum of areas of all the exterior enclosing structures of the building thermal protection enclosure, m²;  
\( A_i \) - the area of the \( i \)-portion of the building thermal protection enclosure, m²;  
\( R_{r,i} \) - the reduced resistance to heat transfer of the \( i \)-portion of the building thermal protection enclosure, (m²·°C)/W.

The overall heat transfer coefficient is the average value of the heat transfer coefficients of all external enclosing structures of the heat-shielding shell of a building, taking into account the surface area of each structure. It is quite natural to use this coefficient to characterize a building, since it is through external fences that the heat fluxes that make up the heating and cooling load on the building maintenance system microclimate systems penetrate the room. Despite the fact that the windows are also characterized by resistance to heat transfer and area, consideration of the annual energy consumption to maintain a given microclimate with different insulation of external walls and coatings was carried out for options with different glazing areas separately, since the thermal performance of the windows is the same in all variants and affect energy consumption only through the area of the windows, and, consequently, the walls. In the problem that is being solved in this article, the window is a source of solar radiation penetrating the room, and the loads on the space heating systems and their cooling systems depend on the window size.
To identify an economically feasible degree of building insulation, there are not enough energy ratings. Economic comparisons should be made. The second important parameter, on the basis of which the generalization of economic indicators was carried out, was chosen the specific heat-shielding characteristic of the building $k_{shc}$, W/(m²·℃), which is equal to the product of compactness coefficients and the overall heat transfer coefficient of the building $K_m$:

$$k_{shc} = K_{comp} K_m$$  \hspace{1cm} (2)

where $K_{comp}$ is the compactness factor of a building, 1/m, equal to the ratio of the total area of all external fences of the heat-resistant shell of the $A_{assn}$ building, m² to the heated building volume $V_{he},$ m³; $K_m$ is the total heat transfer coefficient of the building, W/(m²·℃).

This coefficient was adopted as a characteristic of the heat-shielding properties of a building in SP 50.13330.2012 “Thermal protection of a building”. Updated version of SNiP 23.02.2003. It is more relevant to the economic task than the general heat transfer coefficient of the building, since it relates the average heat transfer resistances of the heat-shielding envelope of the building to its volume.

Figure 1 shows the relationship between the $K_m$ value and the specific options for the buildings examined.

![Correspondence of values of total heat transfer coefficient, $K_m$, W/(m²·℃), to variants of buildings under consideration. Consistently specified: option of building thermal protection, portion of façade glazing, length of building, m, number of floors.](image)

For the economic evaluation of building insulation options, the cumulative discounted costs (SDZ) per 1 m² of the estimated building area, thousand rubles/m², were selected. The values of SDZ taken on the horizon of 10 years, since the service life of refrigeration equipment is approximately equal to this period of time. If the return on investment does not fit into this period, then the option can not be considered profitable. Interestingly, in Soviet times, the payback period in economic calculations for construction was assumed to be $T = 10$ years.

The adopted characteristic of an economic approach to the selection of a suitable thermal protection of a building impersonates individual components of financial expenses to the total amount of SDZ, therefore, the share of facade glazing in various building variants is taken into account on a common basis and is not highlighted as a separate significant factor.

The purpose of this article is to assign combinations of the specific heat-shielding of the building and SDZ of the building options to appropriate levels of thermal protection at the current price level for all components affecting the energy consumption of the microclimate maintenance systems in a building at various levels of internal heat gain and window shading.

3. Method of economic comparison of options

In the Russian regulatory documents [11], so far, when comparing heat protection options, only the cost of heat energy for its heating is taken into account from all energy costs used to maintain thermal conditions in the room. However, it has been repeatedly shown that for buildings in which the required microclimatic conditions are maintained year-round, the energy consumption for both heating and
cooling of buildings should be taken into account. Capital costs in the regulatory method consist only of the cost of insulation.

In the proposed method, as a one-time cost, the SDZ takes into account: the cost of insulation, taking into account its transport and installation; the cost of the heating system, which includes not only pipelines with shut-off and control valves and heating devices, but also a circulation pump [12], heat exchanger and strainer, the cost of equipment for free and machine cooling, the cost of connection to the heat and power networks. Operating costs consist of the cost of heat, cold and depreciation.

The choice of the appropriate level of thermal protection of the building is carried out taking into account the current prices of individual cost components. Previously, we obtained zones of combinations of the specific heat-shielding characteristic of the building, $k_{shsc}$, W/(m$^2$·°C), and total discounted cost of SDZ, thousand rubles/m$^2$, based on the 2016 prices. Therefore, in this paper we consider a solution to the problem without the sun. Firstly, it correctly relates the results of calculations for all levels of solar heat shading, and, secondly, it will allow to evaluate the impact of changes in the values of individual components with time. Below are the accepted values of all components accepted for calculation, with 2016 values in parentheses. The price of building insulation and connection to energy supply systems has not changed.

Since all components of capital and operating costs can vary significantly, the ranges of variation of each of them for 2019 are selected for calculations:
- connection to the power grid from 550 to 100 000 rubles/kW of power supply capacity of the microclimate maintenance systems in the building;
- connection to the heat network from 550 to 50 000 rubles/kW of the heat supply capacity of the microclimate maintenance systems in the building;
- the cost of the heating system is from 17 250 to 115 000 rubles/kW (from 15 000 to 10 000 rubles/kW) of the power of the heating system;
- the cost of heat energy is from 2.2 to 4.5 rubles/kWh (from 1.81 to 3.5 rubles/kWh);
- the cost of natural cold from 0.55 to 0.85 rubles/kWh (from 0.48 to 0.76 rubles/kWh);
- the cost of artificial cold is from 1.5 to 2.2 rubles/kWh (from 1.24 to 1.95 rubles/kWh);
- the cost of electricity from 4.0 to 6.5 rubles/kWh (from 3.61 to 5.68 rubles/kWh);
- the cost of refrigeration equipment for artificial cooling is from 46 000 to 92 000 rubles/kW (from 40 000 to 80 000 rubles/kW);
- the cost of refrigeration equipment for natural cooling is from 1 725 to 8 050 rubles/kW (from 1 500 to 7 000 rubles/kW);
- the cost of building insulation from 9 000 to 22 000 rubles/m$^3$.

Considered discount rate from 5 to 10%.

4. Calculation results
Figures 2 - 4 show the zones of the combination of SDZ and specific heat-shielding shell of buildings. The non-shaded areas in figure 1 refer to buildings above the 40-storey ones with dimensions in terms of more than 115.6x20.2 m that were not considered. The results given refer to a discount rate of 10%.

In figure 2, the results refer to the case of full shading from solar heat. In comparison with the zones of combination of parameters obtained earlier, taking into account the values of 2016, the latest results take into account the increase in capital and operating costs, not related to building insulation. As a result, the boundaries of the zones of expediency of insulation increased due to sanitary and hygienic conditions (the zone of insulation increased according to option 1) and the heat transfer resistance reduced relative to the base heat resistance (the upper limit of the zone of expediency of insulation increased according to option 2). At the same time, zone 2 itself was somewhat reduced due to an increase in the zone of insulation 1. The zone of expediency of the basic insulation of building 3 also decreased. Such changes occurred at all prices for heat insulation accepted for consideration. This indicates a greater feasibility of a low level of insulation due to the fact that the high cost of energy and
capital expenditures on systems to ensure a given indoor microclimate overtakes the increase in prices for insulation. This thesis is also confirmed by the fact that the displacement of the above boundaries upwards is more characteristic of the variants with more expensive insulation than the cheaper ones. Moreover, with increasing heat gains in the premises of the zone, low building insulation feasibility increases due to lower heating costs for heating and the cost of heating systems. Strangely enough, lowering insulation for the cooling period of a building with an increase in internal heat gains in the Moscow climate is also more beneficial because of the possibility of natural heat loss through external walling at indoor air temperature above the outside air temperature.

Figures 3 and 4 show the same zones in terms of adding heat of solar radiation to the internal heat gains with a thermal transmittance of 0.4 and 1 sun shade. Considering figures 3 and 4, it should be borne in mind that the increase in heat gains to the room from solar radiation throughout the year occurs unevenly - less in winter and more in summer. This means that reducing the load on heating occurs to a lesser extent than increasing the load on the cooling system. That is why the increase in zones 1 and 2 occurs to a lesser extent than was observed when only the permanent internal heat gains throughout the year were taken into account. At the same time, the increase in heat transmission by the sun shifts the boundaries of zones 1 and 2 upward, which indicates the increasing feasibility of allowing the free flow of heat flows from the room to the outside.
Figure 2. Economically feasible options for building insulation without solar radiation (red – option 1, blue – option 2, green – option 3) when changing specific thermal characteristics of buildings $k_{shsc}$, W/(m$^3$·°C), with cost of insulation 22 000 rubles/m$^3$ (a, d, g), with cost of insulation 15 000 rubles/m$^3$ (b, e, h), with cost of insulation 9 000 rubles/m$^3$ (c, f, i). With internal heat inflows a, b, c – 0 W/m$^2$, d, e, f – 40 W/m$^2$, g, h, i – 80 W/m$^2$. At discount rate of 10%.
Figure 3. Economically feasible options for building insulation when solar heat is transmitted by sun protection in fraction of 0.4 (red – option 1, blue – option 2, green – option 3) when changing specific thermal characteristics of buildings $k_{shsc}$, W/(m$^3$·°C), with cost of insulation 22 000 rubles/m$^3$ (a, d, g), with cost of insulation 15 000 rubles/m$^3$ (b, e, h), with cost of insulation 9 000 rubles/m$^3$ (c, f, i). With internal heat inflows a, b, c – 0 W/m$^2$, d, e, f – 40 W/m$^2$, g, h, i – 80 W/m$^2$. At discount rate of 10%.
Figure 4. Cost-effective options for insulating buildings in building without sun protection (red – option 1, blue – option 2, green – option 3) when changing specific thermal characteristics of buildings \(k_{\text{shsc}}\), W/(m\(^3\)K), with cost of insulation 22 000 rubles/m\(^3\) (a, d, g), with cost of insulation 15 000 rubles/m\(^3\) (b, e, h), with cost of insulation 9 000 rubles/m\(^3\) (c, f, i). With internal heat inflows a, b, c – 0 W/m\(^2\), d, e, f – 40 W/m\(^2\), g, h, i – 80 W/m\(^2\). At discount rate of 10%.

The value of SDZ when changing the discount rate in the range of 5–10% increases with increasing values of the rate, however, the boundaries of the zones of appropriate thermal protection of buildings practically do not shift.

5. Conclusions
1. Heat gains from solar radiation create an additional load on the building’s cooling systems during the transitional and warm periods of the year. In the cold season, these heat gains reduce the load on the heating system. However, with specific technological heat gains in the room during working hours of 40 W / m\(^2\) and above, there are frequent cases when even during the heating period solar radiation plays a negative role, since its action coincides in time with the internal heat gains that form the load on the premises during the daytime.

2. Increasing heat gains in rooms created by solar radiation increase the appropriate areas for combinations of the specific heat-shielding characteristic of the building and total discounted costs with low thermal protection, as in the cold period of the year the heat gain reduces the load on the heating,
and in the warm period of the year the reduced heat protection contributes to care increased heat gains from the room due to heat transfer through the building envelope.

References
[1] V. I. Bodrov, and A. A. Smykov, Thermophysical characteristics of the thermal contour of buildings with gas infrared emitters, C.O.K., vol. 7, pp. 52–55, 2014.
[2] A. V. Veselov, and V. D. Kornienko, New direction in the design and construction of energy efficient low-rise residential buildings, Building materials, equipment, technologies of the XXI century, vol. 7–8(210–211), pp. 41–44, 2016.
[3] A. I. Ananyev, Durability, humidity conditions and thermal protection properties of external walls of buildings made of hollow brick, AVOK, vol. 3, pp. 70–73, 2018.
[4] O. I. Lobov, A. I. Ananyev, and A. G. Rymarov, Main reasons for non-compliance of factual level of heat protection of external walls of modern buildings with regulatory requirements, Industrial and civil engineering, vol. 11, pp. 56–60, 2016.
[5] I. L. Shubin, Building Physics: Current Condition of the Industry, AVOK, vol. 7, pp. 4–10, 2018.
[6] B. M. Berkovskiy, and E. F. Nogotov Difference methods of research of heat transfer problems, Science and technology, Minsk, 1976.
[7] E. G. Malyavina, and A. A Frolova, Choice of thermal protection of an office building of the transport infrastructure by economic reasons, Advances in Intelligent Systems and Computing, vol. 692, pp. 498–511, 2017.
[8] E. G. Malyavina, and A. A Frolova, Economic justification of the choice of the thermal protection of office buildings, News of higher educational institutions. Construction, vol. 9(717), pp. 56–65, 2018.
[9] E. V. Korkina, E. V. Gorbarenko, and V. G. Gagarin et al, Basic relationships for calculation of solar radiation exposure of walls of separate buildings, Housing construction, vol. 6, pp. 27–33, 2017.
[10] V. K. Savin, Construction climatology: Reference book to Snip 23-01-99*, Sc. And research institute of the construction physics of RASNN, Moscow, 2006.
[11] SP 345.1325800.2017, The buildings are residential and public. Rules of design of thermal protection, Ministry Of Construction, Moscow, 2017
[12] A. A. Frolova, A. V. Savina, and O. V. Astanina et al, Determination of the average cost indicators of the heating system, Success of the modern science and education, vol. 12(5), pp. 62–64, 2016.