Trombe Wall Performance in Multiple Climates: A Simulation Study

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Abstract
Global warming is an increasing concern worldwide, with energy production enhancement being one of the contributing factors. By 2040, the global energy demand is projected to increase by approximately one-third. This paper proposes a study on the efficiency of implementing a simple Trombe wall structure to passively gain solar energy and heat or cool a space. The methodology involves using computational data on heating and cooling energy loads via simulations in the DesignBuilder software. Fifteen climate zones were selected according to the Koppen-Geiger climate classification map, and appropriate building envelopes and simulations were modeled and conducted. The results were controversial for some climate zones and required further investigation. The simulation data demonstrated the efficiency of the Trombe wall installation in one zone and showed its inappropriateness for another climate classification. The specific composition of the wall, roof, and other building structures is crucial for particular climate zones. Another potential reason for Trombe wall performance being negative in terms of energy-saving parameters in heating-dominant zones is the climate classification issue.

Keywords
Global warming; Climate zones; Passive solar energy gaining system; Trombe wall; Energy efficiency

1. Introduction

In recent times, the energy demand is rapidly increasing in the world. It is significantly linked to urbanization and global warming. The energy loads are predicted to be increased by 37% by 2040 globally (IEI RAS, 2013). It inevitably leads to the release of harmful and health-destructive gases into the environment due to energy generation to maintain the comfortable thermal conditions in building envelopes. The building envelopes use heating, ventilating, and cooling (HVAC) systems to maintain an appropriate level of indoor temperatures. One of the ways to minimize emissions from the buildings is to use passive solar energy systems, particularly the Trombe wall structures, both for heating and cooling purposes (Hu et al, 2017). Trombe wall is a structure usually oriented to the south in the Northern hemisphere and usually of dark color with glazing material to transfer solar radiation inside the building (Fig. 1). It has different consistency but mainly it is made of brick, quarry rock, and reinforced concrete (Saadatin et al, 2012). Incorporating the Trombe wall structures in the building envelopes is one of the strategies leading to sustainable development. The Trombe walls are extremely encouraged to be implemented due to their advantages such as simple configuration, high efficiency, and minimized construction and maintenance costs (Hami et al, 2012).

Rabani et al (2015) investigated the potential of the Trombe wall structure in decreasing the energy load needed for heating and cooling purposes in Yazd city, Iran. A design for the Trombe wall was proposed. Specifically, they invented the Trombe wall with glazing surfaces facing east, south, and west directions. Thus, the modified wall received more solar radiation than the ordinary one and the difference accounted for roughly 16%. Likewise, the energy storage of the Trombe wall increased. It achieved 5800 kJ/h in February of energy stored.

Jaber and Ajib (2011) investigated the performance of the Trombe wall for a residential building located in the Mediterranean region. The energy simulations were done by TRNSYS software and the optimum Trombe wall area ratio as a function of the economic and thermal parameters was designed. The Trombe wall structure had the classical configuration used for heating purposes in the Amman region of the Mediterranean region. The prototype building was modeled using ASHRAE Standard 62.2. As a result, after completing simulations, it was calculated that roughly 20% of the annual heating load could be saved by implementing the Trombe wall structure when it was embedded into two bedrooms facing the South facade. Moreover, they reported that the additional embedment of a

Trombe wall to the guest room with two bedrooms increased the savings to 27% of the annual heating energy load. By examining the effect of the Trombe wall ratio on the energy performance, it was inferred that the optimum wall ratio is 37% for the particular building prototype. However, the conclusion implies that the availability of solar radiation plays a big role in the performance of the Trombe wall. Precisely, the higher the solar radiation, the less amount of heating energy is needed to maintain comfort conditions in the building envelope.

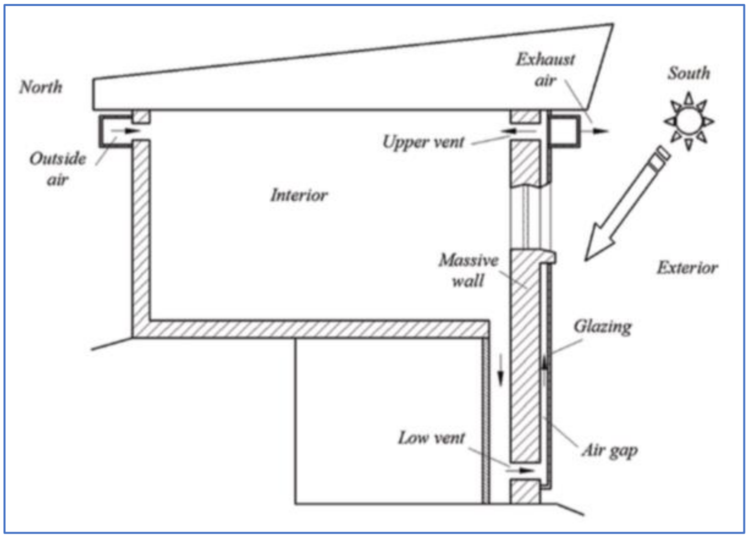

Fig. 1. Simple Trombe wall (Trombe and Michel, 1972).

This research is going to investigate the extent to which the installation of the Trombe wall structure is efficient in diminishing the energy consumption rate of buildings in different climate zones. The abbreviation and location of borderlines for climate zones are presented in Koppen-Geiger updated map (Fig. 2). The question is to be answered by calculating the energy performance of particular building envelopes in selected cities situated in different climate zones. Although Trombe walls are invented at the end of the twentieth century, their energy performance in different climate zones is not studied properly and this research is to fill this gap to some extent. The potential usefulness of this structure is the decline in heating and cooling consumption which could positively affect the environment while decreasing carbon dioxide emissions. Moreover, passive solar energy production does not require the consumption of electricity. The first part of the paper is to design two building envelope models in the DesignBuilder software. Particularly, one is the basic building and another one is modeled using the Trombe wall structure. The second part reports the results of simulations done by the DesignBuilder software. It includes tables and graphs showing the consumption of heating and cooling energy for two building types for the period of 2004-2018. The next part discusses and compares retrieved data with each other. The last part is dedicated to finding the overall trend of efficiency of the Trombe wall structure installation.

2. Methodology

2.1. Koppen-Geiger climate classification map

The selection of cities was done according to the modified Koppen-Geiger classification map (Beck et al, 2018). The research uses the latest version of the Koppen-Geiger climate classification map with a 1 km resolution. This study used a map projected for the present day, particularly for 1980-2016 (Fig. 2). The recent version of the map includes five major climate zones with thirty types of subzones. Zoning is done taking into account the temperature profile and precipitation rate of the specific region. Specifically, the map includes tropical (A), arid (B), temperate (C), cold (D), and polar (E) climates. The following sub-zoning is done following the precipitation rate of location: desert (W), steppe (S), fully humid (f), summer day (s), winter dry (w), and monsoonal (m). Furthermore, the difference in temperature profiles is defined by hot arid (h), cold arid (k), hot summer (a), warm summer (b), cool summer (c), extremely continental (d), and polar frost (F) conditions.

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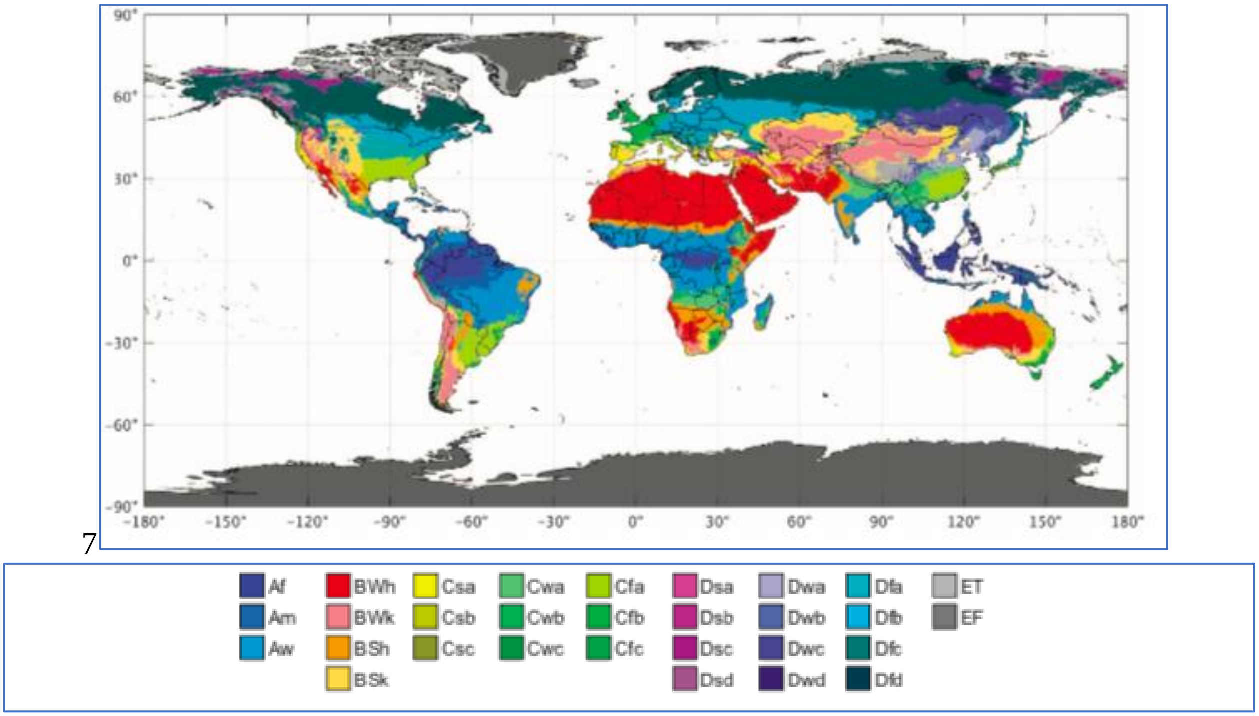

Fig. 2. Koppen-Geiger climate classification map is valid for 1980-2016 (Beck et al, 2018).

2.2. Selection of cities

Three different cities from each climate region were chosen concerning the updated Koppen-Geiger climate map to find the approximate pattern and increase the accuracy of results. Cities are chosen to be not within the boundaries of climate zones to avoid miscalculations in the results of energy consumption. The geographical situation, elevation, and climate classification of each city are represented in Table 2 in the results section.

2.3. Reference buildings

Two different building models were designed in the DesignBuilder software but with the same floor area of 15 m x 15 m dimensions. The floor-to-ceiling height of both buildings is equal to 3.5 m and the chosen window-to-wall ratio accounts for 25%. The window height equals 1.5 m with 5 m spacing between each other. The building is a single-room building that is occupied by a couple of people who go to work every day from 8 am to 7 pm and, subsequently, the occupancy time is designed to be from 7 pm to 8 am during which a couple does not exercise actively. During the occupancy time, they mostly do cook and relax in front of the TV.

The composition of external walls is similar in both envelopes. The visual representation of the wall composition can be found in Fig. 3. The main heat transfer coefficients are convective and radiative are also taken into account and reported in Table 1.

The basic roof structure is chosen in this research. The flat roof is not pitched and the composition and its visual representation are in Fig. 4. The heat transfer coefficients are almost the same as in the external wall structure, particularly it is presented in Table 1.

The following part is to depict the specific composition and designs of buildings without Trombe walls and a building with an incorporated Trombe wall structure.

2.3.1 Basic building envelope

The basic building envelope without a Trombe wall installed is shown in Fig. 5 and is considered to be a single-room box model with eight windows (two windows for each wall). The dimensions of the floor are 15 m x 15 m.

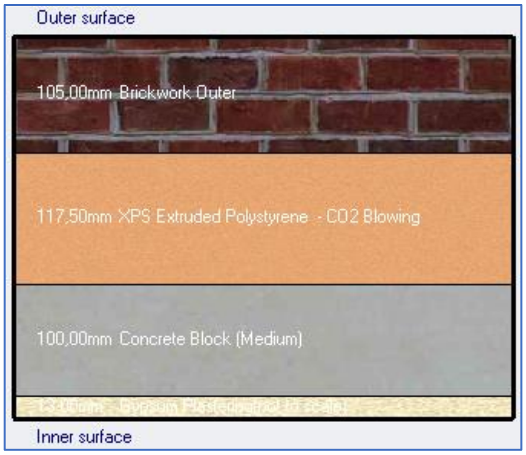

Fig. 3. External wall composition

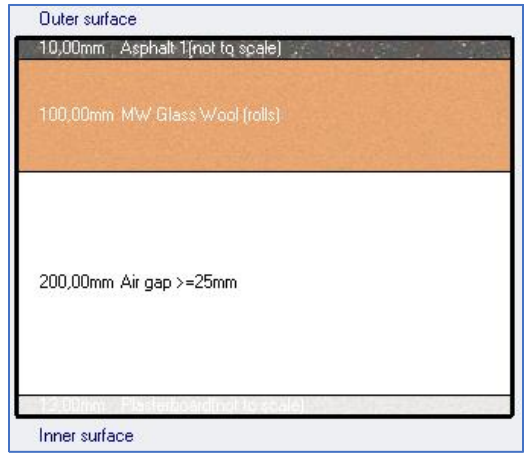

Fig. 4. Flat roof composition

Table 1. Heat transfer coefficients (W/m^2-K) of external wall and flat roof

	External wall and Flat roof	Internal partition wall
Outer surface		
Convective	19.87	2.152
Radiative	5.13	5.54
Inner surface		
Convective	2.152	2.152
Radiative	5.54	5.54

Fig. 5. Rendered view of the building envelope without the Trombe wall

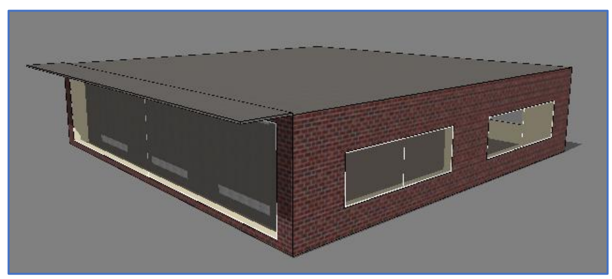

Fig. 6. The rendered view of the building model with Trombe wall

2.3.2. Building envelope with embedded Trombe wall structure

The floor area of living space is lower in the basic building home due to the installation of a Trombe wall, which has a floor area equal to 10.95 m^2, the dimensions are 15 m x 0.73 m (Fig. 6). It was installed instead of one wall, and therefore, the number of windows decreased by two. The Trombe wall is presented in the schematic view in Fig. 7. Taking into account the schematic view, it can be seen that the purple rectangles are the vents. Vents are located at the top and the bottom of the partitioning wall. Air from the bottom three vents is going to circulate and go upward, thus, entering the three upper vents. Each of the vents has a rectangular shape and size of 2.5 m x 0.29 m. Furthermore, the Trombe wall has amended the windows with an outer glazing layer. The dimensions of the glazing surface are 13.85 m x 3 m.

The Trombe wall structure has a shading plate at the top, as the continuation of a flat roof structure. The dimensions of the plate are 15 m x 1.48 m. It is used to protect the building from direct solar radiation during summertime.

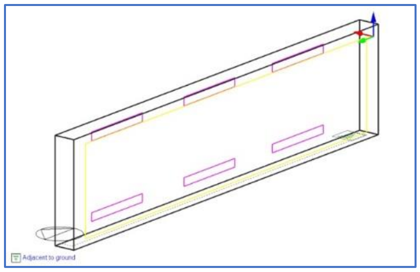

Fig. 7. Schematic view of the Trombe wall

It is determined that at noon of 15 July, the sun is at its peak and no direct sun rays enter the single-room house due to the installed shading plate. Hence, allowing the sun's rays to enter the room during wintertime. Specifically, on 15 December, when the sun is at its peak height over the house, the direct sunlight warms the partition wall of the Trombe wall structure, thereby, increasing the temperature inside the envelope. The internal wall consists of a gypsum plasterboard on its outer surface and an air gap between them (Table 1).

2.4. Energy simulation

One of the potential ways to gauge how the building envelope will be affected by climate change is to look at its energy performance. EnergyPlus software was used to run the simulations with the aid of a reference building that was modeled in DesignBuilder software. EnergyPlus software is operating within the DesignBuilder software to calculate heating, cooling, and annual energy demand in buildings. Properly validated energy simulations are crucial for analyzing the building's heat transfer and changes in energy consumption.

3. Results and Discussions

The hourly weather files needed for performing energy simulations were imported into the software, which was downloaded from the online website climate.onebuilding.org. The hourly weather data then was imported into DesignBuilder software and energy simulations were performed for each climate zone consequently. The results of energy simulations for both the basic building and the building incorporated by the Trombe wall are presented in Table 2.

Table 2. The results for the basic building envelope.

Zone	City	Latitude	Longitude	Elevation (m)	Building without Trombe wall		Building with Trombe wall	
					Heating demand (kWh)	Cooling demand (kWh)	Heating demand (kWh)	Cooling demand (kWh)
Af	Kuala Lumpur, Malaysia	3.1	101.7	66	0	3223	0	3660
	Davao, Philippines	7.1	125.7	18	0	5153	0	5289
	Singapore, Singapore	1.4	103.8	15	0	4060	0	5038
Am	Douala, Cameroon	4	9.7	9	0	21255	0	15935
	Cairns, Australia	-16.9	145.8	8	0	18140	0	14545
	Mumbai, India	19.1	82.9	11	0	17755	0	18556
Aw	Brasilia, Brazil	-15.9	-47.9	1061	0	12679	0	12194
	Caracas, Venezuela	10.5	-66.8	842.8	0	14480	0	14262
	Havana, Cuba	23.2	-82.3	40.2	0	12701	0	17165
BWh	Abu Dhabi, UAE	24.4	54.7	27	0	11819	0	15892
	Cairo, Egypt	30	31.2	23	0	10427	0	7871
	Doha, Qatar	25.3	51.5	7.3	0	16569	0	13145
BSk	Valencia, Spain	39.5	0.5	62	0	3672	0	6543

	Karaganda, Kazakhstan	49.8	73.2	553	6859	0	5395	0
	Tehran, Iran	35.7	51.4	1168.3	0	3214	0	4844
BSh	Lahore, Pakistan	31.5	74.4	217	0	11846	0	8788
	New Delhi, India	28.6	77.2	213.6	0	10252	0	8136
	Tripoli, Libya	32.7	13.1	63	0	9235	0	9221
Cfa	Atlanta, USA	33.7	-84.4	320	3054	4442	0	4002
	Belgrade, Serbia	44.8	20.4	170.3	3032	0	2795	0
	Bucharest, Australia	44.4	26.1	71.6	5512	0	5925	0
Cfb	Amsterdam, Netherlands	52.4	4.9	9.5	3920	0	4300	0
	Bilbao, Spain	43.3	-2.9	39	0	1398	0	4903
	Brussels, Belgium	50.9	4.4	26.7	4102	0	3976	0
Csa	Algiers, Algeria	36.8	3.1	37	0	8511	0	7006
	Athens, Greece	38	23.7	70.3	0	981	0	3904
	Barcelona, Spain	41.4	2.2	9.9	301	0	770	0
Csb	Cannes, France	43.6	7	6.4	0	0	0	4486
	Cape Town, South Africa	-33.9	18.4	14	0	14868	0	15916
	Vancouver, Canada	49.3	-123.1	32	0	4052	0	5034
Cwa	Hanoi, Vietnam	21	105.8	15.7	0	10553	0	6393
	Kathmandu, Nepal	27.7	85.3	1304.8	0	7936	0	6487
	Macau, China	22.2	113.5	40.5	0	12195	0	8977
Cwb	Johannesburg, South Africa	-26.2	28	1755	0	13158	0	12710
	Mexico City, Mexico	19.4	-99.1	2230	0	11867	0	10299
	Harare, Zimbabwe	-17.8	31	1488	0	11673	0	11824
Dfa	Chicago, USA	41.9	-87.6	181.3	2775	0	4946	0
	Minneapolis, USA	45	-93.3	254.8	3119	0	4996	0
	Orenburg, Russia	51.8	55.1	112	8197	0	7042	0
Dfb	Arkhangelsk, Russia	64.5	40.6	1	9137	0	8019	0
	Kyiv, Ukraine	50.5	30.5	157	6296	0	7492	0
	Oslo, Norway	59.9	10.8	5.3	5302	0	5247	0
Dfc	Tromso, Norway	69.7	18.9	10	7191	0	7473	0
	Helsinki, Finland	60.2	24.9	7	7397	0	7540	0
	Bratsk, Russia	56.3	101.8	416	9765	0	9337	0

The Am zone is tropical monsoonal. All cities demonstrated the same pattern. Three cities demand no heating energy and a substantial number of cooling energy. By implementing the Trombe wall structure instead of the wall-oriented South, the cooling energy consumption decreases substantially in Douala from 21255 kWh to 15935 kWh. The same cannot be notified regarding Mumbai city, where the cooling energy demand increased by roughly 800 kWh with the installed Trombe wall. The decrease in cooling demand for Cairns accounted for 20%.

The Aw zone is a tropical winter dry climate area. The annual average solar radiance intensity is higher in Caracas than in other cities, which demonstrates the vulnerability of energy-building performance to changes in the HVAC system (Yang, Li, and Hu, 2006). The same behavior could be noticed, as in Am zone, no heating energy consumption is needed in these cities. However, a bit different results were obtained. For instance, the cooling demand of Brasilia and Caracas almost did not change and was approximately left at that level. Whereas the cooling energy consumption of the building in Havana increased by roughly 5000 kWh with the installation of the Trombe wall.

The BSh zone is arid steppe hot arid. The implementation of the Trombe wall positively reflected the cooling demand parameter. The cooling energy consumption decreased in all three cities of the BSh zone. The least decrease counted for 14 kWh, while the highest number exceeded 2000 kWh. For instance, the change in cooling demand in New Delhi is equal to 2116 kWh. In addition, the least difference was registered in Tripoli and it counted for 14 kWh.

The BSk zone is arid steppe cold arid. The buildings in Karaganda city demonstrated a need for heating energy and the installation of the Trombe wall enabled the fall in heating energy demand in buildings. The decrease in heating energy demand is found to be approximately 1500 kWh. The buildings in Tehran and Valencia showed insignificance in heating energy and the need for cooling energy in the living space. However, the BSk climate zone's results are controversial with the BSh climate zone's values. To be more precise, the cooling demand of Tehran and Valencia increased by roughly 50-100% in comparison with the building envelope without the Trombe wall.

The BWh zone is an arid desert hot arid. It can be seen that the higher value of solar radiation belongs to Doha, which results in a much higher cooling energy load required to maintain comfortable conditions in a building (Yang, Li, and Hu, 2006). These cities are located in the desert area; therefore, the heating energy is non-preferrable and accounts for 0 kWh and all three cities. However, all these cities demand a lot of cooling energy. For example, the implementation of the Trombe structure into the building in Abu Dhabi and Doha cities would increase the demand for cooling energy. The opposite behavior is noticed in Cairo. The cooling energy consumption would decrease substantially with the installation of Trombe wall architecture instead of one wall.

The Cfa zone is a temperate fully humid climate with hot summer. The highest solar radiation intensity in Atlanta justifies the higher energy consumption of a building (Yang, Li, and Hu, 2006). The cities of temperate and fully humid climate zoning demand heating energy of at least 3032 kWh and a maximum of 5512 kWh. It seems to be apparent that with the installation of the Trombe wall structure, the building envelope in Atlanta neglects the usage of heating energy and parallelly the demand for cooling energy decreased in the city. The heating need in Belgrade and Bucharest has a fluctuating behavior. For instance, in Belgrade, the energy demand decreased by only 237 kWh, and in Bucharest, the demand increased by 413 kWh.

The Cfb zone is a temperate fully humid climate with warm summer. The Installation of the Trombe wall had a diverse effect on the energy demand of building envelopes in different cities. In Amsterdam, the heating demand increased by almost 400 kWh, while no cooling demand occurred. In Bilbao, vice versa no heating demand was denoted, however, the increase in cooling energy consumption was considerable and the value increased by roughly 300%. The building in Brussels demonstrated stability with a little decrease in heating demand.

The Csa zone is temperate summer dry and hot summer zone. It seems to be apparent that the solar radiance values are higher in Algiers, which consequently implies more energy demand (Yang, Li, and Hu, 2006). The cooling energy consumption of the building in Algiers was decreased in comparison to the building structure without the Trombe wall. The decrease accounted for 18%. In other cities, Barcelona and Athens, the installation of the Trombe wall had adversely affected energy consumption, specifically, it increased. For instance, in Athens, the cooling energy demand for building with Trombe walls is almost four times of demand for buildings without Trombe wall structures. In Barcelona, the heating demand also increased but only by more than 150%, from 301 to 770 kWh.

The Csb zone is a temperate summer dry and warm summer climate. From the simulation results, it is seen that the installation of the Trombe wall structure negatively affected the energy demand for building envelopes in the Csb region, as the demand increased substantially. For example, if the cooling demand in Cape Town and Vancouver went upward by 1000 kWh, the cooling demand in Cannes increased to 4500 kWh. The reason could be the composition of wall and roof structures.

The Cwa zone is temperate winter dry and hot summer climate area. The implementation of the Trombe wall structure positively reflected the cooling demand parameter in all three selected cities. The cooling energy demand in building envelope located in Hanoi city dwindled by almost 50%, particularly from 10553 kWh to 6393 kWh. The same pattern was denoted in Macau, where the cooling consumption decreased from 12195 kWh to 8977 kWh. The cooling energy load in a building with an installed Trombe wall structure diminished by almost 20% in Kathmandu, Nepal.

The Cwb zone is temperate winter dry and warm summer climate area. The heating energy demand was negligible for selected cities in the Cwb climate zone. The installation of the Trombe wall structure did not change considerably the energy load in cities. A small increase in cooling energy demand was detected in Harare, where the demand changed from 11673 kWh to 11824 kWh. The minimum decrease in cooling energy consumption is identified in Johannesburg (South Africa). More precisely, the demand decreased by approximately 4% in comparison to the results taken from the basic building envelope.

The Dfa zone is cold fully humid and hot summer climate classification. The cities are mainly located in cold areas, which results in high heating energy demand values, and simultaneously the cooling energy load is neglected. The installation of the Trombe wall system decreased the heating energy demand in Chicago and Minneapolis cities. To be more specific, the heating demand in Chicago increased from 2775 kWh to 4946 kWh with the embedment of the Trombe wall, and the demand for building envelope located in Minneapolis changed by roughly 1800 kWh.

The Dfb zone is a cold fully humid and warm summer climate classification. Three cities selected from this climate zone are Arkhangelsk (Russian Federation), Kyiv (Ukraine), and Oslo (Norway). It is apparent fact that the cities located in cold climate regions demand more heating energy rather than cooling energy values. Two cities, particularly Arkhangelsk and Oslo, demonstrate the positive effect of installing the Trombe wall structure into a building envelope by decreasing the heating energy load. To be more precise, the positive change in the Arkhangelsk building envelope's demand accounted for 1118 kWh, and in Oslo only 55 kWh. Whereas the heating consumption increased in Kyiv by approximately 1200 kWh.

The Dfc zone is cold fully humid and cool summer climate classification. The heating energy demand in all three selected cities dwindled with the installation of the Trombe wall structure. The overall decrease was approximately equal to 5% of the energy demand of the basic building envelope. For example, in Bratsk, the heating load decreased from 9765 kWh to 9337 kWh with the installation of the Trombe wall.

4. Conclusions

The research paper observed the efficiency of installing the Trombe wall into the building envelope. It was done by energy simulations in DesignBuilder software and then the extracted energy demand data were compared with each other. The results show that the Trombe wall efficiency in declining the overall annual energy demand in buildings is not high in particular climate conditions. For instance, in the Cwa climate area, which characterizes by dry winter and hot summer, the building with embedded Trombe wall structure decreased the cooling demand in all three selected cities (Hanoi, Kathmandu, Hanoi). The energy load results of building with a Trombe wall in the BSh climate zone also dwindle in comparison with the basic building envelope. However, in other climate conditions, either all or some parameters were increased with the installation of the Trombe wall. Such deviated results could take place due to the inappropriateness of chosen wall and structural elements' compositions. For future studies, it is suggested to select one zone, figure out the relevant wall and roof composition and find out the most fitting parameters to maximally reduce the heating and cooling demand of the building envelope.

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