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A review of the current work potential of a trombe wall

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ABSTRACT

This article is devoted to a review of one of the most effective systems among passive heating systems - the Trombe Wall. The main objective of this study is to revise the current potential of the Trombe Wall for cold climates. This article discusses the main subspecies of the Trombe Wall. A qualitative assessment of the cold climatic conditions use possibility was given for each subspecies. There were analyzed the most interesting studies on each structural element of the Trombe Wall, the possibility of using the Trombe Wall in high-rise buildings. The Trombe Wall effect on the exterior of the whole building was evaluated. A brief technical and economic assessment of the Trombe Wall in cold climatic conditions was carried out to determine the economic potential in this work. Based on the results of the review, the main gaps and problems of the Trombe Wall in cold climatic conditions using were identified, and the most appropriate constructive solution for this was put forward. The main directions for future studies of the Trombe Wall were established such areas as improving the Trombe Wall thermal protection, the influence of the adjustable heat transfer coefficient on the Trombe Wall thermal efficiency, developing a mathematical model that takes into account the combined operation of the Trombe Wall with the central heating source of heat.

1. Introduction

The keen interest in solar energy is due to an energy resource increase in global demand by 37% by 2040 [1,2]. Rising energy prices inevitably follow these actions, and then new energy crises. There is an acute problem with emissions of harmful substances into the environment. Solar energy is available in many places of the globe, and energy will not run out in the next hundreds of thousands of years. It is the reason why many advanced countries (such as Germany, China, the Russian Federation) are successfully developing solar energy [1]. The main advantages of solar energy include the following provisions [3]:

- Solar power plants reduce emission amounts of harmful by-products, e.g.,CO_2, SO_2.
- The installation of solar collectors contributes to the reclamation of degraded lands.
- The utilization of solar energy could protect water resources.
- The utilization of solar energy contributes to the improvement of socio-economic environments. Such as increasing energy independence and providing electricity in hard-to-reach areas of residences.

Today, there is a broad classification of solar power systems that convert solar energy into electrical or thermal energy. All solar systems are divided into active and passive systems. Active systems of solar power plants have the following characteristic features: external solar collectors, storage containers, additional liquid, pumps, fans, an additional energy source to ensure the system operability, and others [4,5]. A passive solar system is the linear building structures, where it is possible to use natural or forced convection for air movement [4]. Passive solar systems have several advantages over active solar systems. It has small primary costs for the construction of the structure, minimum operating costs. It is noted that the passive system operating service life is comparable with the operating service life of the building itself, where this system is used [6,7].

The Trombe wall is the most common passive solar heating system, among other passive systems [8,9]. The history of the Trombe wall construction dates back to the late 19th century. In 1881, Edward Morse first voiced and methodically explored the idea of using solar energy in the engineering systems of a building and patented his device for heating a room [10]. Edward Morse based the functional device conception on natural convection between the room air and the device gap spacing

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[10]. In 1940, Fred Keck designed a low-rise house building. He painted the interior room walls and floor in black [11]. It made it possible to convert solar radiation into thermal energy and accumulate it to heat the room at night. In 1946, Arthur Brown developed his project for a low-rise building, where all living quarters were fenced off by a hallway from the southern building face with maximum glazing [12]. In the hallway, all the walls and floor were painted black, which contributed to the accumulation of thermal energy from solar radiation for heating at night. Based on the researches results [10,12], in 1967, Felix Trombe and Jacques Michel designed a low-rise apartment building, where their patented passive solar heating system was first used [11]. This system is known as the classic Trombe wall [13].

2. Research problem formulation

Because of the planet Earth's unique position in outer space, the climatic conditions on the same parallel may differ from each other. For example, cities such as Harbin and Marseille are almost on the same parallel. However, for Harbin, the average annual air temperature is $4.9^{\circ}C$, and for Marseille is $15.2^{\circ}C$ [14]. The average temperature minimum in January in Harbin is $-23.1^{\circ}C$, and in Marseille $2.9^{\circ}C$ [14]. The absolute minimum temperature for January in Harbin is $-38.1^{\circ}C$, and for Marseille $-12.4^{\circ}C$ [14]. Nevertheless, the values of the average annual incident solar radiation on the surface are almost the same and are about 1500 kW/m^2(Fig. 1) [15].

A brief comparison exercise of climate data leads to the main question. This question is whether the Trombe wall application in climatic conditions, where the harsh winter and summer solar activity are in conjunction with the earth's surface. Thus, the primary purpose of this study is to review the existing literature on the subject. The main objectives of this review analysis are to identify problematic issues and to find the most appropriate structural and design aspects of the Trombe wall for severe climatic conditions.

3. Research methodology

This review is aimed at collecting publications that were devoted to the problem of using the Trombe Wall in building heat supply systems. All monitored publications are grouped by each subspecies and individual structural element of the Trombe Wall. All the results of the studies reviewed are summarized in each section, as well as comments on possible improvements, deficiencies, problems, or missing information for each subspecies and element of the Trombe Wall for cold climatic conditions. In this work, attention was paid not only to a review of the available literature on the existing subspecies of the Trombe Wall and to each of its structural elements. Attention in this work is also to a brief studies content explanation and key conclusions on them. It is also worth emphasizing that the primary purpose of this review is not to describe in detail the results of existing studies, how much to evaluate the current potential of the Trombe Wall in building heating systems for cold climatic conditions. The main attention is focused on the search for the most effective and expedient structural solutions that currently exist for the Trombe Wall in cold climatic conditions. Particular attention is paid to the issue of reducing heat loss through the Trombe Wall. This issue is a key factor affecting the thermal efficiency of the Trombe Wall in cold climates. Determining the most suitable subspecies of the Trombe Wall and its main structural elements for the stable climatic conditions is a difficult task. However, this is a crucial step to study the specific applicability and potential of the Trombe Wall in cold climates. In the review, special measures were taken to establish criteria for the effectiveness of the use of the Trombe Wall in building heating systems for cold climates. The following criteria can be attributed to such established performance criteria: the intensity of solar radiation, the temperature of the outside air during the heating period, the required thermal protection of the building, the complexity of the design, the level of primary and operating costs. Based on the established criteria, several problems and reasons were identified why one or another subspecies of the Trombe Wall could not be used in cold climatic conditions.

This work begins with a brief technical description of the classic Trombe Wall. The following is an overview of the most critical studies of existing Trombe Wall subspecies. Based on the established criteria and the results obtained, an assessment was made of the potential use of each subspecies of the Trombe Wall in cold climatic conditions. Then, a review was made of each structural element of the Trombe Wall, where the results of the most suitable studies on this issue were examined and briefly analyzed. Based on the obtained data, a list of the most suitable structural elements for the Trombe Wall in cold climates was established. In conclusion, a brief economic feasibility demonstration for the buildings heating systems Trombe Wall use in severe climatic conditions is given. This article ends with a discussion and conclusions based on the obtained and studied results, and also presents the main directions for future research.

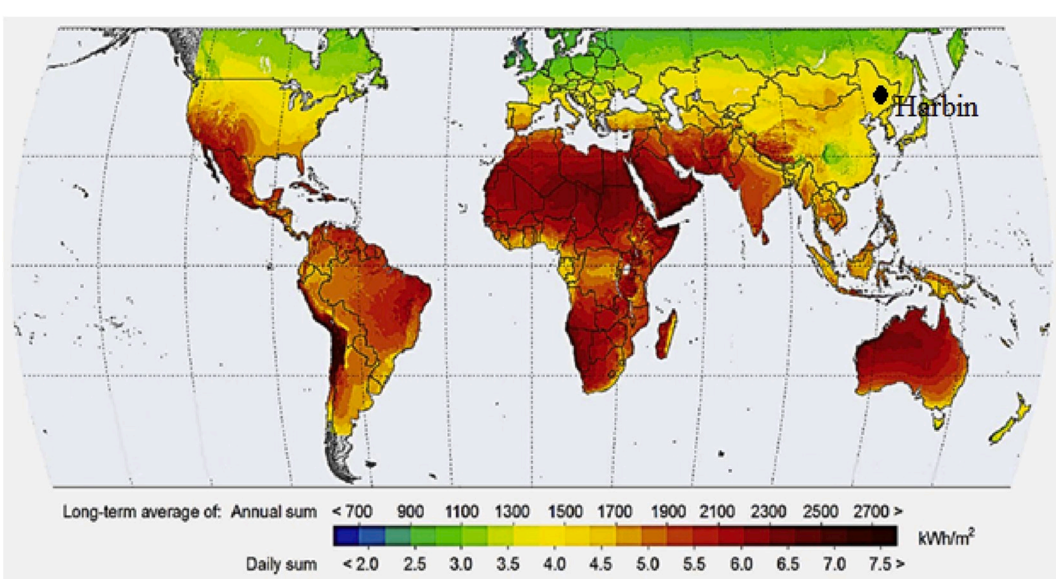

Fig. 1. Map of global horizontal irradiation [15].

3.1. The Trombe wall technical description

Fig. 2 presents a classic Trombe wall. Two French architects Felix Trombe and Jacques Michel designed it in 1967 [16].

The Trombe Wall is a south-oriented dark wall of sizeable thermal mass with glazing material [7,17]. It is possible to make as a load-bearing wall made of brick, quarry rock, reinforced concrete, or a freestanding wall using water containers and other liquid [18]. The Trombe wall operational principle is that solar radiation heats a massive wall. A massive heated wall heats the air in the room by radiation and convective heat exchange [19]. Air vents located in the upper and lower parts of the massive wall are used to ensure the necessary air circulation [20].

4. Classification and description of structural solutions for trombe wall various types

Today there are 9 different types of Trombe wall [18,19]: a modified Trombe wall; a composite Trombe wall; a photovoltaic Trombe wall; a Trombe wall with phase-change material; a zigzag Trombe wall; a solar water wall; a solar trans-wall, a solar hybrid wall-land, a fluidized Trombe wall.

4.1. A modified trombe wall

First of all, to increase the thermal efficiency of the classical Trombe wall, the various wall construction design solutions were undertaken. There are the automatic air vents, fans, ventilating louvers, protective insulation coatings, and other solutions were developed [21,22]. This subvariety is called the modified Trombe wall (Fig. 3) [21].

The operation principle of the modified Trombe wall is no different from the classical wall. A massive wall should be made of materials with a large thermal mass, brick, heavy concrete, natural stone [21]. This subvariety of the Trombe wall is based and developed on the fundamental basis of the classical Trombe wall. As a result, all the problem areas of the classical Trombe wall flowed into the modified Trombe wall.

In winter, the main problem is a thermal loss. So, to control heat loss, ventilating louvers were successfully applied [23,24]. Absorbent material coats one side of such louvers and the other side with reflective material. Thus, a simple configuration solves problems with cooling and overheating. One side of the louvers absorbed the outgoing heat from the massive wall and heated the passing air. The other side of the louvers reflected the incident solar radiation in the summer. It has an impact on the reduction of air overheating in the room [23]. Such a solution made it possible to increase the average temperature of indoor air to $21.7^{\circ}C$ [24] with an average outdoor temperature of $6^{\circ}C$and a daily amount of incident solar energy of 3000 W/m^2 [24].

According to Ref. [25], the use of automatic vent ducts can significantly improve the indoor climate of a room. Specifically, opening ventilation ducts in 2–3 h after sunrise and closing them in 1 h before sunset. Additional ventilation openings in the glazing help in the fight against overheating of the premises in the summer [26,27].

It should be noted that the modified Trombe wall is effortless and does not require substantial primary or operational costs. It is easy to reconstruct the southern wall of almost any low-rise building for a Trombe wall. A brief research results analysis shows that additional technical solutions make it possible to use the modified Trombe wall in severe climatic conditions.

4.2. A composite trombe wall

This Trombe Wall consists of glazing, air gap, a massive wall without ventilation ducts, an air layer, and a heat insulation wall with ventilation ducts [28,29], (Fig. 4).

Fig. 4 shows the operation principle of the composite Trombe wall. This design can solve the problem of heat loss through a massive wall at night [28,29].

When comparing the thermal efficiency of the composite Trombe wall with the classic Trombe wall, it can be noted [31] that in clear weather, the heat flux from the classical Trombe wall is several orders of magnitude higher than from the composite Trombe wall. However, all the thermal efficiency of the classic Trombe wall disappears in obscure weather [31]. This effect is the insulating wall work result, which significantly reduces heat loss through the composite Trombe wall.

Massive and insulating walls thickness depends on climatic conditions [29]. The primary materials for a massive wall are the same as for the classic and composite Trombe walls: brick, heavy concrete, natural stone [13,18]. Heat-insulating materials for an insulating wall should be

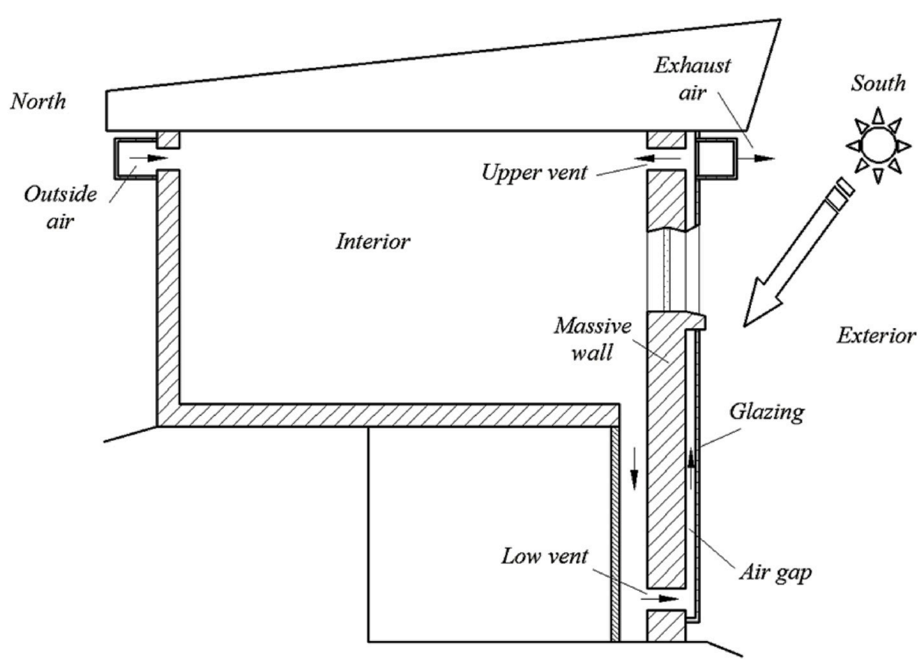

Fig. 2. Constructive diagram of a classical Trombe wall [16].

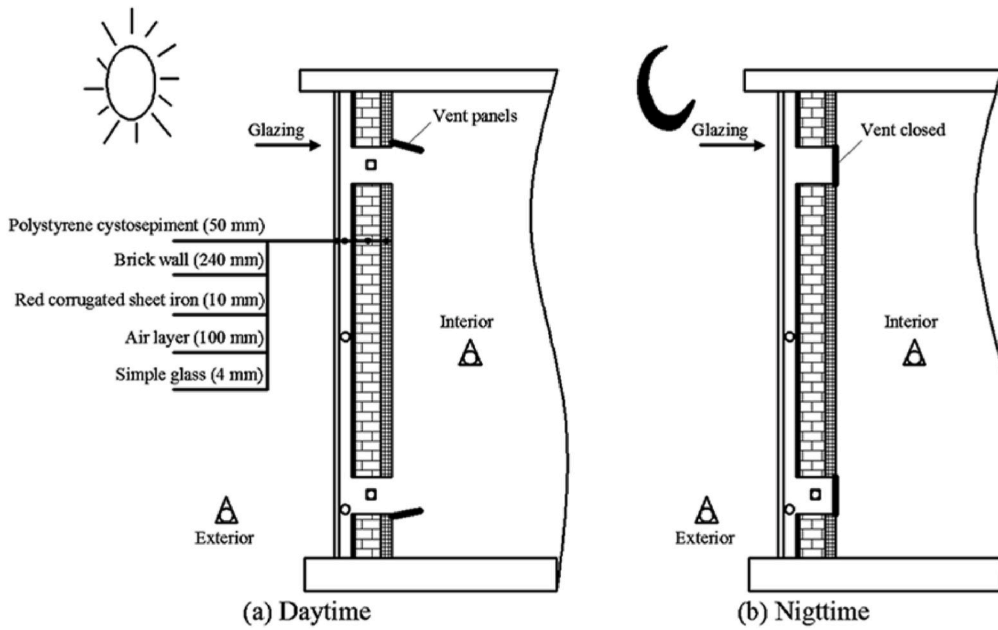

Fig. 3. A modified Trombe wall [21].

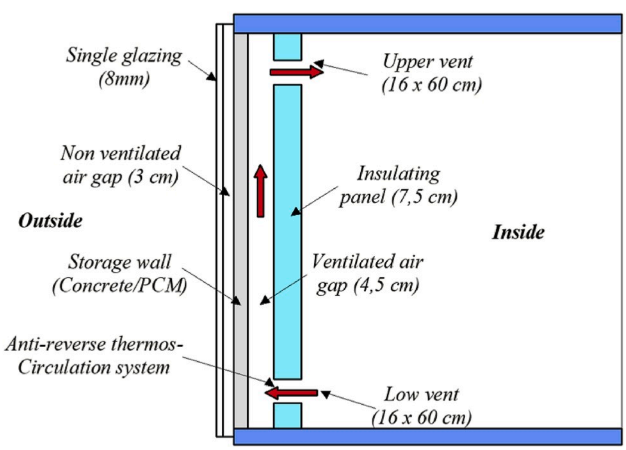

Fig. 4. A composite Trombe wall [13].

protected against moisture. Phase change material (PCM) is possible to increase the amount of accumulated thermal energy. According to the results [13,18], the melting point of PCM should be approximately 40–50 °*C*.

In addition to the problem with reverse thermo circulation [13,18], the composite Trombe wall has other problems. In severe climatic conditions, the temperature difference can be quite significant. In a result, moisture can form in the massive wall. Further, the massive wall generates condensation on the surface due to moisture. If the proper vapor barrier and heat-insulating layer waterproofing is neglected, then mold formation may appear on the heat-insulating layer. This circumstance has a great effect on the indoor room climate [33]. Depending on climatic conditions, the wall thickness can vary greatly. Given what, the useful space of the room is reduced, and the construction is becoming more expensive. Also, the amount of sunlight in the daytime is reduced to illuminate the room, since, often, the Trombe composite wall does not have window openings. During the operating process, it may be difficult to clean the space between the glazing and walls from dust and dirt.

As the research results [30,32], show, if to specify the project carefully and resolve the main problematic issues, the composite Trombe wall is considered as a quite effective solution in severe climatic conditions.

4.3. Trombe wall with PCM materials

Such a Trombe wall introduces design, which includes materials with phase change. A material with a phase change is a substance with a high heat of fusion. It can accumulate and give off a large amount of thermal energy [32,34], when its state is changed. These materials are usually located on the outer surface of the wall. However, it can be placed inside of wall surface [35] (Fig. 5).

There are two types of PCM materials: organic and inorganic [34]. Inorganic materials include salt hydrates and their derivatives. Such materials have excellent heat index and low cost, but these materials are very strongly affected by corrosion and cold [35].

Organic materials include paraffin and fatty acids. Such materials are more thermally stable. There is no corrosion and overcooling. However, these materials are highly flammable and have low thermal conduction [34].

According to Ref. [36], the most effective location of the PCM is near the controlled industrial environment. The most excellent efficiency of PCM is when working with peak loads [32,36]. However, according to Ref. [37], the optimal location of the PCM was the distance, which was $1/5L$ from the outer massive wall surface, where L was the thickness of the insulation cavity. Thus, it can be concluded that the choice of PCM location in a massive wall depends both on climatic conditions and on the choice of the target heat flux on the heated space. If the first factor influences the PCM location of the in a massive wall [37,38], then the second factor has an impact on the choice of the PCM melting temperature [39]. Besides, according to Ref. [18,40], a PCM layer of 3.5 *cm* can successfully replace a concrete wall of 15 *cm*. However, under cold climatic conditions, the calculation of the massive wall thickness should only come from the requirements for room thermal protection. It is because the higher the heat capacity of the PCM, the higher its thermal conductivity [41].

According to Ref. [36,39,42], the use of PCM in the Trombe wall helps to reduce the annual energy consumption from 10 to 30%, depending on climatic conditions. This is due to the fact that PCM can increase the amount of accumulated thermal energy. As a result, the Trombe wall will be able to heat the room for 2–4 h more than without PCM [37,43].

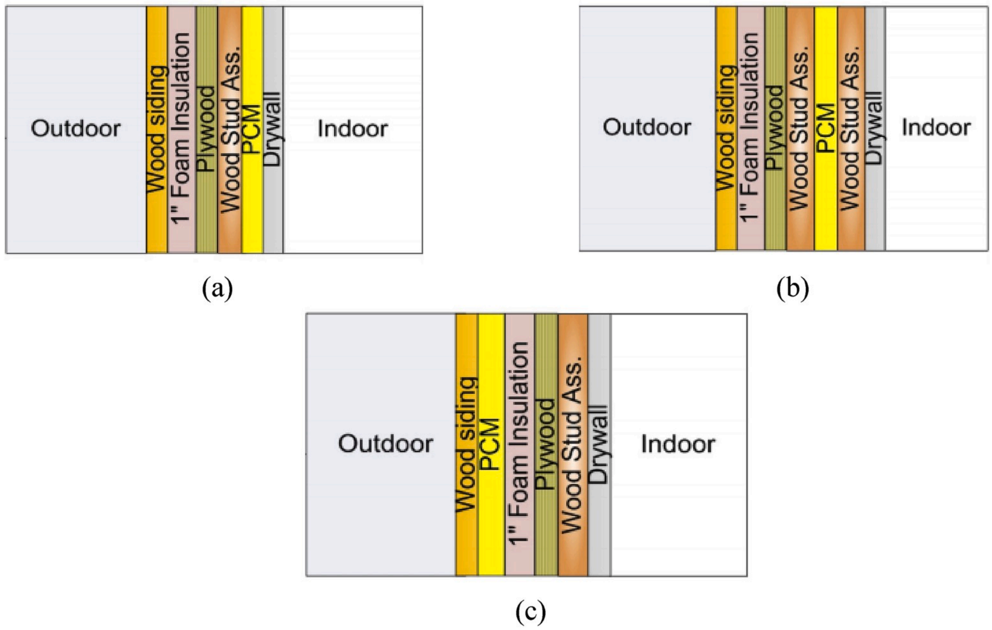

Fig. 5. Location of PCM in a Trombe wall: (a) iPCM; (b) midPCM; (c) ePCM [35].

The Trombe wall with PCM is suitable for use in severe climatic conditions. However, the development of such projects requires a very cautious approach. It is because today, there is a vast number of PCMs that have different characteristics. Many studies cite various PCMs and their thermal characteristics. However, authors provide very little information about the economic component, the durability, and the accumulating efficiency assessment over the durability. The use of PCM can significantly increase the Trombe wall construction cost. As a result, when designing the wall, it is imperative to conduct a comparative technical-economical analysis between PCM and other possible options. For example, the cost of PCMs and their durability is several times greater than the explicit costs for the standard building envelope with enhanced thermal insulation. As a result, it is possible to reduce the emissions of harmful substances into the atmosphere.

4.4. A photovoltaic trombe wall

This Trombe wall type has photovoltaic modules that are located in the air gap or on a massive wall (Fig. 6). Such a wall design allows the conversion of solar radiation into electricity and thermal energy [44, 45].

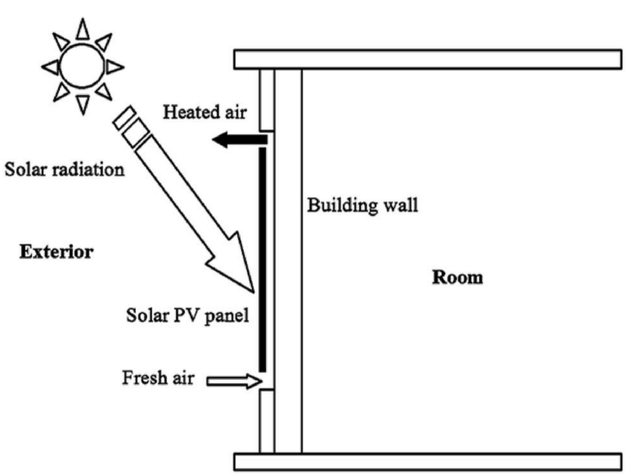

Fig. 6. Scheme a photovoltaic Trombe wall [44].

According to the obtained results [45,46], the photovoltaic Trombe wall is not suitable for work in severe climatic conditions. It is because the photovoltaic Trombe wall heated the room to 14.2 $^{\circ}C$[45], where the climatic conditions of the winter period were not very severe. According to Refs. [47], the photovoltaic Trombe wall with a total efficiency of 53.7% annually generated 16,209 kWh of electric energy and 1531 kWh of thermal energy, with a total area of 65 m^2. According to Ref. [48], the maximum daily power of the module in the photovoltaic Trombe wall was 35.79 W/m^2.

If to consider the results of the study [46], then theoretically photovoltaic Trombe wall may be useful in cold climatic conditions. For example, if an "air-to-air" heat pump is used to heat a room, where a thermoelectric heat element heats the incoming air. However, the primary input and operating costs of a photovoltaic system are enormous. The most problematic part of such solar installations is the batteries' high cost. As a result, the payback period of the photovoltaic Trombe wall project exceeds the equipment operating life [49].

4.5. A solar water trombe wall

Solar water wall works on the same principle as the classic Trombe wall [50]. However, the solar water wall uses water tanks to accumulate solar energy [51]. This choice is because of that the specific heat of water is several times higher than the values of acid brick or reinforced concrete [52]: 4.186 $kJ/(kg*K)$versus 0.840–0.880 $kJ/(kg*K)$.

According to the results of the research [53], this design is intricate and not very useful. Firstly, water conducts heat very well. It causes heat losses to increase during the night. Secondly, in severe climatic conditions, at night, the temperature of the water in the tanks can approach 0 $^{\circ}C$. As a result, most of the daytime solar radiation goes away melting ice in the tanks. Thirdly, a Solar water wall can occupy ample space in a heated room, and it is also impossible to place a window opening in the wall.

Thus, the use of a Solar water wall in severe climatic conditions is not possible.

4.6. A zigzag trombe wall

A zigzag Trombe wall is an ideal solution to two problems: the maximum use of solar radiation to accumulate thermal energy in the wall and provision the room with the required amount of daylight (Fig. 7) [54].

So, to adequately heat the rooms, all the window openings of the southern facade were facing the south-east zone. Meanwhile, the thermal wall faces south-west, where it is possible to get the maximum amount of solar energy by the end of a sunny day [19].

With such decision, it is quick to warm the room in the morning with direct sunlight, which entered through a room window. Further, closer to noon, solar radiation heated the thermal wall, which accumulates thermal energy for the night period. However, there is a big drawback to such a space-planning Trombe wall solution, which increases heat loss through the wall. According to Ref. [55], the heat loss of a building can increase by 12–15% due to the presence of ruggedness of facades, ledges, and other similar space-planning decisions. Also, since in cold climatic conditions, the Trombe wall is only an additional heat source, this 12-15% of heat losses fall on the load of the primary heat source. As a result, the advisability of using zigzag Trombe wall in cold climatic conditions is zero.

4.7. A solar trans –wall

The solar trans-wall is very similar to a water Trombe wall. However, the solar wall trans-wall consists of transparent glass modules on a metal frame. Transparent glass modules form an airtight container with the water. Between these containers, there is an absorber plate. Sunlight heats this plate and then transfers energy to water [56,57].

This design has a large number of disadvantages. The low thermal efficiency of such a Trombe wall is associated with convective heat exchange [13]. According to Ref. [18], microorganisms may appear inside the container with water, which affects the permeability of glass modules. Also, the Solar trans-wall has the same thermal protection issues like a water Trombe wall. As a result, it is almost not possible to use solar trans-wall in cold climatic conditions.

4.8. A solar hybrid wall (solar trans-wall)

The idea of Solar trans-wall is an effective solution for heating in the winter, and for cooling in the summer [13,18]. It is noted here that for other Trombe wall types, there is a problem with the massive wall overheating of in the summer period [21,23,33].

Fig. 8 illustrates The Solar trans wall project to Ref. [58]. The main feature of this Trombe wall is that in winter, solar radiation heats the corrugated metal sheet of 0.8 mm. Further, the metal sheet exchanger heats the air in the air gap through convective heat. Heated air is supplied through the air channel to the distribution leader, where it is heated to the required temperature [58]. In the summer, the air is supplied from the street to the room directly through the leader, bypassing its heating from solar radiation.

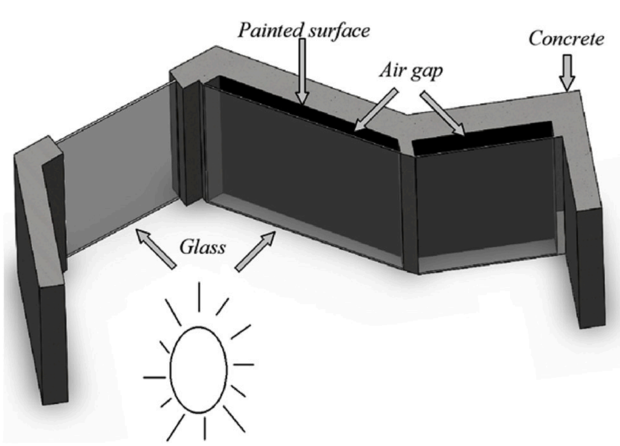

Fig. 7. A zigzag Trombe wall [54].

According to Ref. [18,59], a Trombe wall with a ceramic evaporative cooling wall was developed. If in winter, this project works like a classic Trombe wall, then in the summer, it can be used as an innovative solution. This solution is that water cools the air in the air gap [18]. Porous ceramic plates absorb most of the moisture, which causes the effect of evaporative cooling.

After analyzing this type of Trombe wall, there are two main drawbacks that can be immediately noted: the design complexity and the high cost of equipment. In a superficial assessment, the use of the solar desiccant cooling system in severe climatic conditions is unprofitable. First of all, this conclusion is because of the high cost of the project.

4.9. A fluidized trombe wall

A distinctive feature of fluidized Trombe wall is that a highly absorbent low-density liquid is located in the air gap [18,60].

The principle of operation is as follows: the fan delivers air from the room into the air gap, where the absorbing liquid is located. Further, air passes through this fluid, where it is heated and back into the room. Between the absorbent liquid, two filters protect the supplied air into the room from particles of this liquid [60]. The principle of cold air heating is based on fluidization [60].

According to Ref. [18,61], the thermal efficiency of fluidized Trombe wall is much higher than that of the classic Trombe wall. It is because the coolant, i.e., air directly interacts with an absorbent liquid [60]. However, as with the Solar hybrid wall, fluidized Trombe wall is a sophisticated design for both implementation and maintenance in cold climate conditions. Besides, there are no studies that research the following issues: how the absorbent liquid behaves at significant temperature differences, what is the operating life of this wall, how to clean in the air gap. As a result, this Trombe wall type is rarely suitable for heating rooms and buildings.

5. Structural elements of the trombe wall and their influence on the work efficiency

The main Trombe wall structural elements include the following elements: glazing, air gap, a massive wall, and it is the color of coating, heat insulation, ventilation ducts, windows in a massive wall. According to Refs. [62], when designing a Trombe wall project for established climatic conditions, the designer must take into account the technical and economic parameters of each wall element. However, according to Ref. [18], the most critical aspects of any Trombe wall design are the following: ventilation ducts, fans, and thermal insulation. Many investigations on the main structural elements of a Trombe wall and their influence on the efficiency were conducted by investigators. It is reviewed in this section and results are summarized in Table 1.

5.1. Glazing

Today, in various structures of the Trombe wall, single, double, or energy-efficient Low-e double-glazed windows are used [63,64]. According to Ref. [64,65], glazing has a significant influence on the accumulating efficiency of the Trombe wall. This fact is since a double-glazed window can absorb and reflect some part of the solar radiation spectrum. As a result, the most efficient use of low-emittance double-glazing in the Trombe wall [66,67].

According to the results of Table 1, the choice of glazing depends on climatic conditions and the accepted material for a massive wall. So, for moderate climatic conditions, the use of single glazing and a massive wall of brick or heavy concrete is sufficient. According to Refs. [65], heat loss through glazing is about 60% of the total incident solar radiation. Therefore, for cold climatic conditions, it is necessary to use a double Low-e double-glazed window with a massive wall, which has a high

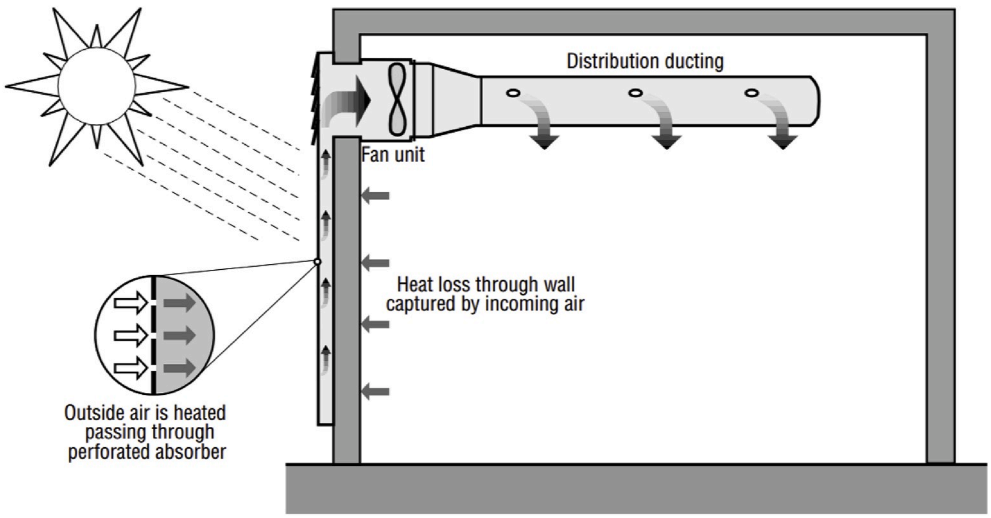

Fig. 8. Solar hybrid wall [58].

thermal resistance.

5.2. Air gap

In the Trombe wall, the coolant is air, which circulates between the heated room and the air gap. Various studies confirm the enormous influence of this element (Table 1), because the room receives most of the heated air thermal energy in the air layer. Air heating in the air gap occurs due to convective heat exchange between the surface of the massive wall and the air. Thus, in this element, the essential characteristic is the convective heat transfer coefficient, which depends on the thickness of the air gap and the speed of the supplied air [68].

The main problem of the air gap is heat loss through glazing using convection. As a result, there is an increase in the load on the central heating source. There are many solutions to combat heat loss through convective heat exchange between the air gap and glazing. So, according to Ref. [62], active isolation using air flow was effectively used. In another study [78], protective shutters were installed in the center of the air layer to combat heat loss.

According to the results (Table 1), the air gap has a significant influence on the temperature of both a massive wall and indoor air. The thermal characteristics of glass have a significant effect on the air gap temperature. Thus, in severe climatic conditions, it is necessary to use an air gap from 29 to 35 *cm* thick [68,78]. In this case, it is preferable to use a double Low-e double-glazed unit with proper thermal protection [67,78]. In order to reduce heat loss, it may be used additional design solutions: protective thermal curtains, additional circulation of the air gap, and others.

5.3. Massive wall

A massive wall directly affects how much heat energy is accumulated on a sunny day. Based on this, a massive wall should have a sufficient thermal mass, which can completely absorb the average monthly predicted value of solar radiation for a day at the calculated location [79]. Very often, PCM is used to increase the thermal mass of a massive wall [36,39].

To date, the following materials are most common for a massive wall: brick, reinforced concrete, autoclaved aerated concrete [79]. According to Ref. [80,81], it is easy to obtain improvised materials (rammed ground [80], marble, and quartzite [81]) near the building area and make a massive wall. Such studies show that there is a wide selection of building materials not yet explored for a massive wall, the thermal efficiency of which can be no less than of especially common materials.

The choice of the massive wall thickness depends on climatic conditions (Table 1), which determine the required value of the reduced heat transfer resistance [82]. Also, according to the results of [83], the thickness of a massive wall affects reducing the consumption of external energy resources from the use of the Trombe wall in the building heat supply system. So, when using electricity in heat supply systems, the thickness of a massive earth block wall should be about 35 *cm*, and when using natural gas about 25 *cm* [83]. It must be kept in mind that this conclusion is based on the experiment results that were conducted only for one established region (France) [83]. As a result, these findings are limited in nature and cannot be fully applied in other countries. Therefore, a technical and economic calculation should be carried out for other countries and with a different cost for energy resources, considering the Trombe wall cost. Consequently, the massive wall thickness should be determined by a technical and economic calculation, which should take into account the climatic conditions of the area, the cost of primary energy, and the designed Trombe wall.

Surface of a massive wall must be painted black to improve the absorption capacity [79]. Ordinary black ink using gives an increase in accumulating thermal energy by 26%[79]. Specialized paints and varnishes with a high absorption coefficient of solar radiation, which showed high efficiency in the operation of the Trombe wall, are studied as well [84]. However, such coatings have a high cost. As a result, there is a significant increase in price and, consequently, the payback period of the project increases.

According to the results (Table 1), for severe climatic conditions, it is most advisable to use a massive wall of heavy concrete with a thickness of 30–35 *cm* with PCM. Such a constructive solution allows for achieving the required thermal protection and thermal massive for accumulating daily average solar activity. It is noted that most of the studies were carried out in warm and moderate climatic conditions (Table 1), and heat insulation is rarely used in a massive wall.

5.4. Heat insulation

One of the main Trombe wall drawbacks is a huge heat loss, especially during the night period [18]. It is because of accumulating a large volume of thermal energy. A massive wall must have high thermal conductance and heat capacity. Otherwise, the accumulation of thermal energy becomes an awkward action [64].

A brief analysis of the results (Table 1) shows that thermal insulation in the modified Trombe wall negatively affects thermal efficiency. According to Ref. [85,86], in cold climatic conditions, the use of the Trombe wall with thermal insulation is not economically feasible. It is

Table 1
Summary of previous research.

Element	Author/Year	Location	Variation	Studied parameter	Main conclusions	Refs.
Glazing	M.Helenice et al., /2012	Portugal	Various glazing materials	Optimization of design and heating load saving	The glazing of Bioclean (4 mm) – Planilux (4 mm) and Diamant (4 mm) – Diamant (4 mm) required less energy consumption for heating	[64]
	F.Stazi et al., /2012	Italy	Single glass, Low-e coated single glass, Double glass	Optimization of design and heating load saving	The best wall performance was achieved with Low-e coated single glass and double glazing	[67]
	I. Hernandez-Lopez et al., /2012	Mexico	Semitransparent wall	Thermal energy losses	It was found that the heat loss through the glazing is from 56 to 64% of all the incident solar energy on the wall	[65]
	F.Stazi et al., /2011	Central Italy	Single-glass, Double-glass	Optimization of design and heating load saving	The best wall performance was achieved with double glazing	[63]
	R.C. Richman et al., /2009	Canada	New type of glazing	Optimization of design and heating load saving	The accumulating efficiency of a Trombe wall was 36.5%	[69]
	L. Zalewski et al., /2002	France	Single-glass, Double-glass, Double-glass with low emittance	Optimization of design and heating load saving	Different versions of a Trombe wall with low double-glazing emittance allow collecting heat energy for the heating season in the range from 189 to 263 kWh/m^2. With single glazing in the range from 107 to 184 kWh/m^2.	[66]
Air layer	M.Olenetset al./ 2015	Poland	Air gap	Natural convection and heat gains	The location of Venetian blinds in the air layer increases the overall heat dissipation factor in a room increases by 14%. Also, the amount of chilled air that can get into the room is able to.	[78]
	M.Sinisa et al., /2013	Serbia	Active and passive thermal insulation	Thermal insulation	The efficiency of active isolation (air gap) is an order of magnitude higher than the efficiency of passive insulation	[62]
	V. Hernandez et al., /2006	Mexico	Air gap	Analytical model	The developed analytical model can determine the temperature change in the air layer with very high accuracy	[70]
	T. Toiliev/1995	Turkmenistan	Air gap	Natural convection and heat gains	The maximum amount of thermal energy is achieved with an air layer thickness of 29 cm	[68]
Massive wall	M. Dabaieh et al., /2015	Egypt	A wall of rammed earth (40 cm) and a concrete wall (30 cm)	Heat gains	The decision made allowed to reduce the thermal load by 94%	[71]
	M. Bojic et al., /2013	France	Wall materials concrete, brick	Annual energy savings of fuel	The choice of thickness of a massive wall depends on the choice of the heat source	[83]
	S. Karta et al., /2010	Turkey	Wall materials:concrete, brick and aerated concrete	Thermal energy storage	The maximum increase in thermal energy was observed with a concrete wall, which was painted black (26.9%)	[79]
Massive wall	Abbassi et al., /2014	Tunisia	0, 1, 2, 3, 4, 5, 8, 12, 16 and 18 m^2	Thermal energy storage	The area of a Trombe wall affects its effectiveness.	[72]
	Ana Briga-S et al., /2014	Portugal	Brick wall thickness of 15 cm, 20 cm, 25 cm, 30 cm, 35 cm and 40 cm	Thermal energy storage	If a Trombe wall has vent holes, then the thermal gain will increase with the increase in the massive thickness of the walls. In the The opposite case, in the unventilated Trombe wall, the thermal load decreases with increasing thickness	[87]
	K. Hami et al., /2012	Algeria	Massive wall	Thermal energy storage and temperature of massive wall	For the construction of a Trombe wall, a massive wall is an important element.	[73]
	F. Fiorito/2012	Australia	PCM position in a massive wall	Heat gains and thermal energy storage	A suitable PCM position has been determined for five different climatic zones.	[74]
Thermal insolation	S. Cui et al., /2016	China	Wall materials: Brick; thermal insulation material: mineral wool	Heat gains	A Trombe wall is ineffective for the established climatic conditions.	[86]
	Sinisa M. et al., /2013	Serbia	Different location of thermal insulation	Room temperature and heat gains	The location of heat insulation on the outer layer of the wall leads to an increase in the internal temperature of the air in the room	[62]
	K. Kotlov/2009	Russia	Wall materials: Brick; thermal insulation material: mineral wool	Heat gains	The results of the study showed that this wall is very inefficient. Since, out of the 7 months of the heating season, a Trombe Wall worked only 3.5 months.	[85]
Ventilation channels	N. Simoes et al., /2015	Portugal	Ventilation ducts	Heat gains and cooling load saving	To refuse overheating in the summer, it is necessary to use louvers and ventilation holes, which can create a flow of cool air in the room;	[88]
	M. Rabani et al., /2015	Iran	New design of ventilation duct	Heat gains and cooling load saving	The new construction of a Trombe wall provided comfortable conditions inside the premises both in winter and in summer	[26]
	Y. Liu. et al., /2013	China	Time of use of ventilation ducts	Heat gains and a temperature room	The optimal mode of opening the ventilation ducts is 2–3 h after sunrise. Optimal mode for closing ventilation ducts: 1 h after sunset	[21]
	S. Dragievi, M. Lambic/2011	Serbia	Ventilation ducts	Heat gains and a temperature room	The maximum efficiency of heat exchange is achieved with ventilation holes of 2.5 cm, where the airspeed should reach 2 m/s	[75]
		China		Mass flow rate		

(*continued on next page*)

Table 1 (*continued*)

Element	Author/Year	Location	Variation	Studied parameter	Main conclusions	Refs.
	Liping and Angui/2006		0.1, 0.2, 0.3, 0.4, 0.5 and 0.6 m		As the width of the air layer increases, mass flow increases	[76] [77]
Windows in a massive wall	E. Bellos et al., /2016	Greece	Location of the window and its size	Heat gains and a temperature room	The developed design has a number of advantages over the traditional a Trombe wall	[90]
	W. Sun et al., /2011	China	Location of the window and its size	Heat gains and a temperature room	The location of the window in a massive wall leads to an increase in heat losses through a massive wall	[89]

because thermal insulation violates the thermal energy accumulation processes inside a massive wall and the transfer of this energy to the room. Based on what, to reduce energy fuel and harmful substances emissions, it is advisable to use an additional layer of thermal insulation for a residential building.

It is observed the most rational and effective constructive solution for the thermal insulation used in the Trombe composite wall [28,30]. However, at such a Trombe wall, there are several problems that designers must consider.

In many studies, individual protective curtains are used to combat heat loss during the night period [18,80]. However, for cold climates, such a method is very inconvenient for everyday life, since the thickness of the insulation should be in the range of 100–150 *mm*. For severe climatic conditions, it is necessary to apply more thorough calculations and the choice of building materials, as well as the use of some new engineering solutions which aim to combat heat losses, for example, the use of new liquid heat-insulating substances, the use of transparent or translucent glass vacuum structures in the Trombe wall.

5.5. Ventilation ducts

The ventilation ducts location is in the upper and lower parts of the massive wall. Its location depends on the size of the Trombe wall. The ventilation ducts provide heat and mass transfer between the room air and the air in the air gap of the Trombe wall [18]. Ventilation channels increase the heating rate of the room due to convective heat and mass transfer between the heated air in the air gap and the room air [21]. According to Ref. [87], ventilation ducts in a massive wall have a decisive influence on thermal efficiency. In the study [21], the authors applied a different mode of operation of the ventilation ducts. In the daytime mode, the ventilation ducts were closed, resulting in the temperature of the massive wall reaching $43^{\circ}C$. During the night, inside the experimental bench, the temperature was higher than the outside by $9^{\circ}C$, which ensured the established requirements for the indoor climate of the room [87]. Thus, the optimal time for opening and closing ventilation ducts is determined based on the geographical location and climatic conditions of the area.

Ventilation ducts not only affect the thermal efficiency of heating a room in winter but also improve the cooling of a room in summer. One of the simplest methods to combat overheating a room in summer is to place an additional ventilation hole in the upper part of the glazing. If the upper ventilation duct in a massive wall is closed, then this solution creates a forced outflow of hot air from the room [18,83].

Numerical studies [88] showed that it is possible to use metal blinds in the air gap to reduce the room air temperature during the summer period. Such a solution made it possible to reduce indoor air temperature by 20%[88]. In their study, Mehran Rabani and others located a new ventilation duct above the air gap of the Trombe wall [26]. Such a solution made it possible to utilize excess hot air from the room and the air gap of the Trombe wall using natural convection [26]. However, from an architectural point of view, the developed constructive solution [26] is difficult to fit into the overall picture of the architectural style of the building. It is because the dimensions of the new ventilation duct only in the experimental stand were $1\ m$ *by* $0,5\ m$, with a total area of the Trombe wall of $3\ m^2$[26].

Many studies have shown that the use of ventilation ducts improves the thermal efficiency of the Trombe wall (Table 1). In cold climate conditions, the lower ventilation ducts should have fans, which create forced heat and mass transfer between the air gap and the room air. For improving the thermal Trombe wall efficiency, automation is required to open and close ventilation ducts in the winter. This solution reduces the load on the central heating source.

5.6. Windows in a massive wall

The location of the window openings in the Trombe wall is ambiguous [18]. On the one hand, with the arrangement of windows in a massive wall, the volume of thermal mass, which accumulates thermal energy, reduces. Also, heat losses increase through windows. On the other hand, the placement of windows in a massive wall allows to heat the room with the help of sunlight quickly, and also daylight makes the room more comfortable for residents. It was precisely to provide the room with thermal energy and daylight that a Zigzag Trombe wall was developed [54,55].

The results of a brief analysis showed (Table 1) that windows have an important place in human life, and of course, in the design of any buildings. Some results show that window openings reduce the amount of accumulating heat in a massive wall. According to Ref. [89], when the windows and the Trombe wall were combined on the southern facade with photovoltaic cells, the convective thermal efficiency was about 20%, without a window on the southern facade the convective thermal efficiency was about 25%. It is because the incident solar radiation penetrating through the window heats the air in the room much faster than the Trombe wall with photovoltaic cells. In this case, the efficiency of the electrical conversion of such a Trombe wall remains practically unchanged [89]. In another study, according to Ref. [90], in the center of the Trombe wall with an area of $15\ m^2$ a window of $2\ m^2$ was placed in the Athens city climatic conditions. A comparative analysis of the air temperature in the room between the Trombe wall with a window and without it showed that the temperature difference is about $0.5K$ during the entire heating regime. In this method, two problems were solved: providing the required amount of thermal energy for the room heating and natural lighting of the room. However, the comfortable climatic conditions of Athens in which this study was conducted should be taken into account. In the coldest month of the heating season (December), the outdoor temperature was about $7\ ^{\circ}C$ [90].

6. The Trombe wall use in high-rise buildings

With the high-rise buildings construction development, the problem of using passive solar heating systems in the heat supply systems of high-rise buildings is very relevant. However, not many works are devoted to this problem. The definition of a high-rise building varies depending on the adopted regulatory framework in different countries, but, usually, buildings with a height of 35–100 m are high-rise, and buildings above 100 m are considered skyscrapers [91]. For the category of buildings from 35 to 100 m, the research results are of considerable interest [92–94]. According to Ref. [92], a comparative analysis of the Trombe wall with a single air gap over the entire height of the southern facade and an air gap for each floor was carried out. The results showed that the Trombe wall construction with an air gap for each floor (Fig. 9) allows better organization of a uniform flow of heated air, which ensures uniform heating of the premises in the building [92]. For high-rise buildings, it is impractical to use a single air gap. This is due to the fact that hot air is lighter than cold and will move upward, which will result in overheating of the upper and under heating of the lower floors.

The possibility of using the Trombe wall in buildings over 100 m is described in detail and evaluated in Ref. [95,96]. In these works, The Pinnacle Tower [95] and Frankfurt Commerzbank [96] are considered. In these buildings, methods and constructive solutions for solar heating were used, which made it possible to get the maximum benefit from solar radiation and reduce the consumption of external energy resources [95,96]. There was the correct orientation of the building with respect to the Sun, atriums with a large glazing area and green plantings that use the effect of the solar pipe, a complex facade system of 3–4 layers with natural ventilation, the location of solar panels on the facades. However, in the buildings under consideration, no technologies were used that contributed to the conversion of incident solar radiation into thermal energy and its accumulation for heating during the night [95,96]. The author mentioned only the potential use of such technologies in a green garden, placing black floor coverings from materials with high thermal mass [96].

Based on the work [94–96], it can be noted that the use of the Trombe wall in high-rise buildings is minimal. There are several reasons for this. Firstly, the use of solar energy is limited by the density of buildings in high-altitude areas. For solving this problem, it is necessary to plan residential and business urban districts well in advance and to emphasize the use of incident solar radiation in heat supply systems. Secondly, the use of massive walls in high-rise buildings is difficult. A massive wall is usually made of heavy materials. And the weight of building structures for high-rise buildings is a very important factor in the design. For solving this problem, it is advisable to use materials with a phase transition, for example, in Ref. [96]. This method can significantly reduce the mass of a massive wall. However, with such a constructive solution, the required thermal protection of the building should be provided. According to Ref. [96], in high-rise buildings, for use as transparent heat-insulating materials, polymethyl methacrylate (PMMA), polycarbonate (PC) or power-efficient glass. For climatic zones with mild and warm winters, it is most advisable to use the Trombe wall with photovoltaic cells using materials with a phase transition in a massive wall. Since such climatic zones require minimal thermal protection, which can only be achieved through transparent thermal insulation materials [97]. At the same time, it is possible to compensate for part of the electricity that will be used for space heating by converting incident solar radiation into electricity using photocells.

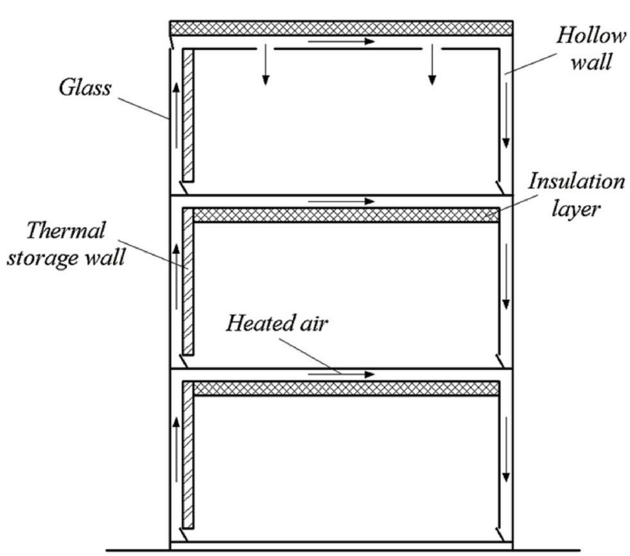

Fig. 9. The Trombe wall construction for high-rise buildings [92].

7. The aesthetic appearance assessing of the trombe wall in buildings

The building aesthetic appearance is completely formed under the influence of such factors as the architectural concept, the used materials, the accepted color scheme, and also depends on the general architectural style of the existing buildings within the established area. Even though that the Trombe wall is a linear structure of the building, it is not always easy to fit into the general architectural style of the building. Firstly, this is due to the Trombe wall design. For example, the construction of the Trombe wall with a wall ventilation duct for removing hot air in the summer [26] will significantly stand out against the general background of the southern building facade. Thus, without additional elements for the exterior decor, it will be difficult to fit such a Trombe wall into a single architectural style of the building. In addition, it is worth mentioning the Trombe wall, which uses photovoltaic cells [44]. Their use can affect the facade color scheme. It is because the photovoltaic cells are mainly made in blue, and this significantly reduces the choice of colors for the building. Secondly, this is due to the building materials used, of which the Trombe wall is made. For example, the Trombe wall made almost from improvised means [98], where the massive wall layer consists of aluminum sheet, paraffin wax, and water bottles. Although the results of the experiment showed excellent thermal efficiency of such a Trombe wall structure, it is almost impossible to fit the Trombe wall from plastic bottles into the modern ergonomic architectural style of an energy-efficient building. Concerning the classic or modified Trombe wall, it is most comfortable to fit into a single building style. For example, the glazing of the Trombe wall on the floor can look advantageous in the exterior, giving some visual illusion or the false impression of the entire southern facade panoramic glazing. Besides, there is the opportunity to create an unusual composition of windows on the building facade. However, this design decision has one disadvantage. If in the daytime the Trombe wall glazing looks like an ordinary window in which the surface of the earth and sky is reflected, then in the nighttime, it looks like a black spot on the facade. For solving this drawback, it is possible to use night illumination of the Trombe wall and the facade as a whole or use design solutions in the form of black rectangles that will create a unique architectural look for the exterior.

It should be borne in mind that the Trombe wall is always located on the southern facade [98], since it is on the southern side of the building that the maximum intensity of incident solar radiation is observed. For this reason, the Trombe wall will not affect or distort the aesthetic appearance of the central facade of the building, which is very important for some residential areas with the same architectural style.

8. Theoretical and numerical models for the trombe wall calculating

Most studies of the Trombe wall were originally built on the basis of numerical experiments using mathematical modeling [31,46,70,78,99], some of which were subsequently confirmed by field studies [21,63,71,77].

Mathematical models of non-stationary processes most accurately describe and consider most of the real factors of radiation-convective heat transfer between the Trombe wall and the air of a heated room [31,46,77,99], Such factors include the temperature of the glazing surfaces and the massive wall, changes in the convective heat transfer coefficients near the surfaces, and the heat transfer inside the massive wall, which changes over time. For solving complex unsteady heat and mass transfer problems, software packages are mainly used.

There are a number of studies [100,101], in which heat and mass transfer between the Trombe wall and the air of a heated room is considered as a stationary process. Such mathematical models make it possible to simplify the calculation since models can be represented as the equations of the heat balance of air in a convective element. However, such a solution gives only an approximate vision of the processes of heat and mass transfer that occur between a massive wall and the air gap.

The main drawback of most existing mathematical models of the Trombe wall [21,31,46,77,99], is that models do not take into account the combined operation of the primary heat source and the Trombe wall. It is because the required amount of thermal energy for heating the room is fully provided by the Trombe wall.

Since not in every climatic condition it is possible to accumulate a sufficient amount of thermal energy for heating during daylight hours, given the inconstancy of incident solar radiation, the main heat source is required. In this case, the difficulty of calculating heat and mass transfer with two heat sources lies in how to regulate the load on the main heat source during daylight hours. The power of the central heating source is directly proportional to the incident solar radiation on a massive wall during the day. The mathematical model should take into account the predicted values of solar intensity depending on the time of day and time of the year, based on which the power of the main heating source should be established in order to provide the room with the required amount of thermal energy and avoid overheating.

9. Economic feasibility of trombe wall using

The economic component of the Trombe wall consists of two components: reducing the consumption of external energy resources and reducing emissions of harmful substances [102]. However, the payback period of the Trombe wall is highly dependent on many different factors: climatic conditions, building materials used, the cost of fuel and heating equipment, and others. According to the results of the study [103], the Trombe wall is a long-term project based on the payback period.

Chel A. and others presented the most detailed economic calculations [104]. According to the results of the technical and economic calculation [104], under the Gwalior climatic conditions, the Trombe wall reduced energy consumption by 134.5 kWh/m^2 per year, and CO_2 emissions by 145 kg/m^2 per year. Since the construction of the Trombe wall was very simple, its payback period was only 7 months [104].

According to Ref. [83], the payback period when using an electric boiler was about 6 years, and when using a gas boiler for about 18 years. Based on the results of [83], it appears how energy prices lead to an increase in the payback period of the Trombe wall.

The thermal efficiency of the Trombe wall is determined as follows [105]:

$$\eta = \frac{Q_{trombewall}}{I_{solar}} \tag{1}$$

here $Q_{trombewall}$ is the amount of accumulated energy in the Trombe wall that is transferred to the room through radiation and convective heat transfer,I_{solar} is the incident solar radiation on the Trombe wall.

Table 2 presents the main results by evaluating the Trombe wall effectiveness. According to the obtained data (Table 2), it is noted that the thermal efficiency of the Trombe wall ranges from 20 to 40%. This difference in the results of evaluating the Trombe wall effectiveness is mainly due only to the influence of climatic conditions. In fact of using the Trombe wall as an additional heat source, it is an economically viable solution for a combined heating system.

The technical and economic potential of the Trombe wall in the Harbin city climatic conditions based on the results of evaluating the Trombe wall thermal efficiency was evaluated. Table 3 presents the main parameters for Harbin's climate.

It was estimated that during the heating season, the building consumes 20,628MJ of thermal energy. It is taken the thermal efficiency of the Trombe wall by 40%. Table 4 presents the main characteristics of energy fuel.

The required amount of energy fuel was determined to generate the required amount of thermal energy for the entire heating season, using the data Table 4 (Fig. 10).

Table 3
Climatic characteristics of the Harbin city.

Parameter	Value
Climatic zone	III, 6
Average annual temperature	+ 5,5 °C
The average temperature of the heating period	− 9,8°C
Annual solar activity	1319kWh/m^2
Solar activity in the heating season	559 kWh/m^2

Table 2
Summary of some case studies performance results of Trombe wall for space heating.

Author/Year	Collector area	Type of collector	Temperature rise	Efficiency	Main achievements	Reference
F. Stazi et al., /2012 (Italy)	6,75 m^2	Aerated concrete 40 cm thick, wood frames and double glazing	N.A	55%	Emission reductions 508.33 $kg\ CO_2\ eq.$	[67]
K. Hami et al., /2012 (Algeria)	7 m^2	Massive wall 40 cm thick, air gap 30 cm thick	18°C–24°C	48,54%	N.A	[73]
I. Hernandez-Lopez et al.,/2012 (Mexico)	9m^2	Concrete wall 30 cm thick, thickness of the semitransparent wall 6 mm	35 °C	N.A	Maximum energy stored is about 109 MJ	[65]
M. Bojic et al.,/2013 (France)	13,75 m^2	Clay brick 1220, double glazing	18°C	N.A	Saving energy during heating is around 20%	[83]
Y. Liu. et al., /2013 (China)	N.A	0,04 cm simple glass, 10 cm air layer, 1 cm red corrugated iron, 24 cm brick wall and a 5 cm polystyrene cystosepiment	22,7 °C	N.A	Maximum energy stored is about 10,6MJ/m^2	[25]
Ana Briga-S et al., /2014(Portugal)	7,5 m^2	Concrete wall 40 cm thick, double glazing	18 °C	16,3%	N.A	[108]
Abbassi et al., /2014 (Tunisia)	10 m^2	Cement plaster 0.02 cm, Plastered brick0.065 cm,12-hole brick 0.15 cm, Cement plaster 0.025 cm	22 °C	N.A	Energy saving compared to base case 1300 kWh	[72]
M. Dabaieh et al., /2015 (Egypt)	10,2 m^2	Rammed earth 40 cm thick, double glazing 6 mm, air gap 60 mm, sheep wool insulation panel 15 cm	19°C	94%	Energy saving compared to base case 53,631 kWh, emission reductions 144,267 $kg\ CO_2\ eq.$	[71]
N. Simoes et al., /2015(Portugal)	8,43 m^2	Brick Masonry 35 cm thick, double glazing	20 °C	21%	N.A	[88]
M. Rabani et al., /2015 (Iraq)	3 m^2	Concrete wall 40 cm thick	15 °C	N.A	Energy saving compared to base case 5800 kJ/h in February	[26]
E. Bellos et al., /2016 (Greece)	15 m^2	Heavyweight concreate 30 cm thick	18,5 °C	25%	N.A	[90]

Based on the results obtained (Fig. 10), the cash costs for the purchase of energy were determined throughout the heating season (Fig. 11).

It is used the following formula to determine the amount of CO_2 emissions into the atmosphere [107]:

$$M_{CO_2} = 3.67 \times 0.01 \times c_p \times B \times (1 - \frac{q_3}{100}) \times \quad (1 - \frac{q_4}{100}) \tag{2}$$

where c_p is the carbon content in the working mass of the fuel,B is the natural fuel consumption for the calculation period,q_3 is the loss of heat from the chemical incompleteness of fuel combustion,q_4 is the loss of heat from the mechanical incompleteness of fuel combustion.

In Fig. 12 presents the calculation results for CO_2 emissions into the atmosphere.

According to the results of a brief technical and economic calculation (Figs. 10–12), the Trombe wall using in Harbin's climatic conditions, the decrease in energy consumption, and cash costs of 32% in January were observed. With an increase in outdoor temperature and solar activity during the heating period, a decrease in energy consumption can reach 50%.

So, at the cost of the Trombe wall \$ 187 per 1 m^2, the annual cost savings of 1 m^2 for the purchase of natural gas in Harbin's climatic conditions will be about \$ 25. The payback period for such a project will be about 8 years. For comparison, the city of Milan is located almost at the same latitude as Harbin, but the average temperature for the coldest month is $-3.5°C$. The annual savings of 1 m^2 for buying natural gas in Milan's climatic conditions will be about \$ 37. The payback period for such a project will be about 5 years. This difference is due to climatic conditions and the high cost of energy fuel. If in Harbin 1 m^3 of natural gas costs 3.68 *CNY*, then in Milan, its cost is about 7 *CNY* for 1 m^3. At the same time, the intensity of incident solar radiation during the heating period is almost identical in the two cities and leaves about 414 kW/m^2.

Thus, the use of the Trombe wall in Harbin's climatic conditions is an economically viable solution for the heating system of a low-rise building. However, it should be noted that the Trombe wall in Harbin's climatic conditions is only an additional source of heat, in contrast to the climatic conditions of Milan, where the Trombe wall can be the primary and only source of heat.

The economic component is an essential factor in the design of energy-efficient buildings, including the design of the Trombe wall. The results of the analysis of Table 2 showed that in various studies, the effectiveness of the Trombe wall is different. It is due to the following three factors: the studied climatic conditions, setting goals and objectives of the study, methods to achieve the goals and objectives. Studies rarely describe the issue of the Trombe wall payback. In this case, a new factor appears that affects the efficiency and payback of the wall, namely the economic situation in the country. According to the results of [64], in European countries, the payback of the Trombe wall is from 6 to 10 years if electricity or gas heats the room. Naturally, this is due to the high price of energy fuel. In other countries where natural resources are cheaper, the payback period is several times higher. Therefore, for the correct assessment of the Trombe wall effectiveness, it is necessary to establish criteria for effectiveness. These performance criteria include cash costs, energy consumption, and emissions.

Table 4
The main parameters of energy fuel [105,106].

Parameters	Coal	Nature gas	Furnacefueloil
Cost, CNY	2.5 CNY/kg	3.68 CNY/m^3	5.487 CNY/kg
Specific heat of combustion, 1kg , 1 m^3	27MJ	33,5MJ	40,61MJ
Carbon content in combustible fuel mas, %	80	75	87
Calorific net value, J/ ton	17,68	48	40,4
Carbon emission factor, ton/ J	25,58	15,04	20,29

10. Conclusion

Despite the apparent simplicity of the Trombe wall problem at first glance, the results of the review show the complexity of these designs and calculations. This situation is since each element of the Trombe wall depends on and affects other elements of the wall structure. Thus, the glazing influences the further selection of massive wall structural solutions. It is because heat losses through glazing can range from 56 to 64% of all incident solar energy on the wall [65]. In this study, a Trombe wall problems literature review over the past 15–20 years was made.

Based on the obtained results, several problematic issues of using the Trombe wall in cold climatic conditions were identified and established, which were either insufficient or not studied at all. Such problematic issues include the increase in Trombe wall thermal protection, in particular through the use of vacuum double-glazed windows, glass blocks; the use of thermal insulation in the Trombe wall construction; overheating of rooms in the summer mathematical modeling of heat and mass transfer, taking into account the joint work of the Trombe wall and the main heat source; optimization of control of the air flow rate in the air gap and regulation of the heat transfer coefficient for each surface; the influence of the aesthetic appearance of the Trombe wall on the building exterior and the limited use of passive heating in high-rise buildings.

Besides, a large part of the scientific research in this survey was carried out in climatic conditions in which severe winters are not observed (Italy, Portugal, Spain, South China, Iraq, Turkey, Egypt, and others). Based on this, the aim was to establish the most appropriate design solutions for the Trombe wall in cold climates, where there is a sufficient amount of solar energy throughout the heating period. Key findings of the structural solution for the Trombe wall in severe climatic conditions:

1) For severe climatic conditions, the following types of Trombe walls are suitable: modified Trombe wall, composite Trombe wall, and Trombe wall with phase changing materials. This choice is due to the ability to provide the necessary thermal protection while maintaining a sufficient level of solar energy storage efficiency [23,24,31].
2) Glazing has a considerable impact on how much solar energy the Trombe wall can accumulate in itself. As glazing for the Trombe wall in severe climatic conditions, it is necessary to use a double double-glass unit window with a massive wall, which has a high thermal resistance.
3) The thickness of the air gap has a significant impact on the temperature of the indoor air. It is necessary to use an air interlayer with a thickness of 29–35 *cm*[68,78], to ensure maximum thermal efficiency of the Trombe wall in severe climatic conditions.
4) A massive wall is the most crucial element in the Trombe wall since it is this element that absorbs solar energy during a sunny day. Therefore, this element requires careful study when designing the Trombe wall. For severe climatic conditions, it is most advisable to use a massive wall of heavy concrete with a thickness of 30–35 *cm* with an external PCM on the sunny side.
5) It is most expedient to use heat-insulating materials in the composite Trombe wall. In other cases, it is more useful to refuse from thermal insulation, since such a solution significantly reduces the Trombe wall thermal efficiency. Protective curtains have the highest thermal insulation efficiency [18,80], which are better in the night period.
6) In severe climatic conditions, the Trombe wall ventilation ducts must necessarily have fans, which must be automated to change the temperature both indoors and in the air layer. Such a solution makes it possible to establish control of massive wall heating on a sunny

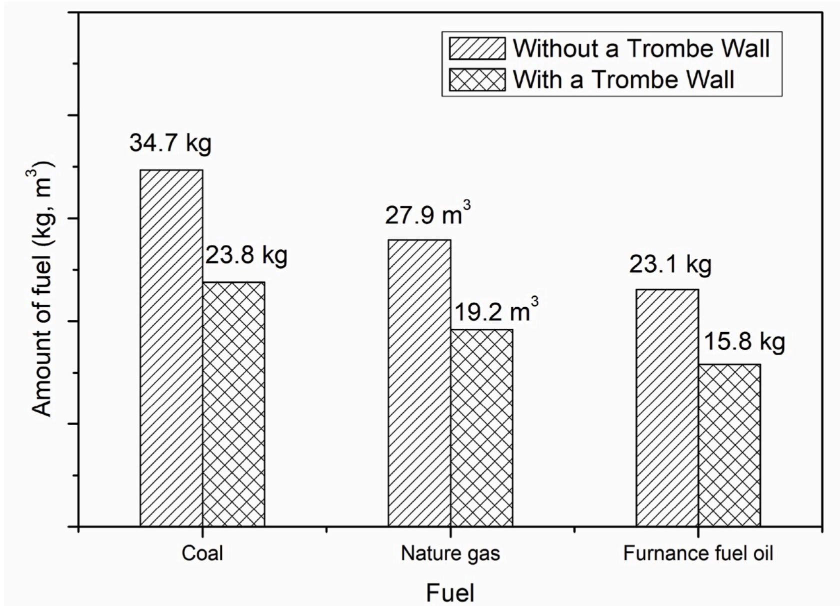

Fig. 10. The amount of fuel consumed in the heating period without and with a Trombe Wall per $1m^2$ of floor space.

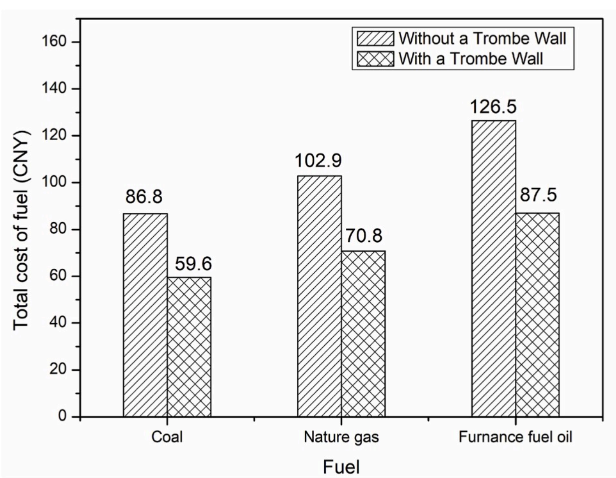

Fig. 11. Cash costs for energy fuel without and with a Trombe Wall per $1m^2$ of floor space.

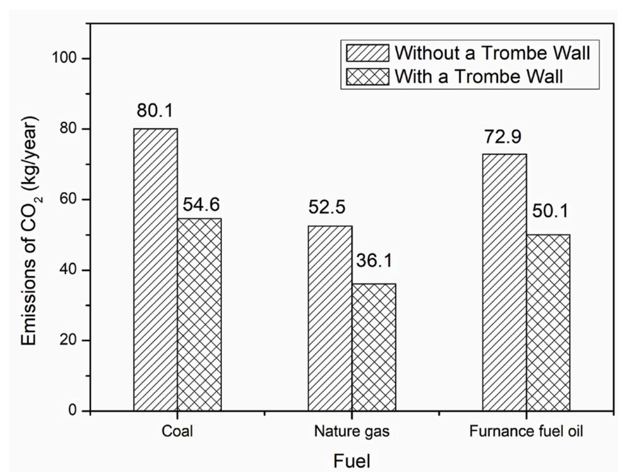

Fig. 12. Emissions of CO_2 from various energy resources without and with a Trombe Wall per $1m^2$ of floor space.

day, and then control the heating of indoor air through convective heat transfer at night.

7) The use of window openings in the Trombe wall for cold climatic conditions is exceptionally undesirable. It affects the storage capacity of the massive wall, as well as heat loss increase. It is more advisable to use windows in adjacent walls or light wells in the roof of the building to ensure the required norm of natural lighting of the room.
8) The results of the overall Trombe wall effectiveness evaluating can be very different when using specific evaluation criteria. These criteria include the following: cash costs, energy consumption, and emissions. As a result, it is required to establish the essential criterion for the established design conditions.
9) In cold climates, the Trombe wall is only an additional source of heat for heating the building. So, for the Harbin climatic conditions, in the coldest month of the heating season, the Trombe wall reduces energy costs to a maximum of 30%. Further, in the moderate months of the heating season, the reduction in energy consumption can reach up to 50%.

Thus, on the review results, it is based and identified the following list of structural elements of modified Trombe wall for cold climatic conditions: a double-glass unit, an air gap of 29 *cm* thickness, a layer of organic PCM with a fusion heat of about 290 *K*, a massive wall of heavy concrete 30 *cm* thick, air vents with fans automated operation in a massive wall, as well as the obligatory temperature sensors location inside a heated room and in the Trombe wall air gap. Temperature sensors allow more efficient use of the leading heating source resources on sunny days.

11. Recommendations for further study

The following recommendations are suggested as further research directions for the Trombe wall. It is recommended to study the Trombe wall aesthetic effect on the general building exterior, which is aimed at developing such design and constructive solutions that will preserve the Trombe wall thermal efficiency and allow it to fit into the overall architectural building design. From the constructive solutions point of view, studies that are aimed at improving the Trombe wall thermal protection should be proposed. Since most of the heat loss is observed through glazing, the main research should be directed to the use of new types of energy-efficient glasses, to assess the possibility of using the glass block in cold climatic conditions. As methods to reduce overheating in the summer, the evaluation of using smart polymers on glazing feasibility is suggested, which allows changing the light transmission of glass. Also, studies of structural solutions are recommended that will help regulate or reduce the overall heat transfer coefficient between the air in the air gap and the glazing. For example, increase the glazing surface area by placing ribs from plexiglas sheets on the inner side of the glazing or set different air flow rates for two surfaces in the air gap using an adjustable space in the air gap. Studies of new materials with a phase transition, which will allow accumulating a sufficient amount of thermal energy, saving the space of a massive wall, are especially relevant for high-rise buildings. Development of efficient facade systems made of energy-efficient glass with PCM, which will allow the accumulation of thermal energy due to incident solar radiation, is recommended. Research on the development of a mathematical model that takes into account the combined heat supply system, in which the Trombe wall and the main heat source work simultaneously, is optional. A study on the development of a software package based on mathematical models of heat and mass transfer, which would determine the optimal settings for a constructive solution of the Trombe wall based on established climatic conditions, the intensity of incident solar radiation, and the cost of energy fuel, is also relevant. It should be noted that any study should consider the economic component, which will affect the payback period of the Trombe wall project.

Declaration of competing interest

The authors declared that they have no conflicts of interest to this work.

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