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ANALYSIS OF THERMAL STABILITY OF WALL ENCLOSING STRUCTURE OF BUILDING FOR CLIMATIC CONDITIONS

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Abstract- The problem of ensuring the thermal stability of the building external structures is relevant from the point of view of ensuring their energy efficiency and comfortable environmental conditions of the premises. In this paper, the calculation and comparative analysis of the thermal stability for the most commonly used wall eclosing structure schemes of the building with a different location of the thermal-insulation layer relative to the main masonry for the climatic conditions of Baku in the warm season are given. It was revealed that when a layer with a lower density is located on the outer side of the main masonry, the amplitude of temperature fluctuations on the inner surface of the wall are almost 2 times less, which means that the best comfortable conditions of the internal microclimate of the premises are provided. The appropriate mutual arrangement of the wall structure layers can increase the wall thermal stability in relation to the effects of solar radiation. The obtained results can be used for a multidisciplinary energy audit of the buildings.

Keywords: Wall Enclosing Structure, Thermal Stability, Climatic Conditions, Amplitude of Temperature Fluctuations, Attenuation of Temperature Fluctuations, Heat Assimilation Coeffitient of the Material, Thermal Inertia.

1. INTRODUCTION

Saving fuel and energy reserves and reducing the greenhouse effect are pressing problems requiring urgent solutions both at the global and regional levels [1]. Buildings and facilities as one of the main consumers of energy and natural resources are acquiring ever greater requirements for their thermal protection, which is dictated by both the aggravating environmental situation and the depletion of natural resources [2]. Building outer structures have a significant weight on the total energy consumption of the building [3]. At the same time, the exceptional variety of climatic conditions on the territory of Baku, caused by its geographical position and the location of the amphitheater on the Caspian Sea coast, as well as its orographic features, imposes very diverse requirements on the external structures of the buildings [4].

A characteristic feature of the climate on the territory of Baku in the summer months is intense solar radiation, high temperature and high air humidity, which have a decisive effect on the thermal regime of the external structures of the buildings and lead to their overheating.

Despite the sufficient study of the problems of accounting for the heat of solar radiation and the development of individual measures to reduce the overheating of external structures, there are still many unresolved issues requiring further study [5]. Besides, the global increase in the average daily air temperature in summer and climate change in general over the past decades makes the task of increasing the thermal resistance of the outer walls of buildings more and more urgent. This paper is devoted to the assessment and comparative analysis of one of the main indicators of the thermal regime of the external walls- their thermal resistance in the warm period of the year for the climatic conditions of Baku. Calculations are made in accordance with local building standards [6] for two types of the wall enclosing structures with the external and internal locations of the thermal-insulation layer. The results obtained can be used to conduct a multidisciplinary energy audit of the buildings and their subsequent certification [7].

2. MATERIALS AND METHODS

The task of evaluating and analyzing the thermal stability of the wall enclosing structures of the buildings for the climate of Baku required analytical and experimental studies, also studying the experience of construction in Azerbaijan, attracting materials from published scientific studies and literary sources [5,8,9]. Climatic zoning of Baku is carried out according to thermal and humidity characteristics, and indicators of the wind regime and solar radiation are taken as additional and corrective characteristics. The design of thermal protection of external walls for the warm period of the year is to assess the thermal stability of them under the action of solar radiation in the hottest month, for Baku in July [11]. The calculation is carried out for the building outer structures designed for the cold season.

Thermal stability is the property of the building enclosing structures to maintain a relatively constant temperature on its inner surface when the temperature of the external air changes. The property of thermal stability of the building outer structures helps to maintain a constant air temperature in the room, which provides comfortable indoor conditions for people. In buildings with the insufficient thermal stability of the building outer structures, the air temperature rises rapidly in summer, and in winter, during interruptions in the operation of the heating system, it quickly drops. In this case, the building outer structures absorb the heat flow to the maximum, a load of air conditioning systems in summer and heating system in winter increase [12]. According to regulatory requirements, even with the maximum absorption of the heat flux by the wall enclosing structure due to the significant effect of solar radiation, the temperature of the inner surface of the wall ($t_{int.w}$) must be less than the limit, i.e. normative ($t^{req.w}$), i.e. $t_{int.w} < t^{req.w}$ [13, 14].

Studies of the transmission of thermal waves in the external enclosures of buildings and the thermal stability of external structures have been successfully described in [15, 16, 17]. In this paper, the calculation and comparative analysis of the thermal stability of the outer wall for the climatic indicators of Baku are carried out for the first time according to the methodology described in [13, 14], which normalizes the value of the required thermal stability to solar radiation of the outer wall.

In this paper, the calculation and comparative analysis of the thermal stability of the most commonly used structures of the outer walls of the building with a different location of the thermal-insulation layer relative to the main masonry for the climatic conditions of Baku in the warm season are given.

2.1. Formulation of the Problem

The protection of outer walls from solar overheating is primarily ensured by choosing the optimal orientation of the building, taking into account the prevailing winds. The massive outer walls of the old buildings of Baku with a thickness of 0.75-1.00 m, which account for up to 16% of the total number of buildings, are made of materials with high thermal capacity and protect against summer overheating very well. From direct sunlight, the wall enclosing structure can be defended both by cornices with a significant extension, and "aivans" - a kind of veranda for the entire width of the house. The modern buildings with a wall thickness of 0.30-0.45 m are less protected from sun exposure due to their certain design features. The intensity of heat transfer through the wall enclosing structure depends on the resistance of the structure to this process [18].

During the summer period of the year, heat fluxes from solar radiation flow directed from the outer surface of the wall to the inner one. The periodic changes in the temperature of the outdoor and indoor air of buildings are significant, which leads to the need to introduce additional requirements for the thermal shielding qualities of external walls, i.e. they must have the property of maintaining a relatively constant temperature on the inner surface (t_{intW} °C) regardless of the temperature changes on the outer surface of the wall (t_{extW} °C), it means that the wall enclosing structures must have high thermal stability and be heat resistant [19].

With the low thermal stability of the walls, the air temperature in the room can change dramatically during the day, for example, rise during the daytime in summer and even exceed the outside air temperature at 5-9 pm [20].

2.2. Climatic Indicators

The temperature of the outer surface of the wall, t_{extW} °C under the influence of solar radiation, mainly depends on the following climatic indicators of the construction area, which are shown in Table 1 [11, 20].

Table 1. The main climatic indicators of Baku, Azerbaijan for July

Name	Symbols	Unit of measurement	Value
Amplitude of outdoor temperature fluctuations during the day- maximum	$A_{maxJuly}$	°C	12.2
Amplitude of outdoor air temperature fluctuations during the day- average	$A_{av.July}$	°C	7.4
Absolute maximum outdoor temperature	t_{extM}	°C	40
Average outdoor temperature	t_{ext}	°C	28.3
Intensity of direct solar radiation for external walls- average (western facade)	S_{av}	$\frac{W}{m^2}$	151
Intensity of direct solar radiation for the outer western walls- maximum (western facade)	S_{max}	$\frac{W}{m^2}$	655
Average wind speed	υ	$\frac{m}{sec}$	4.9
Prevailing direction wind	-	-	North

With daily consideration, the intensity of solar radiation becomes maximum at 3-5 PM hours on the western facade, which predetermines the assessment of the west-facing wall for normative thermal stability for the summer period. Because the temperature of the outside air and the intensity of solar radiation fluctuate throughout the day with a maximum at 1-5 PM of the day, a minimum at 3 AM, then in the wall once a day - within 24 hours - there are attenuating thermal waves from the wall outer surface to the inner one in the thickness of the wall. The attenuation amount depends on:
- the material of the structural layers;
- the sequence of the layer location;
- the material density;
- the thermal indicators of the materials.

The assessment of the thermal stability of the wall is carried out by [14] if the average outdoor air temperature in July is equal to or greater than 21 °C by calculating the temperature fluctuations on the inner surface of the wall A_{int} and then the resulting indicator is compared with the normalized A^{req}. For calculations the design temperature of the indoor air of the premises is accepted t_{int} = 23 °C .

3. CASE STUDY

Because of the climatic indicators of Baku the western facade is the most problematic in terms of the accumulation of solar energy, then the assessment of the studying indicator is carried out specifically for it [5]. A wall with a main masonry from brick and a thermal-insulation layer from expanded polystyrene (Table 2) was studied here.

The required amplitude of temperature fluctuations at the inner surface of the wall A_{int}^{req} is determined by the formula [14]:

$$A_{int}^{req} = 2.5 - 0.1\left(t_{ext} - 21\right)$$
$$A_{int}^{req} = 2.5 - 0.1\left(28.3 - 21\right) = 1.77 \text{ °C} \quad (1)$$

Table 2. Thermal technical indicators of wall enclosing structure

Number of the layer, i		1	2
Name of the layer material		Brickwork	Expanded polystyrene
Thickness of layer δ [m]		0.3	0.06
Density, ρ [$\frac{kg}{m^3}$]		1600	40
Thermal engineering characteristics	Thermal conductivity coefficient λ [$\frac{\text{W}}{\text{m.°C}}$]	0.76	0.041
	Heat assimilation coefficient s [$\frac{\text{W}}{\text{m.°C}}$]	9.2	0.41
Design characteristics	Heat transfer resistance R [$\frac{\text{m}^2\text{.°C}}{\text{W}}$]	0.4	1.46
	Thermal inertia D_i	3.68	0.6

According to [20], the following requirement must be fulfilled:

$$A_{int} < A_{int}^{req} \quad (2)$$

The calculated value of the amplitude of temperature fluctuations of the outer surface of the wall is determined by the next formula:

$$A_{ext} = 0.5A_{\max July} + \frac{\rho\left(S_{\max} - S_{av}\right)}{\alpha_{ext}} \quad (3)$$

The α_{ext} is heat transfer coefficient of the outer surface of the wall in summer, $\frac{\text{W}}{\text{m}^2\text{.°C}}$; ρ is absorption coefficient of solar radiation by the outer surface of the wall, depending mainly on the coating material, ρ=0.3-0.7, for the light coatings ρ=0.5,

$$\alpha_{ext} = 5.8 + 11.6\sqrt{\upsilon} = 31.5 \ \frac{\text{W}}{\text{m}^2\text{.°C}} \quad (4)$$

$\upsilon = 4.9 \ \frac{\text{m}}{\text{sec}}$ is average wind speed of the prevailing direction wind according to normative data for Baku with a northern latitude at 40° (Table 1), although this indicator can reach $11 \div 16 \ \frac{\text{m}}{\text{sec}}$ on some days, as it was in the summer of 2021, according to Equations (3) and (4):

$$A_{ext} = 0.5 \times 12.2 + \frac{0.5 \times \left(655 - 151\right)}{31.5} = 20.2 \text{ °C} \quad (5)$$

The required attenuation of temperature fluctuations in the wall is:

$$\nu^{req} = \frac{A_{ext}}{A_{int}^{req}} = \frac{20.2}{1.77} \approx 12 \quad (6)$$

That is the required amplitude of the temperature fluctuations at the inner surface of the wall in relation to the same normative indicator of the outside surface should be 12 times less. In order to determine whether the wall enclosing structure has enough level of thermal stability in the summer period of the year, it is necessary to compare the required value of the attenuation of the temperature fluctuations ν^{req} with the calculated value ν, it means that the wall meets the requirements for the thermal stability, if the following condition is met: $\nu \geq \nu^{req}$ [13].

It needs to determine the calculated value of the attenuation of the temperature fluctuations for two options and then compare the results:

- option 1: the thermal insulation layer is located outside of the brickwork $\nu_{ext.insul.}$,
- option 2: the thermal insulation layer is located from the inside of the brickwork $\nu_{int.insul.}$.

The numbering of layers for the first option is shown in Figure 1. The value of the attenuation of the temperature fluctuations ν of the outer surface of the wall enclosing structure is calculated by the next formula:

$$\nu = 0.9e^{\frac{\sum D}{\sqrt{2}}} \frac{\left(s_1 + \alpha_{int}\right)\left(s_2 + Y_1\right)\ldots\left(s_n + Y_{n-1}\right)\left(\alpha_{ext} + Y_{ext}\right)}{\left(s_1 + Y_1\right)\left(s_2 + Y_2\right)\ldots\left(s_n + Y_n\right)\alpha_{ext}} \quad (7)$$

where, e = 2.718 is base of natural logarithm; $\sum D_i$ is total thermal inertia of the wall enclosing structure, s_1, s_2 are heat absorption coefficients of structural layers of the wall, $\frac{\text{W}}{\text{m}^2\text{.°C}}$; Y_1, Y_2 are heat absorption coefficients of the outer surface of certain layers of the building outer structures, $\frac{\text{W}}{\text{m}^2\text{.°C}}$; α_{int} is heat transfer coefficient of the inner surface of the wall, $\alpha_{int} = 8.72 \ \frac{\text{W}}{\text{m}^2\text{.°C}}$

The degree of attenuation of temperature fluctuations in the wall is determined by the thermal inertia of the structural layers (Table 2): $D_i = R_i s_i$. The total thermal inertia of the wall is equal to the sum of the thermal inertias of the individual layers: $D = \sum D_i$.

When, $D_i > 1$ heat absorption coefficient of the outer surface of the layer is defined as $Y_i = s_i$.

When, $D_i < 1$ heat absorption coefficient is defined as

$$Y_i = \frac{R_i \cdot s_i^2 + Y_{i-1}}{1 + R_i \cdot Y_{i-1}} \quad (8)$$

In summer conditions, when the outer surface heats up, the calculations should be started from the layer adjacent to the room air.

- Option 1. For the inner layer $D_1 = 3.68 > 1$ it means

$$Y_1 = s_1 = 9.2 \ \frac{\text{W}}{\text{m}^2.°\text{C}}.$$

For the second layer $D_2 = 0.6 < 1$, it means the thermal insulation layer is thin, so it is needed to calculate Y_2 using Formula (8):

$$Y_2 = \frac{R_2 s_2^2 + Y_1}{1 + R_2 Y_1} = \frac{1.46(0.41)^2 + 9.2}{1 + 1.469.2} = 0.65 \ \frac{\text{W}}{\text{m}^2.°\text{C}}$$

The attenuation of the temperature fluctuations in the outer layer is calculated using the following formula:

$$v_{ext} = \frac{Y_2 + \alpha_{ext}}{\alpha_{ext}} = \frac{0.65 + 31.5}{31.5} = 1.02$$

Thus, the attenuation of temperature fluctuations of a wall with an external location of the thermal-insulation layer will be:

$$v_{ext.insul.} = 0.9 e^{\frac{4.28}{\sqrt{2}}} \frac{(9.2 + 8.72)(0.41 + 9.2)}{(9.2 + 9.2)(0.41 + 0.65)} 1.02 \approx 166 \quad (9)$$

- Option 2. For the inner layer $D_1 = 0.6 < 1$, therefore Y_1 is determined by Formula (7):

$$Y_0 = \alpha_{int} = 8.72 \ \frac{\text{W}}{\text{m}^2.°\text{C}}$$

$$Y_1 = \frac{R_1 s_1^2 + Y_0}{1 + R_1 Y_0} = \frac{1.46 \times (0.41)^2 + 8.72}{1 + 1.46 \times 8.72} = 0.65 \ \frac{\text{W}}{\text{m}^2.°\text{C}}$$

$D_2 = 3.68 > 1$, and $Y_2 = s_2 = 9.2 \ \frac{\text{W}}{\text{m}^2.°\text{C}}$

$$v_{ext} = \frac{Y_2 + \alpha_{ext}}{\alpha_{ext}} = \frac{9.2 + 31.5}{31.5} = 1.29$$

The attenuation of temperature fluctuations of a wall with an internal location of thermal-insulation layer is:

$$v_{int.insul.} = 0.9 e^{\frac{4.28}{\sqrt{2}}} \frac{(0.41 + 8.72)(9.2 + 0.65)}{(0.41 + 0.65)(9.2 + 9.2)} 1.29 = 95 \quad (10)$$

The temperature of the wall outer surface is determined according to the formula of A.M. Shklover [21]:

$$t_{extw} = t_{ext} + \frac{\rho \cdot S_{\max}}{\alpha_{ext}} = 28.3 + \frac{0.5 \cdot 655}{31.5} \approx 38.7 \ °\text{C} \quad (11)$$

The amplitude of temperature fluctuations on the inner surface of the wall is determined by the formula [13]:

$$A_{int} = \frac{A_{ext}}{v} \ °\text{C} \quad (12)$$

For the wall enclosing structure with the location of the themal-insulation layer on the outside:

$$A_{int}^1 = \frac{A_{ext}}{v_{ext.insul.}} = \frac{20.2}{166} = 0.12 \ °\text{C} \ll A_{int}^{req} = 1.77 \ °\text{C} \quad (13)$$

For the wall enclosing structure with the location of the themal-insulation layer from the inside:

$$A_{int}^2 = \frac{A_{ext}}{v_{int.insul.}} = \frac{20.2}{95} = 0.23 \ °\text{C} \ll A_{int}^{req} = 1.77 \ °\text{C} \quad (14)$$

4. RESULTS AND DISCUSSIONS

The results of calculations to check the thermal stability of walls with different locations of the thermal-insulation layer for the climatic parameters of Baku based on the methodology and their analysis allow us to draw the following conclusions:

- concerning Formula (6) the amplitude of temperature fluctuations on the inner surface of the wall should be at least 12 times less than on the outer one;
- thermal stability of the multilayer outer wall structure of the building depends on the order of the structural layers, when the less dense structural layer is located on the outside, the best thermal regime of the wall enclosing structure is provided;
- according to Formulas (9), (10) the calculated value of attenuation of temperature fluctuations for both options exceeds the required values:

$v^{req} \approx 12 \ll v_{ext.insul.} = 166$

$v^{req} \approx 12 \ll v_{int.insul.} = 95$

- it corresponds to the normative indicators, that is, a wall designed for winter operating conditions with high thermal resistance to heat transfer turns out to be more thermal stability in the warm season;
- the attenuation value of temperature fluctuations in a two-layer structure increases when the thermal-insulation layer is located outside:

$v_{ext.insul.} > v_{int.insul.}$

It means that this structure has more thermal stability;

- the fulfillment of $A_{int}^1 < A_{int}^2, 0.12 < 0.23$ by Formulas (13) and (14) and Figure 1 show that when a layer with a lower density is located on the outer side of the main masonry, temperature fluctuations on the inner surface of the wall are almost 2 times less, i.e., the best comfortable conditions of the internal microclimate are provided i.e., the appropriate mutual arrangement of the layers in the wall can increase its thermal stability in relation to the effects of solar radiation. As thermal insulation materials, it is preferable to use slag or rock-mineral wool [22].

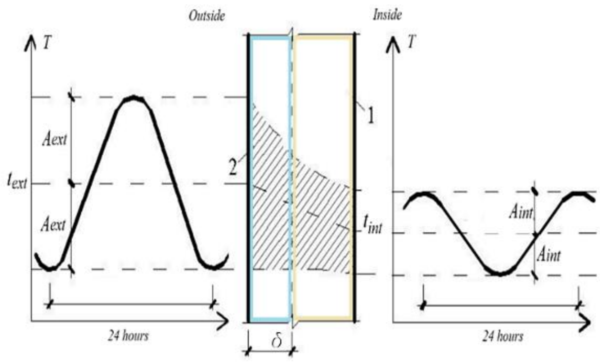

Figure 1. Attenuation of temperature fluctuations in the summer period in the vertical cross-section of the outer wall, with the location of the thermal-insulation layer on its outer surface, where δ is a layer with a twofold decrease in temperature fluctuations

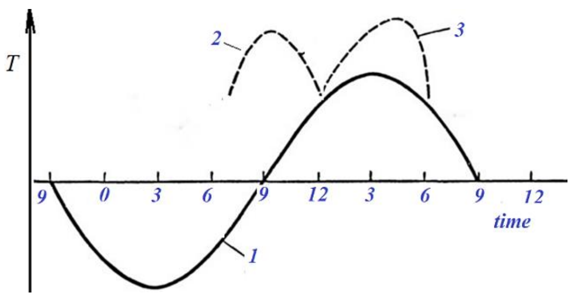

Figure 2. Temperature changes of heat fluxes under the influence of solar radiation for Baku: 1- outdoor air temperature, 2,3- surface temperature of the western and southern facades

Figures 2 and 3 show graphs of temperature changes at the surface of the outer wall of the western, southern and eastern facades, built according to the results of experimental measurements carried out for one of the educational buildings of the Azerbaijan Architecture and Construction University, which are fully correlated with the calculated data.

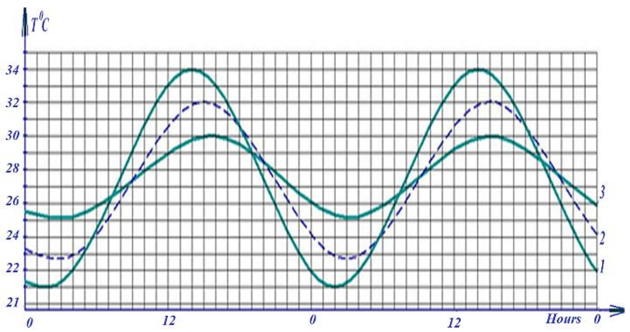

Figure 3. Temperature fluctuations in July for Baku: 1-outside air; 2 - indoor air; 3- at the inner surface of the wall enclosing structure of the eastern façade

The results obtained in this article are fully consistent with the next ones [23, 24, 25], which there are referenced in the proposed article, which confirms their validity. And also the results obtained here can be used for a multidisciplinary energy audit of buildings and their certification.

5. CONCLUSIONS

In this article, the thermal stability of the wall enclosing structure is investigated to determine the sequence of the optimal arrangement of its structural layers. At present, there are very few experimental studies of enclosing structures in summer conditions of their operation in terms of their influence on the thermal regime of premises when considering the interdependent energy system "building outer structures- building microclimate" [26]. Increasing the thermal stability of the wall enclosing structures by the optimal arrangement of structural layers with different thermal inertia in order to reduce the amplitude of temperature fluctuations of the inner surface of the building outer structures is a necessary condition for minimizing the energy consumption of air conditioning systems and the building in the whole [27].

From this point of view, in the hot climatic conditions of Baku, it is necessary to take into account the heat absorption and thermal stability of external structures and make appropriate calculations. Local specialists need to continue research in this direction because the correct design solutions for the building external structures make it possible to save energy for air conditioning and ventilation, and create comfortable conditions for human well-being

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