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Passive Solar Techniques to Improve Thermal Comfort and Reduce Energy Consumption of Domestic Use

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Abstract**—**Passive design responds to improve indoor thermal comfort and minimize the energy consumption. The present research analyzed the how efficiently passive solar technologies generate heating and cooling and provide the system integration for domestic applications. In addition to this, the aim of this study is to increase the efficiency of solar systems system with integration some innovation and optimization. As a result, outputs of the project might start a new sector to provide environmentally friendly and cheap cooling for domestic use.

Keywords**—**Passive Solar Systems, Heating, Cooling, Thermal Comfort, Ventilation Systems.

I. Introduction

IN recent 30 years, the energy crisis and environment pollution have become the focus of attention the world with the increasing world population and economic development. Buildings consume the major energy consumption and carbon emissions worldwide. Passive cooling strategies on the buildings with the basic principles of selected technologies provide to use energy resources more efficiently and reduce the carbon emissions.

The current study analyzed the passive solar systems with the all-natural processes and techniques for heating and cooling buildings. The techniques are also closely linked to the thermal comfort of the occupants.

Solar heating and cooling for domestic usage is broadly categorized under two sections as active and passive systems. Many facades designs applied for solar heating and cooling mechanisms through active and passive designs. Table I represents active and passive designs for solar heating and cooling mechanisms.

II. Passive Solar Air Heating and Ventilation Systems

Passive solar heating and air natural systems have similar working process. Buoyancy effect, which is occurred due to the air density difference at the inlet and outlet, is the driving force for both systems. In order to capture or store the heat; or produce air movement to provide ventilation for cooling impacts, flexible options are used for the facades.

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Some of previous studies for the passive solar facade are demonstrated in Table II. The studies involve the researches of collector performance, energy analysis and some suggestions.

A. Trombe Wall

The classical Trombe wall is a sun-facing wall that separated from the outdoors by glazing and air channel (see Fig. 1). The Trombe wall captures sunrays and then stores the solar energy through the glazing. Some of absorbed solar energy is released towards to the interior of the building by conduction. Furthermore, the lower temperature air is transferred to air space from the building through the lower vent of the wall. The air is heated up by the wall and flows upward because of the buoyancy effect. After this process, the heated air turns back to the building through the upper vent of the wall. There are some following challenges for the classical Trombe wall design:

- Low thermal resistance- Once the wall absorbs small amount of solar energy such as during night and overcast condition, extreme heat loss from the building can be occurred because some heat flux is released from the inside to outside of the building [10].
- During the winter or cold climate condition at insufficient solar energy, inverse thermo-siphons case can be happened. Once the indoor temperature is higher than the wall temperature, reverse air circulation occurs from the upper vent to the lower vent, which results decreasing the building temperature [10], [11].
- It is not possible to measure heat transfer exactly due to the air movement depending on solar energy. The solar radiation is not stable and periodical, which causes temperature fluctuations of the wall [11].
- Size of the inlet and outlet openings is affected the convection process and thus impacts the overall heating temperature [11], [12].
- Low aesthetic value [13].

Some studies are available to improve classical Trombe wall system. The studies can be classified within three main topics which are inlet and outlet air openings control, thermal insulation projects and air channel designs. In order to improve summer cooling and winter heating performance of the Trombe wall, adjustable vents of the building and adjustable dampers at the glazing can be used [12], [13]. According to Fig. 1, in summer damper A and upper vent are closed. Buoyancy effect, that is occurred solar heated air between the warm wall and glazing draws building air and then the heated air is transferred to outside through open damper B. As a result of this, the Trombe wall can help solar cooling with an air movement during summer term. Also, if the outdoor is colder than indoor temperature, lower and upper vents are closed for the Trombe wall without any dampers in summer time whereas during winter, damper B is closed while lower, upper vents and damper A are left open, which causes to circulate the heated air return to the building [10].

TABLE I
SOLAR HEATING AND COOLING TECHNOLOGIES BY ACTIVE AND PASSIVE DESIGNS [1]

	Heating	Cooling
Active solar Uses electrical or mechanical equipment such as pumps and fans, to increase the usable heat in a system	-Uses solar where the absorber component absorbs solar radiation energy, converts into heat, and transfer the heat to a transport medium or fluid that flowing through the collector. The collected solar energy is hence carried from the fluid to heat exchanger or storage tank that satisfying heating needs. -Solar collectors: devices such as flat plate, parabolic tough or evacuate tube.	-Uses the collected solar heat as energy source of air-conditioners, commonly known as solar assisted air-conditioning systems. -Devices: chillers such as absorption chillers, solid or liquid desiccant systems.
Passive solar Without using active mechanical devices; the system do not use or uses only small amount of external energy	-Able to gain or trap heat through passive solar energy. Heat from solar radiation is absorbed, stored or used to preheat or evacuate tube. -Solar collectors: building components such as facade or roof.	-Generates and channels airflows, hence remove heat and create cooling effects; natural ventilation is among the most common type. -Devices: building components such as facade or roof.

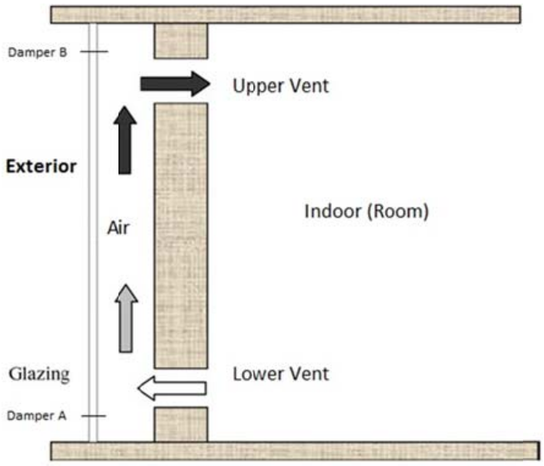

Fig. 1 Schematic diagram of traditional Trombe wall

Surface temperature and fluid flow rate is affected by two insulation methods which are insulation of glazing and storage wall. These insulation methods characterize their own positive sides in different climate conditions. For instance, in order to minimize heat loss through glazing for winter heating, thermal resistance of glazing can be increased. This method also helps to use of conductive heat transfer from storage wall to building. Some of insulation methods for improving performance of Trombe wall have been studied previously. For example, low-e coating on a spandrel glass has been represented to reduce radioactive losses to the outside [14]. Another way is a double glazing method which is introduced to increase flow rate by Gan [15]. PV-Trombe wall project has been designed to absorb heats from solar rays and provide to reduce PV cells temperature at the same time [13]. On the one hand, in the summer conditions, interior part of the wall can be insulated to prevent excessive overheating because of south facing glazing [12]. Matuska and Sourek proposed that applying sufficient insulation layers on the storage wall provide indoor comfort [16]. Moreover, composite Trombe-Michel wall concept has been designed to reduce heat loss from interior to outside of the building [10]. In comparison to a classical Trombe wall, this concept has insulation wall at back of the Trombe wall. Basically, conduction through the Trombe wall provides to transport the thermal layer from outside to inside air space. After that, the thermal energy is carried to indoor via convection that is occurred by thermo-circulation process between the Trombe wall and insulating wall. Also, during insufficient solar radiation such as winter or night times, the vents can be closed, which results minimizing the thermal heat flux that transferring inside to outside of the building.

According to the previous descriptions, the Trombe wall can be defined as a sensible heat storage wall as well. Hence, another interesting design of the Trombe wall has been done to store latent heat. In this concept, filling phase change material (PCM) in the masonry wall is used as a Trombe wall. In comparison the traditional Trombe wall, the PCM is lightweight and needs less space for a given amount of heat storage [17]. In addition to this, concrete-PCM combination can be used to improve low energy house which supplies remarkable energy storage [18], [19].

One of the important aspect of the Trombe wall is the design parameters of the air channel that affect convection process directly because air movement and energy in the channel are managed by natural convection [11]. On the other hand, channel width does not affect the air flow rate but the height of the wall influences the air flow rate. Once the wall height increases, the air flow rate increases simultaneously.

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TABLE II
SUMMARY OF SOME OF THE SELECTED PREVIOUS RESEARCHES

Facade / roof designs	Special features	Performance			Cost and energy analysis	Benefits/findings	Limitations /recommendations	Ref.
		Given conditions	Temperatures (Instantaneous efficiency, %)	Flow rate				
Solar Chimney	Vertical, similar to Trombe wall	*I= 650 W/m²* air gap depth=0.2 m	Exhaust air=39 ˚C Indoor air=30 ˚C (41%)		N.A	-Temperature rise and air velocity increased with solar radiation -Temperature rise decreased with air gap depth. -No reserve air flow circulation was observed even at large of 0.3 m.	N.A	[2]
Solar Chimney	Under hot and humid climate conditions, studies included during clear sky, partly cloudy and cloudy days	1-Clear sky: T_a=35 ˚C; *I* =800 W/m²; wind velocity=2.6 m/s 2- Partly cloudy: T_a=34 ˚C; *I* =594 W/m²; wind velocity=2.5 m/s 3-Cloudy day: T_a=32 ˚C; *I* =509 W/m²; wind velocity=1.8 m/s	1-Exhaust air=38 ˚C; indoor air=33 ˚C. 2- Exhaust air=36˚C; Indoor air=32 ˚C 3- Exhaust air=33˚C; indoor air=32 ˚C.	N.A	N.A	-Solar chimney can reduce indoor temperature by 1.0-3.5 ˚C compared to the ambient temperature of 32-40 ˚C.	Indoor temperature can be further reduced by 2.0-6.2 ˚C with combination of spraying of water on the roof.	[3]
Double facades	1-Outer skin: glaze; inner skin: glaze 2-Outer skin: PV panel; inner skin: glaze	Cavity width=0.8 m; inlet area=outlet area	N.A	1-Airflow rate=0.27 m³/ms. 2.Airflow rate = 0.36 m³/ms.	PV facade increased-electricity conversion efficiency by reducing the cell temperature	-PV facade increased the efficiency of PV cells when outdoor air temperature is higher than indoor.	-The outer skin temperature of PV panel increased depending on the degree of transparency.	[4]
Single-sided heated solar chimney	Adjacent walls are insulated	Length= 1 m; breath/height=0.1; inlet temperature=20 ˚C	Exhaust air=33 ˚C	Airflow rate=0.5 kg/s.	N.A	-The airflow rate reaches maximum when breath/height =0.1	-The optimised height can be determined according to the optimised section ratio of breath to height and available practical field conditions.	[5]
Solar wall	Similar to Trombe wall, consists of glass cover, air gap, black metallic plate, insulator,	*I=406 W/m²* T_a=30 ˚C; height =1 m; air gap =0.145 m	Exhaust air=42 ˚C Indoor air=28 ˚C	Mass flow rate=0.016 kg/s	N.A	-Temperature increased with increased wall height and decreased gap	-In very hot season, providing residents` comfort is insufficient by natural ventilation but it is able to reduce the heat gain which in turn reduces the cooling load.	[6]
Roof-integrated water solar collector	Roof integrated, combining the conventional roof and flat plat, solar collector by replacing water-coil and internal insulation with water pond and metallic sheet.	N.A	N.A	N.A	150-200 USD/m² compare to 160-220 USD/m² of conventional air-conditioner; taking one-third of construction time that represents 15 USD/m². Average daily energy absorbed=0.68 GJ. Annual energy=247 GJ.	-Able to control heat delivery to adapt with the environmental conditions. -Able to create heating or cooling effects. -Provide hot domestic hot water during winter.	Large area of roof is needed.	[7]
Roof solar collector	Single and double pass designs.	*I* = 500 W/m²; T_a=0˚C; mass flow rate 2000 kg/h	1-Single pass: supply air = 12˚C; indoor air=8 ˚C (27%). 2-Double pass: supply air=18 ˚C; indoor air=13 ˚C (39%).	N.A	Choosing suitable fan is important to reduce initial investment and operating cost.	-Instantaneous efficiency of double pass was 10% higher than single pass collector whether spacing heating or natural ventilation.	-Two or more shorter collectors in parallel are recommended instead of one longer collector.	[8]
Roof solar collector	Air gap and openings of roof solar collector	N.A	N.A	10-100 m³/h	Insignificant extra cost of construction	-Larger air gap larger and equal size of openings induced higher rate of airflow rate	-Insufficient natural ventilation to satisfy resident`s comfort. -Another device such as Trombe wall might be needed to improve comfort performance.	[9]

B. Unglazed Transpired Solar Facade

The facade of a building could be made of metal sheet with holes that absorb heat up the air without additional heat storage facility. The schematic diagram of this type of solar collector is shown in Fig. 2. This collector design called as unglazed perforated-absorber collector by the Air System Working Group of International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 14 while the Conserval Engineering Inc. refers as Solarwall. Unglazed transpired solar collector definition is also used by other researchers. Solar radiation heated metal cladding warms the air and ventilation fans help drawing the solar heated air through the holes of transpired metal sheet. Then via a connection to the heating, ventilation and air-conditioning (HVAC) intake, the heated air directed into the building. More information on descriptions and installations of this technology can be found in [20]–[22]. Results for space heating from the case studies performance (summarised in Table III) showed that the heating system is able to save the premises energy consumption up to 1 MWh/m^2/year depends on the collector designs. Additionally, comparing the system to glaze wall ones such Trombe wall in term of material cost, it is able to reduce cost and suitable for retrofitting.

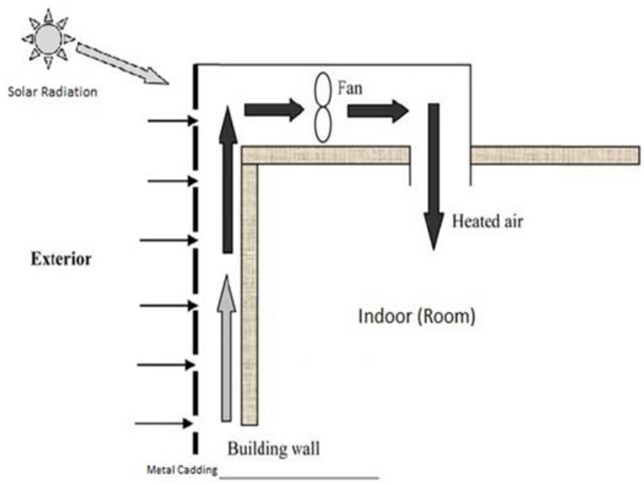

Fig. 2 Schematic diagram of unglazed transpired solar facade

C. Solar Roof

Passive cooling using solar roof methods can be listed as water firm, roof pond, roof garden and thermal insulation provide. Roof collectors provide higher air exit temperature due to the larger surface area to collect the solar energy. Therefore, solar roof ventilation may perform better than Trombe wall design in climates where the solar altitude is large [23]. However, [9] reported that there is little potential to satisfy room thermal comfort with only roof solar collector system. Especially in hot climate, another device such as Trombe wall should be introduced the solar roof collector system to provide better cooling effect. Hence, the thermal performance of the ventilated roof was studied by Dimoudi et al. by employing reinforced concrete slab and insulation layer with an air gap between the insulation and the upper prefabricated slab during summer and winter seasons [24], [25]. There was no clear improvement of the thermal performance during the winter period. However, insulation properties of ventilated roof yielded protection from the solar gains during the summer period. Moreover, [8] has studied double pass roof collector instead of single pass roof solar collector in terms of the efficiency. Double pass of air gap induced more air change rate with 10% higher efficiency (Table II). Juanico [7] was integrated a water solar collector to solar roof collector where several layers of glass followed by water chamber and metallic sheet at the bottom. This combined system could be used for domestic heating and cooling systems.

D. Solar Chimney

A solar chimney consists mainly of one heat absorbing glazed surface and it is constructed on the wall facing the direction of the sun. The solar chimney acts as a thermal engine by converting thermal energy into kinetic energy of air movement. The solar chimney generates airflow through a building and the density difference of air at inlet and outlet of the chimney during the ventilation provides either cooling or heating. The working mechanism of the attached to wall solar chimney is similar to Trombe wall. The heated warm air obtained from the solar collector supplies passive heating. Natural ventilation depends on the outdoor temperature and the system provides passive cooling when the temperature outside the chimney is lower than the indoor. However, for hot weather climate countries where the sky is frequently overcast, it operates as thermal insulation to reduce heat gain of the room [29].

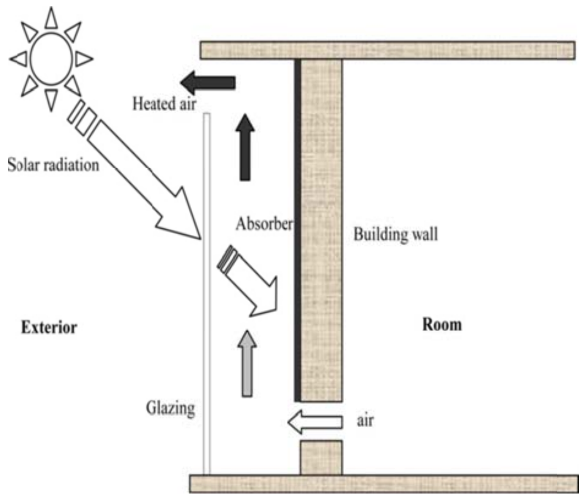

Fig. 3 Schematic diagram of solar chimney [30]

TABLE III
SUMMARY OF SOME OF THE SELECTED PREVIOUS STUDIES PERFORMANCE RESULTS OF UNGLAZED TRANSPIRED SOLAR WALL

Case study	Collector area and type	Airflow rate ($m^3/h/m^2$)	Temperature rise	Efficiency	Energy saving	Cost analysis (reference year)	Reference
GM, Oshawa	420 m^2 gross; 2% porosity on wall, 1% on canopy	72	13 ˚C (solar radiation 500 W/m^2)	52%	754 kWH/m^2/year	Cost of delivered energy= 59 USD/GJ/year(1991)	[21], [26]
Ford Canada	1877 m^2; vertical wall;2% porosity on wall,1% canopy	125	12 ˚C (sunny day)	52%	917 kWH/m^2/year	Cost of delivered energy= 25 USD/GJ/year(1990)	[21]
Windsor Housing Authority	335 m^2; corrugated dark brown aluminium	N.A	N.A		195,700 kWh/year (estimated)	Estimated saving: 4184 USD/year (2.2 cents/kWh of natural gas)	[27]
NREL Waste Handling Facility	27.9 m^2; 2% porosity	N.A	N.A	63-68 %	N.A	N.A	[21]
Combined PV/solarwall panel	Solarwall panel area= 1.1664 m^2; PV cells covered 24% of solarwall surface	100	N.A	(Solar radiation 600 W/m^2) Thermal efficiency=48% combined efficiency=51%	Energy saving= 500-1000 kWh/m^2/year; PV power =18.5 W; estimated 50-100 kWh/m^2/year of electricity generated	N.A	[28]

Note: NREL= National Renewable Energy Laboratory; N.A= not applicable

III. CONCLUSION

A detailed literature review for some passive solar technologies opaque solar facades has been performed. The researches reviewed were grouped into the following four systems: building-integrated Trombe wall, unglazed transpired solar façade, solar roof, and solar chimney.

With this study, many passive solar designs for heating and cooling have been analyzed; they generally have their own limitations. Single passive solar designs might not sufficient to provide indoor thermal comfort, particularly regions that have extreme climates. For instance, although Trombe wall and solar chimney is a less advanced technology, some energy efficiency gains are expected. However, there is still significant potential for optimization. As a result, this study presented that all these technologies are promising. However, more studies are needed to bring them to their optimum performance to improve thermal comfort and reduce energy consumption.

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