Employment of a Trombe wall in Modern Heating Systems

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Abstract. This article is devoted to the problems of passive solar heating systems application in the modern heat supply systems. During the last decades a Trombe wall is the most popular system among other passive heat supply systems. Solar radiation intensity is the main factor, which has the huge impact on the thermal effectiveness of a Trombe wall. Making a decision regarding Trombe wall application in a heat supply system depends on the correct forecasting of solar radiation intensity on the surface during the heating period. This article contains the brief calculation for forecasting of solar radiation intensity on a Trombe wall surface. The main innovations in the calculation under consideration are taking into account of clouds impact, as well as determination of solar radiation intensity on a horizontal surface, if there are no values for the set city in NASA data bases. The calculation results has showed, that in case of Harbin climatic conditions a Trombe wall can allow to provide 32% of required amount of heat energy in the coldest month. Annual savings of heat energy are approximately 61%. Thus, a Trombe wall, as an additional heat source, is a reasonable option for the heat supply system in the set climatic conditions.

1. Introduction
A Trombe wall is the most common passive system of solar heating among other passive systems [1,2]. In 1967 Felix Trombe and Jacques Michel designed and built a residential low storey house, where their patented passive system of solar heating was used for the first time [3]. This system is known as the classic Trombe wall [4]. The main objectives of a Trombe wall are transformation of incident solar radiation into heat energy, its accumulation in a massive wall and heating of rooms of a building.

2. The brief analysis of a Trombe wall technical and design solution
Classic Trombe wall layout is shown on Figure 1 [5]. This structure shall be oriented directly to the south side, since it is possible to get the maximum solar radiation on the vertical surface of the wall at this side. The external surface of the massive wall shall be painted black [3].

Operating principle of such wall is as follows: the massive wall and the air gap are warmed up through glass panels by sun beams during a solar day. A warmed massive wall transfers accumulated heat into the room due to the radiative and convective heat-mass-exchange. Two or three valves at the
upper and lower parts of the massive wall are used for control of air circulation. Automatic control over air vent valves allows to maintain the required amount of air circulating between the room being serviced and the air gap [4, 6].

3. Setting of the research objective
If to judge by the above-mentioned statements, it is clear, that thermal effectiveness of a Trombe wall is in direct proportion to incident solar radiation on the massive wall surface. Solar activity has a random nature because of clouds, and it means that a Trombe wall cannot be the single source of heat in a room. However, theoretically in warm climatic conditions a Trombe wall can be the single source of heat during the winter season. If to say about moderate and cold climatic conditions, so Trombe walls are used only as an additional source of heat during the winter season. Consequently, when developing the Trombe wall design for the set climatic conditions, first it is necessary to forecast the amount of incident solar radiation for each solar hour during the whole heating period.

Thus, the main objective of this work is elaboration of a calculation of incident solar radiation intensity on a Trombe wall surface.

![Figure 1. The schematic layout of the classic Trombe wall [4].](image)

1 – glass panels; 2 – an air gap; 3 – a massive wall; 4 – ventilation holes

4. Solar radiation intensity calculation
According to [6-8] solar radiation, which reaches the surface of the Earth through the atmosphere of the Earth, can be divided into two components: direct radiation and diffused radiation. The direct solar radiation is an emission flux, which comes directly from the solar disk and is measured on the plane being perpendicular to the direction of the sun beam [9]. The diffused radiation flux is such solar radiation flux, which was diffused in the atmosphere of the Earth because of clouds among other causes [9].

The first step of the calculation is to estimate the solar declination. The solar declination is an angle between the equator and the imaginary line, which link the centers of the Earth and the Sun [9]. The solar declination depends on a season. The Earth's rotational axis has the permanent inclination of 23,45° the declination angle is between 23,45° and −23,45°. The declination angle becomes equal to zero during the vernal and autumnal equinox. The solar declination shall be estimated as per the following formula [7]:

$$\delta = 23.45° \cdot \sin \left( 360 \cdot \frac{284 + n}{365} \right),$$

where \( n \) – a day of a year.
The next step of the calculation is estimation of the time difference between the local time and the true time. It occurs due to the existence of the Earth’s orbit inclination and establishment of the time zones on the Earth [9]. In order to estimate the true solar time, the following formula shall be applied [9]:

\[
\text{Solar time} = \text{Standart time} + \frac{4 \times (L_{st} - L_{loc}) + e}{60},
\]

(2)

where \(\text{Solar time}\) – the local solar time, hours; \(\text{Standart time}\) – the local time, hours; \(L_{st}\) – the local standard time meridian, degree; \(L_{loc}\) – longitude, degree; \(e\) – the equation of time, min.

The local standard time meridian shall be used for designation of a certain time zone and for setting the mean Greenwich time [10].

The equation of time \((e)\) takes into account the correction for eccentricity of the Earth’s orbit and tilt of the Earth’s axis [10]:

\[
e = 9.87sin2B - 7.5cosB - 1.5sinB
\]

(3)

where, 

\(B = \frac{360(n - 81)}{364}, 1 < n < 365\)

Hour angle shall be estimated as follows [10]:

\[
\omega = 15^\circ(\text{Solar time} - 12).
\]

(4)

In order to estimate location of the Sun in space it is necessary to estimate two key values: Azimuth and elevation angle of the Sun. The elevation angle of the Sun is height of the Sun on the dome of the sky, which is measured in degrees from the horizontal position [9]:

\[
sinh = \sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cos\omega
\]

(5)

where \(\varphi\) – the local latitude, degree; \(\delta\) – the solar declination, degree; \(\omega\) – the hour angle of the Sun, degree.

The azimuth of the Sun is the arc of the mathematical horizon from the south point up to the vertical circle of the Sun [9]:

\[
\cos a = \frac{\sin h \cdot \sin \varphi - \sin \delta}{\cosh \cdot \cos \varphi},
\]

(6)

where \(h\) – the elevation angle of the Sun, degree.

Having the main parameters of the Earth and the Sun location in space estimated, it is possible to get values of the global solar radiation on the horizontal surface [8]:

\[
I = I_b + I_d,
\]

(7)

where \(I_b\) – the direct flux of the solar radiation per area unit of the horizontal surface, W/m²; \(I_d\) – the diffused flux of the solar radiation per area unit of the horizontal surface, W/m².

In order to estimate the global solar radiation on the horizontal surface, the following formula shall be applied [8]:

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

(8)

where \(I_{b\gamma}\) – the direct flux of the solar radiation per area unit of the vertical surface, W/m²; \(I_{d\gamma}\) – the diffused flux of the solar radiation per area unit of the vertical surface, W/m²; \(I_{g\gamma}\) – the radiation flux reflected from the earth surface per area unit of the vertical surface, W/m².

According to [17], the solar activity on a vertical surface depends on the solar radiation on a horizontal surface. The values of the solar radiation intensity on the horizontal surface from NASA databases are often used during many researches, when estimating incident solar radiation on the vertical surface. This method has one significant drawback, such as: the database contains the limited number of cities. If required values are absent in the data base for the set city, so it is possible to use the following formula [12]:

\[
I_b = I_0 \left(\frac{d}{d_0}\right)^2 (\sin\varphi \cdot \sin\delta + \cos\varphi \cdot \cos\delta \cdot \cosh),
\]

(9)
where \( I_b \) – the solar flux per area unit of the horizontal surface, W/m\(^2\); \( I_0 \) – the solar constant, W/m\(^2\); \( d \) – the mean distance for flux density, km; \( d \) – actual distance from the Sun, km; \( h \) – the hour angle of the Sun, degree.

For the vertical surface of a Trombe wall, calculation of the direct solar radiation intensity can be done according to the following formula [7]:

\[
I_{b\beta y} = I_b \cdot \cosh \cdot \cos a,
\]

(10)

where \( I_b \) – 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.

Upon calculation of the direct solar radiation intensity, it is necessary to estimate the diffused solar radiation intensity for the horizontal surface [11]:

\[
I_d = \frac{1}{2} \cdot (S_0 - S_t) \cdot \sinh,
\]

(11)

where \( S_0 \) – the solar radiation intensity according to the zones, W/m\(^2\); \( S_t \) – the direct radiation intensity at the solar altitude \( h \), W/m\(^2\); \( \sinh \) – the elevation angle of the Sun, degree.

Diffused solar radiation intensity for the vertical surface shall be estimated as follows [11]:

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

(12)

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

For a vertical wall the intensity of the earth surface reflection shall be estimated as follows [11]:

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

(13)

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

The solar radiation intensity value depends on many different factors. One of the main factors having huge impact on the solar radiation intensity value is presence of clouds [12]. The following formula shall be applied for estimation of the global solar radiation on the vertical surface in case of clouds (for 0-60\(^\circ\) of the north latitude) [12]:

\[
I_{\beta y} = I_{\beta y} \cdot [1 - 0.38 \cdot (1 + n) \cdot n],
\]

(14)

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

According to [8] appearance of clouds in the sky is a random parameter. Then, in order to estimate hourly values of cloud amount during each solar day, it is possible to apply the method of continuous equal distribution of a random value. Such method implies distribution of an accidental real value, which belongs to the following interval [12]:

\[
[a, b] \equiv \{ x \in \mathbb{R}; a \leq x \leq b \}.
\]

(15)

It is possible to estimate the lower and the upper limits of cloud amount value for each month using this method. Therefore, the calculation results are hourly values of cloud amount for one month, which in case of summing up will be close to the values of NASA meteorological data for the cloud cover.

The calculations were done in order to assess possibility of Trombe wall application in Harbin climatic conditions. During these calculations the daily need of heat energy for the room being heated was estimated in the first instance. Required amount of heat energy per day can be estimated as follows [13]:

\[
Q^c_0 = Q^c_0(t_i - t^c_i)/(t_i - t^c_o) \frac{k_t(t^c_i)}{k_t(t^c_o)} n_i,
\]

(16)

where \( Q^c_0 \) – the total design heat losses, kWh; \( t_i \) – the internal design temperature of a room being heated, \( ^\circ\)C; \( t^c_i \) – the average ambient air temperature, \( ^\circ\)C; \( t^c_o \) – the design ambient air temperature during the heating period, \( ^\circ\)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 shall be estimated as follows [13]:

\[ Q_0' = Q_{enc} + Q_{inf} - \sum Q_{gen}, \]  

(17)

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

In order to estimate the coefficient \( k_t \) the following formula shall be applied [13]:

\[ k_t = \{1 + \alpha_i (t_i - t_0^\circ)1.667 / [(t_i + 273)(t_0^\circ + 273)]^{0.667} \}, \]  

(18)

Where \( \alpha_i \) – the indicator of infiltration.

The following shall be assumed in order to assess possibility of Trombe wall application in Harbin climatic conditions: the area of the room being heated is 22.4 m², the area of a Trombe wall is 8 m². The heating period in Harbin lasts 7 months. The coldest day in each month of the heating period is chosen to calculate the daily need of heat energy and to forecast the incident solar radiation intensity at clear and cloudy weather. The brief results of the performed calculations are shown on Figure 2.

![Figure 2. The results of the engineering calculation.](image)

**Figure 2.** The results of the engineering calculation.

5. Conclusions
1) A Trombe wall can provide the complete heat supply of a room in October and from March till April during the heating season. For the remaining time from November till February the energy of incident solar radiation is not enough for heat supply of a building and it is required to use an additional source of heat.
2) Application of a Trombe wall in the heat supply system of buildings allows to provide up to 32% of energy in the coldest month. Annual savings of heat energy are approximately 61%.
3) Taking into account heat losses through a Trombe wall in the calculation, the annual saving of heat energy will be reduced down to 50%.

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