Comparative technical and economic analysis of the Trombe wall use in the heat supply system at different climatic conditions

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Abstract. This article is devoted to the problems of using any solar heating systems, the Trombe wall in particular, in modern heating systems and various climatic conditions. The main problem in solar heating systems is that the climatic conditions can be very different in one latitude, while the appropriateness of the Trombe wall using in heat supply systems will depend on the ratio between the incident solar energy and the room heat load. The main goal of this work is to determine the most effective climate divide for the Trombe wall using. This paper presents an algorithm for the technical and economic analysis of the Trombe wall effectiveness. The calculation results showed that the most appropriate Trombe wall use in the heat supply system is observed in the range of latitudes from 55° to 40° N. At the same time, the payback period of the Trombe wall is in the range from 3.5 to 10 years.

1. Introduction

Today, solar passive heating systems are widely used in low-rise construction. The most widely known solar passive heating system is the Trombe wall. Its principle is based on the solar radiation accumulation in a massive wall and the accumulated thermal energy transfer to the room. It is transferred through radiant and convective heat-mass exchange during the day [1]. This concept was developed by Edward Morse in 1881 [2]. However, this concept gained worldwide fame in the 1970s, when Felix Trombe and Jacques Michel patented their classic Trombe wall [3]. The classic Trombe wall includes [4]: glazing from single or double glass; a massive wall of brick or concrete with a thickness of 20 to 40 cm, which should be painted black; several ventilation ducts on the lower and upper tiers of the massive wall.

2. A brief literature review

Figure 1 shows the scheme of the Trombe wall in winter. A massive wall is heated by solar radiation during the day. At this point, to accelerate and maximize heating of the massive wall, warm air is supplied from the room through the lower ventilation channel to the upper (Fig. 1). At night, the lower ventilation duct is closed, and warm air is supplied into the room through the upper ventilation duct, which has been heated by a massive wall. In the summer, only the lower ventilation duct remains open in the massive wall. According to [5], the opening of ventilation ducts must be carried out 2 hours after sunrise and closing 1 hour before sunset.
According to [5-8], the Trombe wall allows reducing the consumption of external energy resources from 20 to 40\%, depending on location and climatic conditions. This means that each latitude requires its individual Trombe wall design. For example, if the outdoor temperature does not drop to $-10 \ldots -12^\circ\text{C}$ in a fixed place, then it is enough to use a single glass pane for glazing. Otherwise, to reduce heat loss through the glazing, it is necessary to use a Low-e double-glazed window [9]. The choice of glazing can have a significant impact on the Trombe wall thermal efficiency. Besides, it can have from 5 to 7 elements, the choice of which can have a positive or negative effect on thermal efficiency. Helenice M. Sacht, et al. [10] dealt with similar problems, where the effectiveness of the new Trombe wall design was studied in various latitudes of Portugal. The study took 3 cities of Portugal, which were located in latitudes between 37° and 41° N. According to the results of the study [10, 11], the reduction in energy consumption ranged from 45\% to 64\%, depending on the adopted structural elements and decisions.

3. Statement of the research problem

Because of various climatic factors, ranging from the seas and oceans cities remoteness and their warm currents, proximity to mountainous terrain and the varying amount of incident solar radiation due to the inclination of the earth's axis, climatic conditions at one latitude can vary greatly, which greatly affects the number of decrease in external energy consumption due to the solar energy accumulation. For example, cities such as Kyiv and Haihe are located at 50° N, but the average air temperature during the winter period for the first city is $-5.4^\circ\text{C}$, and for the second $-23^\circ\text{C}$. At the same time, during the winter period, about 83 $kW$ falls by 1 $m^2$ for the first city and about 140 $kW$ for the second. It should also take into account the cash costs of external energy. As a result, the economic benefits of the Trombe wall will be different for the same latitude in different settlements. Based on what, the question arises of determining and establishing climatic boundaries for the Trombe wall, in which you can get the greatest economic benefit in a modern heating system.

It is also clear that there are geographical boundaries for the application of systems using solar energy for heating. Below a certain degree of latitude (approximately less than 30°) due to the general increase in air temperature, heating systems are not used at all and there is no need to spend additional funds.

At high latitudes, especially closer to the Arctic Circle and the South Pole, daylight hours, therefore, the incident light energy is greatly reduced. Beyond the Arctic Circle, a polar night generally sets in with no incident solar energy. In these conditions, the use of heating systems using solar energy is also ineffective.

In this paper, the establishment of cost-effective boundaries for the solar heating systems use is considered.

Thus, the main goal of this work is a comparative technical and economic analysis of the Trombe wall use at different planet latitudes and under different climatic conditions. In the calculation
participated 32 cities, which were located from 50° N up to 25° N. We should note that this comparative analysis will determine the economic efficiency not only for passive solar systems, such as the Trombe wall but also for any other solar power plants that currently exist and are used in heating systems.

In the calculations, the following Trombe wall structure will be used: a glass block with a thickness of 8 cm; air gap with a thickness of 29 cm; massive wall made of heavy reinforced concrete with a thickness of 30 cm, on which there is a layer of materials with a phase transition and ventilation openings with a fan. The total Trombe wall area is 8 m² and the heated room area is 22 m². A gas boiler with an efficiency of 98%, which will run on natural gas, will be considered as the main source of heat. The total cost of the considered Trombe wall is $ 1,500.

4. The feasibility study of the effectiveness of a Trombe wall

The first step of the calculation is to estimate the total incident radiation on the massive wall during the heating period for each selected latitude and longitude. Because this parameter affects the thermal efficiency of a Trombe wall. The total incident radiation on the massive wall shall be estimated as follows [12]:

\[ I_{p} = I_{b} + I_{d} + I_{g}, \]  

(1)

where \( I_{b} \) – the direct flux of the solar radiation per unit area of the vertical surface, \( W/m^2 \); \( I_{d} \) – the diffused flux of the solar radiation per unit area of the vertical surface, \( W/m^2 \); \( I_{g} \) – the radiation flux reflected from the earth surface per unit area of the vertical surface, \( W/m^2 \).

For the vertical surface of a Trombe wall, calculation of the direct solar radiation intensity can be done according to the following formula [13]:

\[ I_{b} = I_{h} \cdot \cosh \cdot \cos a, \]  

(2)

where \( I_{h} \) – the direct solar flux per area unit of the horizontal surface, \( W/m^2 \); \( h \) – the hour angle of the Sun, \( degree \); \( a \) – the azimuth of the Sun, \( degree \).

For the vertical surface of a Trombe wall, diffused solar radiation intensity shall be estimated as follows [14]:

\[ I_{d} = I_{d} \cdot \frac{1 + \cos \beta}{2}, \]  

(3)

where \( I_{d} \) – the solar flux per area unit of the horizontal surface, \( W/m^2 \); \( \beta \) – the surface inclination angle, \( degree \).

For the vertical surface of a Trombe wall, the intensity of the earth surface reflection shall be estimated as follows [14]:

\[ I_{g} = I \cdot \rho_0 \cdot \frac{1 - \cos \beta}{2}, \]  

(4)

where \( I \) – the global solar radiation on the horizontal surface, \( W/m^2 \); \( \rho_0 \) – the earth albedo.

The following formula shall be applied for estimation of the global solar radiation on the vertical surface of a Trombe wall in case of clouds (for 0-60° of the north latitude) [15]:

\[ I' = I_{p} \cdot [1 - 0.3 \cdot (1 + n) \cdot n], \]  

(5)

where, \( I' \) – the global solar radiation on the vertical surface in case of clouds, \( W/m^2 \); \( I_{p} \) – the global solar radiation on the vertical surface, \( W/m^2 \); \( n \) – cloud amount.

In order to estimate the solar flux per unit area of the horizontal surface \( I_{d} \) NASA databases shall be applied [16].

The intensity of incident solar energy is required to calculate every hour. Since the height of the Sun above the horizon changes every hour. The incident energy is defined as the product of intensity
per area of Trombe wall and time. The resulting energy values are summed per day and per month. Thus, the energy received by a Trombe wall ($Q_{solar}$) is determined in a specified time.

The second step of the calculation is to estimate the heat loss of the room during each month of the heating period for each selected latitude. The heat loss of the room shall be estimated as follows [17]:

$$Q_{0}^{ci} = [Q_{0}^{ci}(t_{i} - t_{0}^{ci})/(t_{i} - t_{0}^{ci})]k_{t}(t_{0}^{ci})n_{i},$$

where $Q_{0}^{ci}$ – the total design heat losses, kWh; $t_{i}$ – the internal design temperature of a room being heated, °C; $t_{0}^{ci}$ – the average ambient air temperature, °C; $t_{0}^{ci}$ – the design ambient air temperature during the heating period, °C; $k_{t}$ – the coefficient considering influence of the ambient air temperature on heat losses because of infiltration; $n_{i}$ – duration of $i$ period, h.

The total design heat losses of a building shall be estimated as follows [17]:

$$Q_{0} = Q_{enc} + Q_{inf} - \sum Q_{gen},$$

where $Q_{enc}$ – the heat losses through enclosing structures, kWh; $Q_{inf}$ – the heat losses due to infiltration, kWh; $Q_{gen}$ – the total heat emission into the room, kWh.

In order to estimate the coefficient $k_{t}$ the following formula shall be applied [17]:

$$k_{t} = \{1 + \alpha_{t}(t_{i} - t_{0}^{ci})^{1.667}/[(t_{i} + 273)(t_{0}^{ci} + 273)]^{0.667}\},$$

where $\alpha_{t}$ – the indicator of infiltration.

Since solar radiation is not a constant factor, it requires a primary heat source to heat the room. Accordingly, in the third step of the calculation is to estimate the heating power of the main source. This source heating power is determined based on the predicted solar radiation and the required amount of heat. In order to estimate the heating power of the main source the following formula shall be applied:

$$N_{source} = \frac{Q_{0}^{ci} - Q_{e}}{t_{h}}.$$

where $Q_{e}$ – the saved amount of thermal energy by a Trombe wall per month, kWh; $t_{h}$ - hours per month, h.

It should be noted that $N_{source}$ is a variable and changes every month, the heat loss of the building and the incident solar energy also change during this period.

$$Q_{e} = Q_{solar} \cdot k_{trombe},$$

where $k_{trombe}$ - the coefficient taking into account losses of incident solar radiation on a Trombe wall.; $Q_{solar}$ - Monthly incident solar energy on a Trombe wall, kWh.

The final step of the calculation is to estimate the amount of cash costs that the use of a Trombe wall could bring (and any other ways of using solar energy in heat supply systems). In order to estimate the amount of cash costs the following formula shall be applied:

$$C_{e} = \frac{Q_{e}}{q_{f} * \eta_{ef}} * c_{f},$$

where $q_{f}$ – calorific value of natural gas, 10000 kcal/m³; $\eta_{ef}$ – gas boiler efficiency, 98%; $c_{f}$ – cost of 1 m³ of natural gas in each country, $.

5. Results and Discussion

The calculation results are presented in tables 1 and 2. Table 1 presents the total amount of incident solar energy per year calculated for various cities, differing both in the latitude of the terrain and the
average temperature of the coldest month in the heating period. Also when calculating the incident solar energy, we took into account cloud coverage, which reduces the target value.

Table 1. The total amount of incident solar energy and the cost of energy saved.

| Temperature | City          | 65° | 60° | 55° | 50° | 45° | 40° | 35° | 30° | 25° |
|-------------|---------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| -38°C       | Yakutsk       | 2368| 97  |     |     |     |     |     |     |     |
| -32°C       | Ulaangom      |     |     |     |     | 3816| 400 |     |     |     |
| -26°C       | Komsomols k-on-Amur |     |     |     | 161 |     |     |     |     |     |
| -24°C       | Heihe         | 2296|     |     |     |     |     |     |     |     |
| -22°C       | Surgut        |     | 94  |     |     | 3931| 4284|     |     |     |
| -20°C       | Regina        | 302 |     |     |     |     |     | 198 |     |     |
|             | Harbin        |     |     |     |     |     |     |     |     | 4284|
| -18°C       | Krasnoyarsk   | 123 |     |     |     | 3549| 4320|     |     |     |
| -14°C       | Quebec        | 2433|     |     |     | 273 | 200 | 4561|     |     |
| -12°C       | Kazan         | 1987|     |     |     | 100 |     | 211 |     | 4802|
|             | Shenyang      |     |     |     |     |     |     |     |     |     |
| -10°C       | Anchorage     | 1864|     |     |     | 2174| 3744|     |     |     |
|             | St. Petersburg| 76  |     |     |     | 95  | 176 |     |     |     |
| -8°C        | Minsk         | 65° |     |     |     |     |     |     |     |     |
|             | Kashgar       |     |     |     |     |     |     |     |     |     |
Table 1 presents the solar energy total value per year (kWh), the name of the city and the cost of saved heat energy ($). We can see it from the data (Table 1) that the amount of incident solar energy increases in the terrain decreasing latitude from 1461 kWh at 65 degrees latitude to 5120 kWh at 35 degrees latitude. We should also note that even at the same latitude, fluctuations in the incident solar energy are observed.
energy are very significant and the amount is (0.35-1) of the maximum value. This is because of the various cloud coverage presence that greatly reduce the incident energy.

Table 2 presents the values equal to the total incident solar energy ratio to the required energy which is needed for building heating. This value shows how much of the energy needed for heating can be saved by incident solar radiation. The values of this quantity lie in the range (0.2-1) and increase with decreasing latitude. Values greater than 1 are obtained at latitudes less than 30 degrees and in these cases, the incident solar energy is enough for heating and an additional heat source is not required.

**Table 2.** The ratio of total incident solar energy to the required thermal energy for heating a building.

|                  | 65° | 60° | 55° | 50° | 45° | 40° | 35° | 30° | 25° |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| -38°C            | 0.2 |     |     |     |     |     |     |     |     |
| -32°C            |     | 0.35|     |     |     |     |     |     |     |
| -26°C            |     | 0.43|     |     |     |     |     |     |     |
| -24°C            |     | 0.54|     |     |     |     |     |     |     |
| -22°C            | 0.25|     |     |     |     |     |     |     |     |
| -20°C            |     | 0.47| 0.69|     |     |     |     |     |     |
| -18°C            |     | 0.36|     |     |     |     |     |     |     |
| -14°C            |     |     | 0.48| 0.8 |     |     |     |     |     |
| -12°C            |     |     | 0.34| 0.88|     |     |     |     |     |
| -10°C            | 0.27|     |     |     | 0.8 |     |     |     |     |
| -8°C             | 0.30| 0.36|     |     | 0.70|     |     |     |     |
| -6°C             | 0.28| 0.35| 0.50| 0.73| 1.26| 0.99|     |     |     |
| -4°C             | 0.31|     | 0.48| 0.62| 0.89|     |     |     |     |
| -2°C             | 0.26|     | 0.63| 0.83| 0.93|     |     |     |     |
| 0°C              |     | 0.45| 0.51| 0.58| 1.01|     |     |     |     |
| 2°C              |     |     |     |     |     |     | 0.91| 0.78| 1.39|
| 4°C              |     |     |     |     |     | 0.69|     |     | 1.08|
| 6°C              |     |     |     |     |     |     |     |     | 0.53|

**6. Conclusions**

1) Because climatic conditions are different at one latitude, the total amount of incident solar energy is also different, as well as the cost of energy resources can vary significantly, therefore, a thorough technical and economic calculation of the Trombe wall for each area is always required.

2) The most efficient Trombe wall use in heat supply systems is advisable in the latitude range of the terrain from 55° to 40° N. In this range, the Trombe wall allows reducing the consumption of external energy resources by 30-70%.

3) The use of the Trombe wall in modern heating systems is an economically feasible option to reduce the monetary costs of fuel buying, and therefore, to reduce emissions of harmful substances into the environment. The payback period of the Trombe wall in the range of latitudes from 55° to 40° N is from 3.5 to 10 years, depending on the fuel cost.

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