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Determination of Rational Values of the Parameters of an Unventilated Trombe Wall Using the Method of Multicriteria Optimization for the Climatic Conditions of Uzbekistan

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Abstract: The energy demands of the construction sector are expected to multiply over the next decade, driven by population growth, rising incomes, accelerating urbanization and changes in consumption patterns. This process is also dramatically affected by the depletion of fossil resources and high specific energy consumption for heating buildings. Under these conditions, it is necessary to develop comprehensive energy efficiency measures in these areas to meet the energy demands of residential, commercial and administrative buildings. In this work, using the methods of degree-day, multicriteria optimization and regression analysis, the optimal combinations of factors for an unventilated Trombe wall are determined: the orientation of the building, the thermal support of the translucent enclosure of the unventilated Trombe wall and the ratio of the surface of the unventilated Trombe wall to the surface of the building facade. The calculations were performed for three levels of thermal protection for buildings in the climatic conditions of the city of Tashkent (Uzbekistan). A typical one-storey three-room house was chosen as the object. As the calculation results show, within the considered range of values, the relative dominances of the factors are as follows: orientation - 5.37%; thermal support of translucent barriers - 72.95%; and area ratio - 21.68%. Using the optimal values, the specific energy consumption of buildings for heating can be reduced from an average of 12.9-14.8% to 52.6-65.3%. Additionally, the CO_2 emissions are reduced from 5621.8 kg to 12435.5 kg per year. The discounted payback period, depending on the investment, ranges from 18.7 to 40.9 years. Regression equations are proposed for three levels of thermal protection of the considered object, making it possible to determine the specific energy consumption for heating.

Keywords: Trombe wall, energy evaluation, economic evaluation, environmental evaluation, heating load

1. Introduction

In 2018, the share of energy consumption in buildings in Uzbekistan was approximately 40% of the total energy balance of the country; this figure worldwide is 20% on average ("International Energy Agency Statistics," n.d.). It is expected that by 2050, the area of the housing stock in Uzbekistan may increase to 949-987 million m2. This in turn would lead to an increase in energy consumption. Approximately 70% of the energy consumed in residential buildings is spent on heating(Third National Communication of the Republic of Uzbekistan on the UN Framework Convention on Climate Change, 2016).

In Uzbekistan, at the state level, attention has been given to addressing these issues. Since 2020, all construction sites must use energy-saving technologies (Decree of the President of the Republic of Uzbekistan "On additional

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measures to improve state regulation in the construction sector," 2018), and a number of building codes and regulations have been changed(Construction norms and rules " KMK 2.01.18-2018 "Standards of energy consumption for heating, ventilation and air conditioning of buildings and structures," 2018, Construction norms and rules "KMK 2.01.04-2018" Construction heat engineering", 2018, Construction norms and rules "KMK 2.03.10-2019 - "Roofs," 2019, Construction norms and rules "KMK 2.03.13-19 - "Floors," 2019, Construction norms and rules "ShNK 2.04.16-2018 "Solar equipment for hot water supply," 2018).

On the other hand, Uzbekistan has a very large potential for the use of renewable energy sources, which are estimated at approximately 51 billion toe, and 97% of the potential of renewable energy sources falls on solar energy(Third National Communication of the Republic of Uzbekistan on the UN Framework Convention on Climate Change, 2016). Because buildings constructed in Uzbekistan before 2018 are based on building codes adopted in 1997, their annual estimated energy consumption is 218.9 kWh/m2 for the first level of thermal protection, 151.8 kW·h/m2 for the second level and 123.4 kW·h/m2 for the third level(Analysis of Results of Energy Monitoring over the Heating Season of 2014-2015 after Application of Energy-Efficient Measures and Renewable Energy in a Pilot Four-Room Rural House, 2015). In the Republic, 40% of the generated electricity is used for heating and lighting, and this value is 400 kW·h/m2 per year, which is 2.35 times higher than that in developed countries("Energy audit of the rural housing in Uzbekistan," 2020). Energy consumption can be reduced at the design stage of a building by taking into account the full load for heating and cooling (Pacheco et al., 2012) by optimizing the geometric and thermal parameters of the building envelope(Halimov et al., 2020) using passive solar heating systems (Avezova et al., 2021). Using passive solar heating systems can reduce the cooling and heating loads by up to 54% and 87%, respectively (Harkouss et al., 2018) .

As one option for a partial solution to this problem, passive solar heating systems are used through the Trombe wall(Duffie and Beckman, 2013) . The Trombe wall was first developed by Edward Morse in the 19th century in the USA (MORSE, 1881), and then in the second half of the last century, it was improved by the French engineer Felix Trombe and the architect Jacques Michel (Trombe and Jacques, 1972) . A Trombe wall consists of translucent fences, ventilated or nonventilated (unventilated) air space, and a wall made of various materials (brickwork, concrete, etc.) with a high heat capacity and blackened from the outer surface. A Trombe wall in the Northern Hemisphere is set to be oriented to the south and that in the Southern Hemisphere to the north to receive maximum solar radiation. The principle of operation of a Trombe wall is as follows: the sun's rays falling on the front surface of the translucent fence are partially reflected, partially absorbed and partially transmitted. The transmitted sun rays fall on the surface of the wall and are absorbed. As a result, the wall temperature rises, and heat is transferred to the indoor air.

In different regions, Trombe walls are called by different names, for example, a Trombe-Michel wall, a solar wall, a heat storage wall, an accumulating wall collector or a simple storage wall (Duffie and Beckman, 2013). To date, various modifications of the Trombe wall have been proposed (Saadatian et al., 2012; Wang et al., 2020): the classic Trombe wall, Trombe composite wall, Trombe wall made of phase change material, Trombe photovoltaic wall, Trombe water wall, Trombe wall with a fluidized bed, Trombe wall for air purification, electrochromic Trombe wall, and Trombe wall with translucent insulation. Analysis shows that in recent years, the number of scientific articles on Trombe wall systems published in various databases (Science Direct, Springer Link, Taylor & Francis Online, SAGE Journals, Wiley Online Library and MDPI) has increased; for example, in 2019, there were 10 times more studies published than in 2001 (Duffie and Beckman, 2013). On the basis of energy and exergy analysis, the influences of various factors on the thermal efficiency of the Trombe wall has been studied. An increase in a certain parameter such as the thickness of the air channel and the intensity of solar radiation have a beneficial effect on the operation of the systems. Additionally, a decrease in the emissivity of a glass coating is an effective method for increasing the energy and exergy efficiencies (Duan et al., 2016).

An analytical and experimental analysis of the thermal characteristics of the Trombe wall was carried out under various operating conditions for the ventilation openings and the operation of the occlusion device. Experimental analysis identified the temperature fluctuations, heat flux, heat retention and air velocity at the vents. Experimental results showed that for similar outdoor conditions, an increase in the maximum temperature of the outer surface of a massive wall of approximately 75% was achieved when the external occlusion device was removed. At the same time, an increase in the internal temperature of 61% was obtained. In the absence of an occlusive device, the temperatures of the outer surface of the massive wall exceeded 60 °C, and when it was installed, they decreased to 30 °C or below (Briga Sá et al., 2018). Using the life cycle cost (LCC) method, the optimal ratio of the Trombe wall area from a thermal and economic point of view is 37%. This optimal ratio lowered the LCC by 2.4%. In addition, this corresponds to an annual reduction of approximately 445 kg of CO_2 emitted(Jaber and Ajib, 2011) . The use of a thermal rib on the Trombe wall increases the internal temperature of the room and decreases the temperature of the outer surface of the Trombe wall. This leads to a significant increase in the thermal efficiency of this solar system compared to that of a similar environment without thermal fins (Abbassi and Dehmani, 2015).

It was found by numerical simulation that a heat-storage wall 0.08 m thick, made of hydrated $CaCl_2 \cdot 6H_2O$ salt, maintained a temperature close to the temperature of comfort, with the smaller temperature fluctuations in the room than in those with a 0.02 m thick concrete wall and a 0.05 m thick paraffin wall. The room temperature was found to range from 18 to 22 °C for the hydrated salt wall compared to 15-25 °C for the other two types. Accordingly, it is recommended to use such materials as heat storage for passive solar heating in modern homes (Khalifa and Abbas, 2009). There are studies of passive solar heating systems dedicated to the climatic conditions of Uzbekistan and Turkmenistan. A mathematical model of the thermal regime of a room with passive solar heating systems with three-layer ventilated translucent barriers has been developed(Samiev, 2009) . The influence of indicators of the heat resistance and thermal efficiency of a residential building with a Trombe wall combined with heat pipes (Toiliev, K, Ashirbaev, 1987; Toiliev, K Annaev, 1987) has been investigated. The fuel replacement coefficients in passive solar heating systems with a heat-accumulating wall and with three-layer translucent barriers have been determined(Avezova and Sadykov, 2012; Samiev, 2008) . The analysis of scientific research shows that there are very few studies on optimizing the parameters of the classic version of the Trombe wall for the climatic conditions of Uzbekistan. This paper considers the problem of the influence of the orientation of the southern wall of a building, the ratio of the surface of the Trombe wall to the surface of the facade of the building, the thermal support of the translucent fence and air flow through the Trombe wall on a number of parameters such as the specific heat consumption of the building, reduction of CO2 emissions to the atmosphere, and simple and discounted payback period.

2. Methodology

The methods described in (Avezova et al., 2021; ISO 13790:2008 (E), Energy Performance of Buildings–Calculation of Energy Use for Space Heating and Cooling, 2008; Kreider et al., 2010; Malyavina, 2007; Zhang and Shu, 2019) were used to determine the change in the thermal properties of a selected object when a Trombe wall is installed.

2.1 Energy Evaluation

The demand for thermal energy for the needs of heating the building during the heating period, taking into account the heating of the ventilation rate of air Q_h^y, is found by the formula (Kreider et al., 2010; Malyavina, 2007) :

$$Q_h^y = [Q_h - (\Delta Q + Q_{gain})\nu\xi]\beta_h \tag{1}$$

where Q_h- total heat loss of the building for the heating period, kW · h; ΔQ- reduction of heat loss of the building due to the use of the Trombe wall, kW · h; Q_{gain}- heat gain from the unventilated Trombe wall, kW · h; ν- coefficient of the heat gain reduction due to the thermal inertia of the enclosing structures; ξ - coefficient of the efficiency of the automatic regulation of the heat supply to the heating systems; and β_h - coefficient accounting for the additional heat consumption of the heating system.

The total heat loss of the building during the heating period is (Kreider et al., 2010)

$$Q_h = U_{tot} HDD \cdot A_{e.sum} \tag{2}$$

where U_{tot}- total heat transfer coefficient of the building, W/(m2 · °C); HDD- degree-day of the heating period, degree · day; and $A_{e.sum}$- total area of the external enclosing structures of the heated part of the building, m2. The total heat transfer coefficient of a building is determined by the sum of the transmission (U_{tr}) and infiltration (U_{inf}) heat transfer coefficients:

$$U_{tot} = U_{tr} + U_{inf}. \tag{3}$$

The heat transfer coefficient of a building is determined by the following equation:

$$U_{tr} = (U_{wall}A_{wall} + U_cA_c + U_fA_f + U_wA_w + U_{ed}A_{ed})/A_{e.sum} \tag{4}$$

where U_{wall}, U_c, U_f, U_w, and U_{ed} - heat transfer coefficients of the walls, ceilings, floors, windows, entrance doors to the building, respectively, W/(m2 · °C); A_{wall}, A_c, A_f, A_w, and A_{ed}- the areas of the outer surfaces of the walls, ceilings, floors, windows, entrance doors to the building, respectively, m2.

$$U_{inf} = c\rho n_a V \tag{5}$$

where c - specific heat capacity of the indoor air, J/(kg ° C); ρ- indoor air density, kg/m3; V- heated building volume, m3; and n_a- air exchange rate, 1/s;

Total heat loss of the building with the Trombe wall during the heating period

$$Q_{h.sw} = U_{tot.sw} HDD \cdot A_{e.sum} \tag{6}$$

The total heat transfer coefficient and the heat transfer coefficient of a building with a Trombe wall are determined by the following equation:

$$U_{tot.sw} = U_{tr.sw} + U_{inf} \tag{7}$$

$$U_{tr.sw} = \left(U_{wall}A_{wall} + U_cA_c + U_fA_f + U_wA_w + U_{ed}A_{ed} + U_{sw}A_{sw}\right)/A_{e.sum} \tag{8}$$

where A_{sw} - Trombe wall surface area, m2; U_{sw}- heat transfer coefficient through the Trombe wall, W/(m2 · ° C). The reduction in heat losses ΔQ due only to the use of the Trombe wall in the construction of buildings is equal to

$$\Delta Q = Q_h - Q_{h.sw}. \tag{9}$$

The heat gain from the unventilated Trombe wall during the heating period is [30,31]

$$Q_{gain} = I_w A_{SW} \alpha_{sol} \tau_w F_S F_F F_W \cdot U_o(R_e + R_1) \tag{10}$$

where I_w - total solar radiation during the heating calculation period, kW·h/m2; α_{sol} - coefficient of the radiation absorption of the outer surface of a massive wall; F_F - frame reduction ratio; F_S - shading reduction factor; F_W - correction factor for nonscattering glasses; τ_w - total solar radiation transmittance of a translucent fence; R_e - thermal resistance of the translucent fence between the air layer and the external environment, m2·K/W; R_i - thermal resistance of a Trombe wall between the air layer and the internal air, m2·K/W; R_1 - thermal resistance of the air layer, m2·K/W; U_e - heat transfer coefficient of a translucent fence, W/(m2·K).

2.2 Economic Evaluation

The annual capital savings S is determined by the following equation:

$$S = \frac{(Q_h - Q_h^y)P_d}{g_u \eta_u} \tag{11}$$

where P_d- fuel cost, USD; g_u- specific calorific value of fuel, kW·h/kg; and η_u- heat source efficiency.

The simple payback period is calculated as

$$SPP = \frac{C_{TW}}{S} \tag{12}$$

The discounted payback period DPP is determined by the following equation(Halimov et al., 2020) :

$$DPP = \frac{ln\left[1 - \frac{r \cdot C_{TW}}{S}\right]}{ln(1+r)}. \tag{13}$$

where C_{TW} - initial investment (Trombe wall value), USD.

$$r = \frac{i-g}{1+g}, \quad if \quad i > g \tag{14}$$

$$r = \frac{g-i}{1+i}, \quad if \quad i < g \tag{15}$$

where i - inflation rate a d g - base rate.
The discount factor is determined as follows (Zhang and Shu, 2019)

if $i \neq r$

$$DF = \frac{(1+r)^{LC} - 1}{r(1 + r^{LC})} \tag{16}$$

if $i = g$

$$DF = \frac{LC}{1+i}. \tag{17}$$

where LC- period of operation, year.

2.3 Environmental Evaluation

The reduction in carbon dioxide emissions per year can be calculated using the following formula(Zhang and Shu, 2019)

$$M_{CO_2} = \frac{Q_h - Q_h^y}{g_u \eta_u} F_{CO_2} \frac{44}{12} \qquad (18)$$

where M_{CO_2} - the amount of carbon dioxide reduction when using a Trombe wall instead of a regular wall per year and F_{CO_2} - carbon emission factor of various energy sources.

3. Descriptions of The Investigated Object

To carry out the study, a typical three-room residential building was taken as the study object (Fig. 1). The geometric indicators of a 3-room residential building are shown in Table 1. An unventilated Trombe wall is installed on an outer wall of the facility(Avezova et al., 2021) . As the translucent part of the Trombe wall, various double-glazed windows are used, and their characteristics are given in Table. 2 (“http://okna-akfa.uz/,” 2021, Interstate Standard, Glued glass units for construction purposes, Technical conditions [Mejgosudarstvenniy Standart, Steklopaketi kleenie stroitelnogo naznacheniya, Texnicheskie usloviya], (in Russian), 2000).

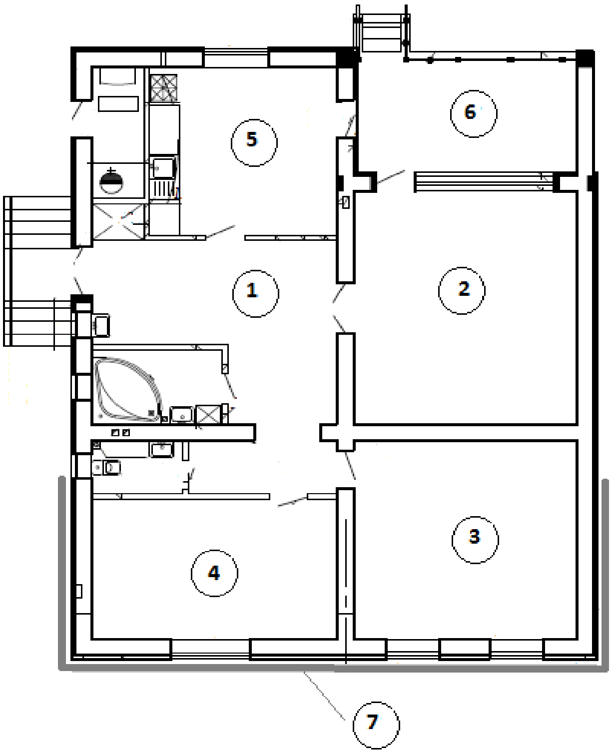

Fig. 1 - Typical three-room residential building: 1-entrance hall; 2-common room; 3-master bedroom; 4-bedroom; 5-kitchen; 6-enclosed porch; 7-Trombe wall

4. Calculation Method

To determine rational values for the parameters of the Trombe wall, a thirteenth-level and four-factor scheme was selected, as shown in Table 3. The calculations were performed using the full factorial experiment method (Montgomery, 2013) . The calculations used the values given in Table 4(Construction norms and rules “ KMK 2.01.01-94 “Climatic and physical-geological data for design,” 1994, Construction norms and rules “ShNQ 2.08.01-2019 “Residential buildings,” 2019, “https://cbu.uz/ru/press_center/releases/549560/,” 2021, ISO 13790:2008 (E), Energy Performance of Buildings–Calculation of Energy Use for Space Heating and Cooling, 2008) . The cost of coal for the billing period is 674 100 soums/ton (October 11-15, 2021, the US dollar exchange rate was 10 700.03 soums) (“https://bank.uz/currency/archive/15-10-2021,” 2021, “https://uzex.uz/uz-Cyrl/pages/weekly-quotes,” 2021) .

Table 1 - Geometric dimensions of a 3-room residential building

Index	Designation and units	Estimated (design) value
Living space	A_c, m^2	126.3
Heated volume	V_h, m^3	381.4

The total area of the external enclosing structures of the building	A_c^{sum}, m^2	417.08
including:		
facades	A_{fas}, m^2	140
windows and balcony doors	A_w, m^2	19
entrance doors	A_d, m^2	2.54
attic	A_{at}	199.28

Table 2 - Characteristics of double-glazed windows

Glazing options	Total solar energy transmittance	Reduced resistance to heat transfer, m2·K/W	Cost, US dollars*
4M1-8-4M1	0.78	0.28	60.50
4M1-16-4M1	0.78	0.32	61.75
4M1- Ar16-4M1	0.78	0.34	62.40
4M1-8-К4	0.76	0.47	66.60
4M1-10-К4	0.76	0.49	67.20
4M1-16-К4	0.76	0.53	68.44
4M1-Ar10-К4	0.76	0.55	69.08
4M1-Ar16-К4	0.76	0.59	70.40
4M1-Ar10-И4	0.51	0.60	70.70
4M1-Ar12-И4	0.51	0.63	71.60
4M1-Ar16-И4	0.51	0.66	72.60
4M1-Ar12-4M1-Ar12-К4	0.72	0.68	73.22
4M1-Ar16-4M1-Ar16-К4	0.72	0.72	74.50

5. Model Validation

The validation of the developed models was carried out by comparing the results given in (Ruiz-Pardo et al., 2010; Tas`demirog`lu and Tinaut, 1985) . As the results in Table 5 show, the root mean square error is 169041.415 J, the root mean square error in percentage form is 8.876%, and the square of the correlation coefficient is $R^2 = 0.765$.

The results presented in this work for determining the specific energy consumption of a building for heating were compared with the data presented in(Analysis of Results of Energy Monitoring over the Heating Season of 2014-2015 after Application of Energy-Efficient Measures and Renewable Energy in a Pilot Four-Room Rural House, 2015) . The comparison shows that the relative error between the results given in (Analysis of Results of Energy Monitoring over the Heating Season of 2014-2015 after Application of Energy-Efficient Measures and Renewable Energy in a Pilot Four-Room Rural House, 2015) and the results of this study is 0.4–1.5%.

Table 3 - Test factors and associated levels

Levels	Factors		
	Building orientation BO,°	Area ratio AR	Reduced resistance to heat transfer $R_{ee.sum}$, m^2·K/W
1.	-90	0	0.28
2.	-75	0.083	0.32

3.	-60	0.166	0.34
4.	-45	0.249	0.47
5.	-30	0.332	0.49
6.	-15	0.415	0.53
7.	0	0.498	0.55
8.	15	0.581	0.59
9.	30	0.664	0.60
10.	45	0.747	0.63
11.	60	0.83	0.66
12.	75	0.913	0.68
13.	90	0.996	0.72

Table 4 - Parameter values used in the calculation

Parameter	Values
g_u	25.1 MJ/kg
HDD	2571 degree-day (18°C)
n_a	0.5 hr-1
F_{CO_2}	0.726
η_u	0.47
r	14%
i	10.7%
LC	30 year
ν	0.85
ξ	0.85
β_h	1

Table 5 - Comparison of analytical, experimental and calculated results

Month (heating period)	The total incident solar radiation on the front surface of the southern wall, MJ/month		Total heat gains, MJ/month		
	E	A	Э	A	C
January	4.649	4.719	1.444	1.682	1.783
February	4.967	5.216	1.360	1.700	1.905
March	5.051	5.309	1.202	1.379	1.637
November	6.100	6.265	2.073	2.411	2.34
December	4.842	5.155	1.578	1.995	1.857

E – experiment; A – analytical result; C – calculation results using Formula (11)

6. Results and Discussion

For the calculation, a computer program was developed in the language Python to determine the specific characteristics of the considered typical three-room residential building. Using a full factorial experiment, rational combinations of the parameters used were determined. Pareto fronts were determined for three levels of thermal protection for the climatic conditions of the city of Tashkent (Fig. 2 and Tables 6-8).

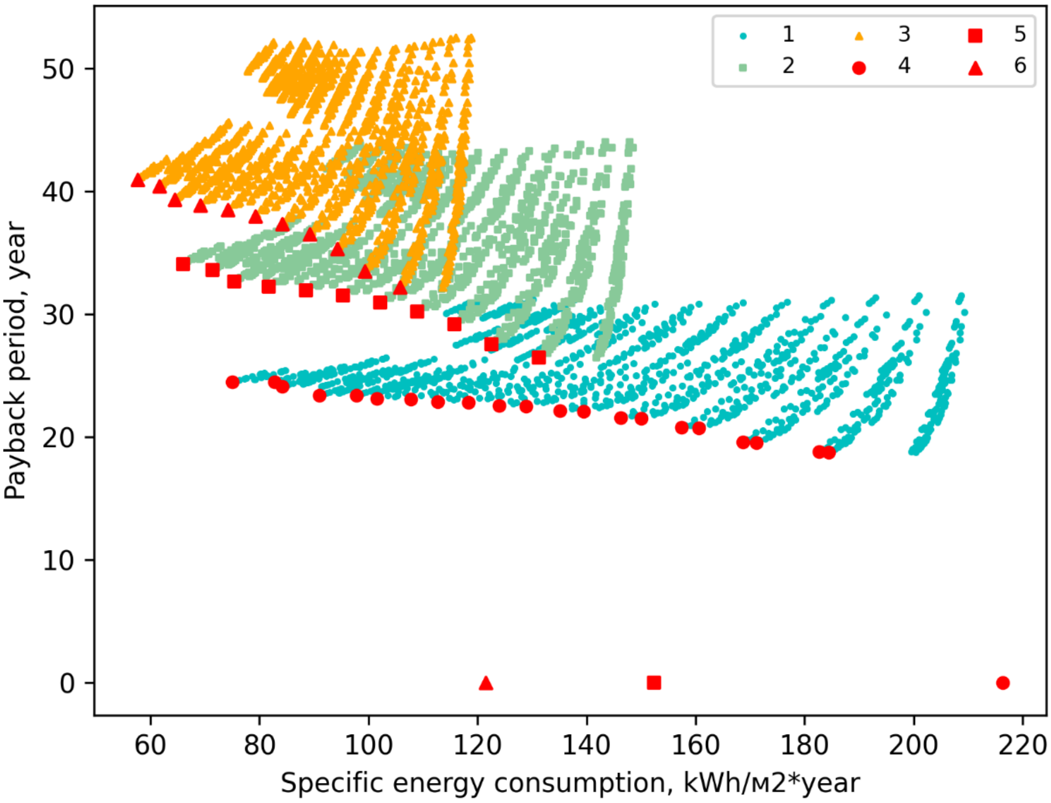

Fig. 2 - The results of the calculations to determine the boundary of the Pareto front: 1, 2, 3 - data belonging to the first, second and third levels of thermal protection; 4, 5 and 6 - data belonging to the Pareto front for the first, second and third levels of thermal protection

For the Pareto front of the first level of thermal protection of buildings, there are only 22 points (Table 6). As seen from Table 6, the first line contains data for a building without a Trombe wall, and the specific energy consumption is 216.4 kWh/m2. The values highlighted in red in Table 6 give a rational combination of parameters. The specific energy consumption is 184.447 kWh/m2, which is 14.8% lower than the baseline value.

Table 7 shows the calculations for level 2 thermal protection, at which the specific energy consumption is 131.31 kWh/m2, with a percentage reduction in energy consumption of 13.8%.

Table 8 shows the calculations for level 3 thermal protection, at which the specific energy consumption is 105.778 kWh/m2, and the percentage value of the reduction in energy consumption is 13%.

An analysis of Tables 6-8 shows that it is practically possible to reduce the specific energy consumption from 81.2% to 84.6%.

Based on the results of the calculations performed, regression equations for three levels of thermal protection are obtained (Table 9).

Table 6 - Results of the best combination for the first level of thermal protection

Calculation run	South wall orientation, °	Area ratio	Reduced resistance of the translucent part of the Trombe wall, (m2·K/W)	Investment, US dollars	Specific energy consumption, kW·hr/(m2·year)	Simple payback period, year	Discounted payback period, year	Reducing CO2 emissions, kg/year
1	0	0	0	0	216.376	0	0	0
1048	**0**	**0.166**	**0.59**	**1635.672**	**184.447**	**24.602**	**18.726**	**2809.308**
1053	0	0.166	0.72	1730.931	182.71	24.691	18.779	2962.135
1061	0	0.249	0.59	2453.508	171.117	26.033	19.554	3982.194
1066	0	0.249	0.72	2596.397	168.635	26.117	19.602	4200.571
1074	0	0.332	0.59	3271.344	160.555	28.143	20.739	4911.567
1079	0	0.332	0.72	3461.862	157.457	28.217	20.779	5184.082
1087	0	0.415	0.59	4089.179	149.992	29.582	21.524	5840.939
1092	0	0.415	0.72	4327.328	146.28	29.646	21.559	6167.592
1100	0	0.498	0.59	4907.015	139.43	30.625	22.082	6770.312
1105	0	0.498	0.72	5192.793	135.102	30.683	22.112	7151.103
1113	0	0.581	0.59	5724.851	128.867	31.417	22.499	7699.685
1118	0	0.581	0.72	6058.259	123.924	31.469	22.526	8134.614
1126	0	0.664	0.59	6542.687	118.305	32.038	22.823	8629.057
1131	0	0.664	0.72	6923.724	112.746	32.085	22.848	9118.124
1139	0	0.747	0.59	7360.523	107.742	32.538	23.082	9558.43
1144	0	0.747	0.72	7789.19	101.569	32.581	23.104	10101.64
1321	15	0.83	0.59	8178.359	97.81	33.125	23.383	10432.36
1326	15	0.83	0.72	8654.655	91.05	33.163	23.402	11027.1
1339	15	0.913	0.72	9520.121	84.18	34.583	24.119	11631.65
2192	90	0.996	0.59	9814.031	82.749	35.27	24.461	11757.5
2197	90	0.996	0.72	10385.59	75.044	35.289	24.47	12435.51

Table 7 - Results of the best combination for the second level of thermal protection

Calculation run	South wall orientation, °	Area ratio	Reduced resistance of the translucent part of the Trombe wall, (m2·K/W)	Investment, US dollars	Specific energy consumption, kW·hr/(m2·year)	Simple payback period, year	Discounted payback period, year	Reducing CO2 emissions, kg/year
1	0	0	0	0	152.399	0	0	0
1053	**0**	**0.166**	**0.72**	**1730.931**	**131.307**	**39.409**	**26.449**	**1855.868**
1066	0	0.249	0.72	2596.397	122.586	41.823	27.557	2623.158
1079	0	0.332	0.72	3461.862	115.784	45.404	29.138	3221.664
1092	0	0.415	0.72	4327.328	108.982	47.864	30.182	3820.17
1105	0	0.498	0.72	5192.793	102.18	49.657	30.924	4418.677
1118	0	0.581	0.72	6058.259	95.378	51.022	31.478	5017.183
1131	0	0.664	0.72	6923.724	88.576	52.096	31.907	5615.689
1144	0	0.747	0.72	7789.19	81.773	52.963	32.25	6214.195
1326	15	0.83	0.72	8654.655	75.408	53.983	32.649	6774.269
1339	15	0.913	0.72	9520.121	71.457	56.483	33.608	7121.87
2197	90	0.996	0.72	10385.59	66.007	57.73	34.076	7601.427

Table 8 - Results of the best combination for the third level of thermal protection

Calculation run	South wall orientation, °	Area ratio	Reduced resistance of the translucent part of the Trombe wall, (m2·K/W)	Investment, US dollars	Specific energy consumption, kW·hr/(m2·year)	Simple payback period, year	Discounted payback period, year	Reducing CO2 emissions, kg/year
1	0	0	0	0	121.519	0	0	0
1053	**0**	**0.166**	**0.72**	**1730.931**	**105.778**	**52.805**	**32.188**	**1385.069**
1066	0	0.249	0.72	2596.397	99.296	56.106	33.465	1955.378
1079	0	0.332	0.72	3461.862	94.274	61.018	35.281	2397.27
1092	0	0.415	0.72	4327.328	89.252	64.402	36.478	2839.162
1105	0	0.498	0.72	5192.793	84.23	66.874	37.327	3281.053
1118	0	0.581	0.72	6058.259	79.207	68.759	37.96	3722.945
1131	0	0.664	0.72	6923.724	74.185	70.244	38.45	4164.837
1144	0	0.747	0.72	7789.19	69.163	71.444	38.842	4606.728
1326	15	0.83	0.72	8654.655	64.473	72.856	39.297	5019.379
1339	15	0.913	0.72	9520.121	61.621	76.325	40.389	5270.372
2197	90	0.996	0.72	10385.59	57.627	78.06	40.922	5621.762

Table 9 - Regression Equations for Determining the Specific Energy Consumption

Thermal protection level	Regression Equations	R^2
I	$Q_I = 232.55 - 6.28 \cdot 10^{-3} \cdot BO - 112.68 \cdot AR - 38.35 \cdot R_{ee.sum}$	0.9307
II	$Q_{II} = 165.22 - 3.98 \cdot 10^{-3} \cdot BO - 65.85 \cdot AR - 29.19 \cdot R_{ee.sum}$	0.9155
III	$Q_{III} = 131.91 - 2.98 \cdot 10^{-3} \cdot BO - 47.75 \cdot AR - 23.35 \cdot R_{ee.sum}$	0.9091

7. Conclusions

In this study, for the first time, the parameters of the classical type of Trombe wall for the climatic conditions of Uzbekistan were investigated, and the optimal values of these factors were determined by multiparametric optimization. Four factors were taken as optimization parameters: the orientation of the southern wall of the building, the ratio of the Trombe wall surface to the total area of the facade surfaces, the reduced resistance to heat transfer of the translucent part of the Trombe wall, and the air flow through the Trombe wall. As the calculation results show, within the considered range of values, the relative dominances of the factors are as follows: orientation - 5.37%; area ratio - 72.95%; and reduced heat transfer resistance - 21.68%. Using the optimal values, the specific energy consumption of buildings for heating can be reduced on average by 12.9-14.8% to 52.6-65.3%. Additionally, the CO2 emissions are reduced from 5621.8 kg to 12435.5 kg per year when using coal and from 641.2 kg to 33055.9 kg per year when using electricity. The discounted payback period, depending on the investment, ranges from 18.7 to 40.9 years. Regression equations are proposed for three levels of thermal protection of the considered object, making it possible to determine the specific energy consumption for heating.

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