The influence of the climatic features of the construction area on the level of energy-efficient thermal protection of the office buildings

A A Frolova and E G Malyavina

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

E-mail address: FrolovaAA@mgsu.ru

Abstract. The choice of the level of the building thermal protection should be based on economic indicators of these buildings, taking into account the cost of maintaining a given room thermal microclimate. However, an economic calculation can only be performed after evaluating the impact of the thermal protection level on the building energy performance. The specific energy consumption of a building is affected by the size of the building, since in the buildings of different lengths and number of storeys, the ratio of ordinary rooms on the intermediate and the upper floors is different, as is the number of ordinary and corner rooms. The purpose of the article is to identify the energy consumption for heating, free and machine cooling of the buildings of various sizes and number of storeys in the areas which differ by the heating period duration and the solar radiation intensity, i.e. in Moscow and in Astrakhan. Three options of the building thermal protection have been considered herewith, differing from each other in the resistance to heat transfer of the outer wall and the coating. The area of the windows made 55% of the facade area. The calculation has been performed for several values of the outdoor air temperature during the year in each city.

1. Introduction

According to various estimates, the energy consumption for maintaining the thermal microclimate of buildings in Russia range from 30% to 40% of the energy of all extracted fuel [1]. That is why, reducing these energy consumption is an important task [2, 3]. A higher thermal protection of external enclosing structures should be considered as the most effective measure to save energy for maintaining thermal conditions in the building rooms [4].

When calculating the actual energy consumption of the systems that support the room specified thermal conditions, provision shall be made of taking into account the solar radiation heat inputs, that penetrate through the windows, as well as the heat coming from internal domestic or technological sources.

It is known [5-7] that the specific energy consumption of a building is influenced by the size of the building, since the ratio of ordinary rooms of intermediate and upper floors is different in the buildings of different lengths and storeys, as is the number of ordinary and corner rooms. Of great importance is the ratio of the size and the resistances to heat transfer of the windows and the exterior walls, due to the fact that in modern buildings the thermal insulation of the walls considerably exceeds the thermal performance of the windows, even of those having a bigger heat transfer resistance, in residential and most public buildings, according to the recent changes in the building rules SP 50.13330.2012.
The purpose of this work is to evaluate the energy performance of the buildings of various sizes and storeys in areas with different heating periods and solar radiation intensity: in Moscow and in Astrakhan.

2. Object of research
The study was performed by calculation. The calculation has been performed for the buildings of rectangular shape with the same width, equal to 20.2 m in external measurement. The length of the buildings varied from 13.6 m to 115.6 m. All end walls of the buildings are blind (without windows). The number of storeys of the buildings varied from 1 to 40 floors. The percentage of glazing of longitudinal walls is 0.55. The windows are dense enough to prevent infiltration. Individual characteristics of some buildings are shown in table 1.

| Table 1. Main geometrical characteristics of the building. |
|-----------------------------------------------------------|
| Denomination of the value | The building option |
|---------------------------|---------------------|
| Building length, m        | 1 2 3 4 5 6 7       |
| 20.4                      | 40.2 20.4 61.2 40.2 |
| 3                         | 12 12 12 12         |
| 1,236                     | 2473 4,945 37,09   |
| 1,362                     | 2,252 4,212 3,141  |
| 4,820                     | 9,643 16,427 12,250|
| 1,379/1.371              |                      |
| 1.226/1.2236             |                      |
| Outer wall                | 1.226/1.2236        |
| Coating                   | 1.379/1.371         |
| Window                    | 0.66                |
| 6                         | 115.6 9,890 14,835  |
| 3                         | 40 93,405           |
| 16,427                    | 6,534 8,855         |
| 25,483                    | 14,835 93,405       |
| 34,535                    | 44,705              |
| 174,350                   |                     |
|                          |                     |
| The buildings include four types of the rooms of the same size 6.8×10.1×3.9(h): row rooms of intermediate floors, row rooms of the upper floor, corner rooms on intermediate floors, corner rooms on the upper floor.

Three variants of the building thermal protection have been considered, differing from each other in the resistance to heat transfer of the outer wall and the coating. For option 1, the resistance to heat transfer of the external wall and the coating is close to the values, which are normalized by the formula (5.4) of SP 50.13330.2012 "Thermal protection of buildings" for sanitary and hygienic conditions. The option 3 of the thermal protection corresponds to the basic standards, based on the energy savings according to table 3 of the above mentioned SP. For option 2, the heat transfer resistances of the external walls and the coatings have been calculated using the formula (5.1) of the mentioned SP using a 0.63 reduction coefficient for the walls and 0.8 for the coating in relation to the option 3. The heat transfer resistance values, m²°C/W, for external enclosing structures corresponding to options 1, 2 and 3 are shown in table 2.

The specific heat access to the premises has been considered from 9 a.m. to 18 p.m. and selected at 3 levels: 0 W/m², 40 W/m², 80 W/m². This value does not include the solar radiation coming through the windows.

| Table 2. Heat transfer resistance of enclosing structures, m²°C/W. |
|---------------------------------------------------------------|
| City                      | Denomination of the enclosing structure | Heat protection option 1 | Heat protection option 2 | Heat protection option 3 |
|---------------------------|----------------------------------------|--------------------------|--------------------------|--------------------------|
| Moscow                    | Outer wall                             | 1.226/1.2236             | 1.619/1.621              | 2.57/2.576               |
|                           | Coating                                | 1.379/1.371              | 2.74/2.7475              | 3.42/3.4226              |
|                           | Window                                 | 0.66                     | 0.66                     | 0.66                     |
| Astrakhan                 | Outer wall                             | 1.05/1.05667             | 1.40/1.40042             | 2.22/2.223676            |
|                           | Coating                                | 1.18                     | 2.37/2.37091             | 2.96/2.966502            |
|                           | Window                                 | 0.59                     | 0.59                     | 0.59                     |

Note: The values of the heat transfer resistance required by the norms are shown above the line, and the calculated values are shown below the line.
During the heating season, i.e. when the outdoor temperature is +8 °C and below, a 24-hour operation of the heating system, which maintains the internal temperature of 20 °C round the clock, has been taken into account. It has been assumed, that the room cooling system worked only during the working hours, maintaining 22 °C in the room at this time.

Attention shall be drawn to the fact that the annual energy consumption considered only the building needs in heat and cold to maintain the specified room thermal microclimate. No losses due to inefficiency and additional energy consumption for the preparation of the required heat transfer agents for heating and cooling systems were considered. When calculating, it was assumed that the natural cooling shall be provided at an outdoor temperature not higher than +5 °C.

**Table 3. Number of days in the year of the outdoor temperature monitoring.**

| Temperature range of the outdoor air (°C) | The interval average temperature (°C) | Duration (days) |
|-----------------------------------------|---------------------------------------|-----------------|
| Moscow                                  |                                       |                 |
| +22 ≤ t                                 | +28                                   | 12              |
| +18 ≤ t <+21.9                          | +20.5                                 | 29              |
| +8 ≤ t <+17.9                           | +13                                   | 110             |
| -2 ≤ t <+7.9                            | +3                                    | 117             |
| -10 ≤ t <-2.1                           | -4                                    | 59              |
| -20 ≤ t <-10.1                          | -15                                   | 31              |
| t ≤-20.1                                | -25                                   | 8               |
| Astrakhan                               |                                       |                 |
| Above 30 °C                             | 35                                    | 12              |
| 22 ≤ t <29.9                            | 26                                    | 62              |
| 16 ≤ t < 21.9                           | 19                                    | 62              |
| 8 ≤ t < 15.9                            | 12                                    | 65              |
| 2 ≤ t < 7.9                             | 5                                     | 54              |
| -4 ≤ t < 1.9                            | -1                                    | 62              |
| -18 ≤ t <+4.1                           | -11                                   | 44              |
| -26 ≤ t <+18.1                          | -21                                   | 4               |

It should be noted, that in Moscow the heating period takes 205 days and its average temperature is -2.2 °C. In Astrakhan the heating period is shorter i.e.169 days, and its average temperature is much higher: -0.8 °C.

To determine the energy consumption for maintaining a specified microclimate of the rooms having different heat transfer resistances of the external enclosing structures, provision has been made of a direct calculation of the office non-stationary thermal mode at different values of the outdoor air temperature, when the external air temperature was above +8 °C. No 24-hour maintenance of the room set temperature conditions and non-round-the-clock heat release explain the non-stationary character of the heat process. As a research tool, a program for calculating the non-stationary thermal regime of a room has been adopted; it is based on the calculation in finite differences with the construction of an implicit difference scheme using the heat balance method [8].

The calculations were performed at various outdoor air temperature values during the year: from the design temperature for heating to the design one for air conditioning in the warm season. The entire year was divided into several intervals in which the selected temperature values were the midpoints. The duration of the temperature monitoring was determined by [9] and is shown in the table 3.
3. The solar radiation thermal energy accounting method

It is known that the intensity of direct and scattered radiation varies from month to month. In addition, weather conditions change daily. However, the average monthly amounts of direct and scattered solar radiation intensity in multi-year terms are given by climatologists in reference books [9].

The total solar radiation, which inflows each month of the year on a horizontal surface, is the initial material for calculating the heat access to the rooms through translucent structures [10].

Actinometrists separately record in reference books [9] the monthly amounts of solar radiation in cloudy (actual cloud conditions) and clear (cloudless) sky. The monthly amounts of the solar radiation under actual cloud conditions shall be determined by averaging the measurement data under actual cloud conditions with any shape and number of clouds. However, the measurements are not taken into account when the sky is clear. Therefore, for each month, the sums of solar radiation should be put together for two states of the sky [11]. In this case, the monthly sum of the total solar radiation inflowing to the vertical surface takes into account the direct, scattered and reflected solar radiation according to the formula:

\[
I_{\text{sept},m} = (S_{\text{x},\text{rop},m} + S_{\text{oboa},\text{rop},m}) K_{\text{r},m} + (D_{\text{x},\text{rop},m} + D_{\text{oboa},\text{rop},m})/2 + (I_{\text{x},\text{rop},m} + I_{\text{oboa},\text{rop},m}) A_m/200
\]

where:

- \( S_{\text{x},\text{rop},m} \) – monthly amounts of direct solar radiation on clear days and under actual cloud conditions to the horizontal surface in the \( m \) month, MJ/m²;
- \( D_{\text{x},\text{rop},m} \) – monthly amounts of scattered solar radiation on clear days and under actual cloud conditions on a horizontal surface in the \( m \) month, MJ/m²;
- \( I_{\text{x},\text{rop},m} \) – monthly amounts of the summarized solar radiation on clear days and under actual cloud conditions on a horizontal surface in the \( m \) month, MJ/m²;
- \( K_{\text{r},m} \) – coefficient of conversion of direct solar radiation from the horizontal surface to the vertical one, that is oriented to the East and West sides, in the \( m \) month;
- \( A_m \) – albedo of the underlying surface in the \( m \) month.

When considering the solar radiation heat inflows, the coefficients of total solar energy transmission by a 0.72 window double-chamber double-glazing, 0.8 bindings and circa 0.4 sun protection facilities have been taken into account.

4. Calculation results

The calculation investigated the need for heat and cold to maintain a given thermal mode in the building rooms within the year. Moreover, during the cold period of the year, the need for heating at night and cooling during the day was taken into account on certain days. The requirement to take into account the year-round maintenance of the specified temperature conditions in the rooms has been confirmed [12] by the fact that cold is required within a long period of time, when the outdoor air temperature is below the maximum allowable room temperature of 22 °C. At this time, increasing the resistance to heat transfer of walls and coverings plays a negative role, as it prevents the heat natural outflow from the room.

In Moscow, the heating period takes on average 205 days, i.e. the biggest part of the year, and in Astrakhan – 169 days, which is slightly less than half of the year. So, in Moscow, the main load is carried by the heating facilities and utilities, and in Astrakhan – by the cooling ones.

Calculations of the annual heat and cold consumption have been performed for the outdoor air temperatures indicated in the table 3. The intensity of solar radiation falling on the outer surface of the window was correlated with the value of the outdoor temperature. The consumed heat and cold have been estimated according to the primary fuel consumption. At the same time, the annual heat consumption of the building, MW·h, has been provided equal to the amount of the primary energy, MW·h. When recalculating the free cooling, the 6.95 electric energy use coefficient was taken into account, and in addition, the fuel efficiency coefficient at the power plant was equal to 0.3. When recalculating the machine cooling, the coefficient EER=3.31 has been entered, and the fuel use efficiency coefficient at the power plant has been provided equal to 0.3.
### Table 4. Specific annual consumption of heat and cold by the building as a whole, kW·h/m².

| The specific heat access | The specific needs for heat, free and machine cold | The building № 1 Heat protection option | The building № 2 Heat protection option | The building № 3 Heat protection option | The building № 4 Heat protection option |
|-------------------------|-----------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                         | Heat                                           | 1                                   | 2                                   | 3                                   | 1                                   | 2                                   | 3                                   | 1                                   | 2                                   | 3                                   |
| 0 W/m²                  | Heat                                           | 76.95                               | 55.36                               | 43.65                               | 66.30                               | 49.43                               | 41.04                               | 60.20                               | 48.00                               | 38.29                               |
|                         | Heat                                           | 9.06                                | 12.79                               | 17.51                               | 13.78                               | 10.63                               | 20.77                               | 12.09                               | 15.31                               | 20.06                               |
|                         | Heat                                           | 29.39                               | 20.61                               | 32.86                               | 38.67                               | 39.69                               | 41.49                               | 60.83                               | 62.07                               | 63.56                               |
| 40 W/m²                 | Heat                                           | 69.22                               | 53.21                               | 42.95                               | 62.81                               | 48.53                               | 40.70                               | 56.73                               | 47.05                               | 38.00                               |
|                         | Heat                                           | 58.27                               | 67.51                               | 73.74                               | 60.77                               | 70.07                               | 74.19                               | 65.55                               | 71.27                               | 76.71                               |
|                         | Heat                                           | 82.90                               | 84.84                               | 87.09                               | 92.49                               | 94.10                               | 95.90                               | 134.88                              | 136.30                              | 137.79                              |
| 80 W/m²                 | Heat                                           | 69.04                               | 53.21                               | 42.95                               | 62.73                               | 48.53                               | 40.70                               | 56.68                               | 47.05                               | 38.00                               |
|                         | Heat                                           | 115.03                              | 124.52                              | 130.68                              | 116.17                              | 124.69                              | 131.39                              | 122.44                              | 128.22                              | 133.65                              |
|                         | Heat                                           | 207.86                              | 209.08                              | 211.33                              | 208.15                              | 209.52                              | 211.32                              | 209.30                              | 210.54                              | 212.03                              |

### Table 5. Specific annual consumption of heat and cold by the building as a whole, kW·h/m².

| The specific heat access | The specific needs for heat, free and machine cold | The building № 5 Heat protection option | The building № 6 Heat protection option | The building № 7 Heat protection option |
|-------------------------|-----------------------------------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                         | Heat                                           | 1                                   | 2                                   | 3                                   | 1                                   | 2                                   | 3                                   |
| 0 W/m²                  | Heat                                           | 48.20                               | 39.57                               | 33.13                               | 44.20                               | 36.76                               | 31.41                               | 36.97                               |
|                         | Heat                                           | 17.04                               | 19.66                               | 22.96                               | 18.69                               | 21.11                               | 23.92                               | 21.38                               |
|                         | Heat                                           | 62.50                               | 63.22                               | 64.37                               | 63.04                               | 63.60                               | 64.65                               | 63.93                               |
| 40 W/m²                 | Heat                                           | 46.11                               | 39.05                               | 32.97                               | 42.57                               | 36.39                               | 31.29                               | 36.36                               |
|                         | Heat                                           | 71.88                               | 76.04                               | 79.73                               | 73.99                               | 77.64                               | 80.74                               | 77.71                               |
|                         | Heat                                           | 136.65                              | 137.45                              | 138.61                              | 137.24                              | 137.84                              | 138.88                              | 138.16                              |
| 80 W/m²                 | Heat                                           | 46.09                               | 39.05                               | 32.97                               | 42.56                               | 36.39                               | 31.29                               | 36.35                               |
|                         | Heat                                           | 128.80                              | 133.02                              | 136.67                              | 130.92                              | 134.62                              | 137.68                              | 134.64                              |
|                         | Heat                                           | 210.98                              | 211.69                              | 212.85                              | 211.53                              | 212.07                              | 213.12                              | 212.40                              |

The tables 4 and 5 show the specific needs for heat, free and machine cold per 1 m² of the floor space for buildings of various length and number of storeys in Moscow and Astrakhan.

As mentioned above, the calculation of the whole daily consumption shall take into account the heat of solar radiation that penetrates through the window, and the internal heat gain during the
working hours, as given in the left part of the table 4. The fact that the heat demand at the internal heat gain of 40 W/m² and 80 W/m² of the floor are the same, specifies that all heat loss of the rooms is covered even with the heat gain of 40 W/m². The heat supply "excess" make a load of the room cooling. It is quite clear, that with an increasing heat protection (from option 1 to option 3), the heating load goes down, and the fact that this load falls with an increase in the length and the number of storeys of the building, may be explained by a smaller number of corner and upper rooms with regard to the number of ordinary ones.

It is interesting that the need for free and machine cold is growing from the option 1 to the option 3 of insulation of enclosing structure heat insulation, because the structures with a high heat transfer resistance actively prevent the heat outflow from the room. In a longer building, the loads on the room cooling under the free cooling mode increase in both cities, because of a long period of the free cooling time, when the outdoor air temperature is lower than the indoor air temperature of 22 °C. At the same time, an increasing share of ordinary rooms out of the total number of them plays a significant role.

The need for machine cold is formed during periods when the outdoor air temperature is lower than the indoor air temperature of 22 °C, and when the outdoor temperature is higher than the indoor one. During this second period, the load on the machine cold decreases with the increasing thermal protection. Despite the fact that this period is long in Astrakhan, the influence of the period with a lower outdoor temperature prevails in the formation of the machine cooling load, and the total annual load on the machine cooling increases with increasing the thermal protection. An increase in the size of a building leads to reduction the specific load on machine cooling.

The tables 6, 7 show the specific needs for primary energy per 1 m² of the floor space to maintain the specified thermal conditions in the buildings with different thermal protection. From the data in table 5, it follows that in both cities, with different sizes and storeys of buildings, it is energetically advantageous to provide the heat protection according to the option 3, that is, with basic heat transfer resistances in accordance with the building rules SP 50.13330.2012.

| Table 6. Specific annual primary energy consumption by the building as a whole |
|---|---|---|---|---|---|
| The specific heat access | The building № 1 Heat protection option | The building № 2 Heat protection option | The building № 3 Heat protection option | The building № 4 Heat protection option |
| № | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 | 1 | 2 | 3 |
| Moscow |
| 0 W/m² | 134.69 | 115.81 | 108.18 | 112.04 | 98.62 | 93.65 | 120.55 | 110.87 | 104.56 | 110.38 | 90.10 | 90.60 |
| 40 W/m² | 214.83 | 204.56 | 199.03 | 189.27 | 180.03 | 175.61 | 207.27 | 201.35 | 196.00 | 170.65 | 167.59 | 154.98 |
| 80 W/m² | 307.09 | 296.46 | 290.90 | 272.14 | 262.86 | 258.69 | 299.23 | 293.22 | 287.86 | 250.63 | 240.53 | 235.83 |
| Astrakhan |
| 0 W/m² | 132.39 | 122.35 | 115.40 | 121.25 | 113.39 | 108.64 | 119.58 | 114.07 | 108.08 | 120.19 | 110.06 | 105.74 |
| 40 W/m² | 223.61 | 213.37 | 206.58 | 210.41 | 202.26 | 197.64 | 208.07 | 202.47 | 196.49 | 205.06 | 200.13 | 181.84 |
| 80 W/m² | 310.38 | 300.08 | 293.54 | 299.32 | 293.22 | 286.75 | 296.46 | 290.91 | 284.93 | 275.76 | 261.77 |

| Table 7. Specific annual primary energy consumption by the building as a whole |
|---|---|---|---|
| The specific heat access | The building № 5 Heat protection option | The building № 6 Heat protection option |
| № | 1 | 2 | 3 | 1 | 2 | 3 |
| Moscow |
| 0 W/m² | 112.20 | 105.36 | 101.38 | 109.40 | 103.52 | 100.33 |
| 40 W/m² | 200.99 | 196.45 | 193.01 | 198.89 | 194.83 | 192.01 |
| 80 W/m² | 292.91 | 288.33 | 284.88 | 290.79 | 286.71 | 283.88 |
| Astrakhan |
| 0 W/m² | 117.03 | 112.78 | 108.40 | 114.64 | 110.93 | 107.14 |
| 40 W/m² | 208.06 | 203.96 | 199.50 | 205.73 | 202.11 | 198.31 |
| 80 W/m² | 296.18 | 292.05 | 287.60 | 294.84 | 291.23 | 287.55 |
5. Conclusions
As a result of the study it was found that the greatest thermal protection is the most appropriate in all cases in terms of the energy indicators in the cities under investigation. The solar radiation heat inflows an additional load on the building's cooling systems during the transitional and warm periods of the year. During the cold season these heat inputs reduce the load on the heating system. However, when the specific technological heat inflows to the room make 40 W/m$^2$ and more during the working hours, the need in the building cooling occurs rather frequently even during the heating period.

The obtained result confirms the economic calculations which compare the cost of the insulation material with the cost of the energy to maintain a given building mode. However the impact of the thermal protection on the economic component is not limited to these two cost indicators. The final decision should be taken after detailed economic calculations.

References
[1] Ardakani O, Bhattacharya A and Culler D 2018 Non-intrusive occupancy monitoring for energy conservation in commercial buildings Energy and Buildings 179 pp 311-23 (DOI: 10.1016/j.enbuild.2018.09.033)
[2] Korniyenko S 2018 Complex analysis of energy efficiency in operated high-rise residential building: Case study E3S Web of Conferences 32 02005
[3] Kwon M, Remoy H. Van Den Dobbelsteen A and Knaack U 2019 Personal control and environmental user satisfaction in office buildings: Results of case studies in the Netherlands Building and Envir. 149 pp 428-35 (DOI: 10.1016/j.buildenv.2018.12.021)
[4] Mingottia N, Chenvidyakarn T and Woods A W 2013 Combined impacts of climate and wall insulation on the energy benefit of an extra layer of glazing in the façade Energy and Buildings 58 pp 237–49
[5] Prozumonts A, Borodinecs A, Odineca T and Nemova D 2020 Long-Term Buildings’ Space Heating Estimation Method Lecture notes in civil engineering 70 pp 539-50
[6] Malyavina E and Frolova A 2019 Influence of solar radiation heat input into room on level of economically-efficient thermal protection of building IOP Conf. Ser.: Mater. Sci. Eng. 97 03022
[7] Malyavina E and Frolova A 2014 The energetic and economic analysis of outdoor temperature to enable the transition to free cooling for conditioned rooms 9th Int. Conf. on Environmental Engineering. ICEE 2014
[8] Berkovskiy B M and Nogotov E F 1976 Difference methods of research of heat transfer problems (Minsk: Science and technology)
[9] Scientific and applied reference book on the climate of the USSR. Episode 3. Multiyear data. (Hydrometeoizdat. St. Petersburg. 1989 – 1998)
[10] Bodrov V I Smyko A A 2014 J. C.O.K. 7 p 52 – 55
[11] Korkina E V, Gorbarenko E V, Gagarin V G and Shmarov I 2017 J. Housing constr. 6 pp 27–33
[12] Malyavina E and Frolova A 2019 The influence of the solar radiation heat input into the room on the level of energy-efficient thermal protection of the building E3S Web of Conferences 97 03022