Renewable and Sustainable Energy Reviews 141 (2021) 110795

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

A critical review of combined natural ventilation techniques in sustainable buildings

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ARTICLE INFO

Keywords:
Renewable energy
Natural ventilation
Solar chimney
Heating and cooling
Energy saving
Integrated system

ABSTRACT

Combination of natural ventilation approaches is a new trend for free space cooling/heating in buildings. A critical review was then undertaken to provide an overview of the combined technologies that hope to initialize new ideas and promote future endeavors. The advantages of the integrated natural ventilation systems can be summarized into several principles, including achieving beyond the existing performance by single system, maintaining indoor temperature stability, realizing heat energy recovery, overcoming the inadequacy of a single system, and providing a more comprehensive and useful energy-saving scheme. Most of the existing studies on combined systems are found based on thermal buoyancy, while only a small amount dealt with the combination of wind-driven and buoyancy-induce due to the complexity. Parametric studies in most previous studies focused on several major ones, so a systematic analysis is critically needed to address the performance of the overall combination to achieve stable and durable performance. A thoughtful investigation is also required to avert unpredictable delivery of air flow, such as through the manipulation of external wind forces. The related research focuses should also be shifted following the trend of multi-storey buildings under the rapidly growing population. No guideline was found that arranges these natural ventilation systems in terms of performance and applicability for their practical selections and usages. Also, the thermal bridge breaking in cold winter and condensation in summer may compromise the natural ventilation performance and durability, and longevity of buildings. The studies on the coupling between different natural ventilation systems are still insufficient, requiring quite a bit of effort in future works.

1. Introduction

Under the great consequences of global warming, a growing portion of stakeholders have transferred their focuses from conventional to renewable energy resources to release the pressure of high energy costs at present. Globally, heating, ventilation, and air-conditioning (HVAC) systems have the most significant proportion, which was 40–60% of the total energy consumption of the building sector [1,2]. Ventilation systems have attracted increasing attention from building developers and end-users thanks to their significant functions, such as removing indoor air pollutants and moisture and avoidance of mold [3,4]. According to different driving forces, typical modes of ventilation refer to natural, mechanical, and hybrid ventilation methods according to different driven forces.

A large portion of modern buildings relies exclusively on the mechanical ventilation system (active system). They are with high energy consumption and take up the useable space due to their complexity and significant volume. Ruparathna et al. [5] discussed energy efficiency (*i.e.*, mechanical components (*i.e.*, HVAC), lighting systems (such as the LED), building envelope, power generation (such as BIPVT)), building operations, and energy management methods in commercial buildings, and developed an energy performance strategy map. The most frequently adopted methods are fan-assisted devices in mechanical ventilation systems. Also, ventilation systems advocated are usually combined with evaporative cooling systems, heat recovery ventilation devices (HRV), energy recovery ventilator (ERV) [6–8], and compression and adsorption chiller systems [9,10] to achieve indoor thermal comfort. The applicable conditions of mechanical ventilation require the building to be highly airtight to reduce air infiltration and exfiltration,

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https://doi.org/10.1016/j.rser.2021.110795
Received 30 May 2020; Received in revised form 22 January 2021; Accepted 3 February 2021
Available online 17 February 2021

Abbreviation

ACH	Air change per hour	NC	nocturnal cooling applications
A/C	atria & courtyard	NPL	Neutral pressure plane
CFD	Computational Fluid Dynamics	NV	Natural ventilation
DSF	Double-skin facades	PCM	Phase change material
EAHE	Earth-air heat exchanger	PV	solar walls with photovoltaic module
ERV	Energy recovery ventilator	RC	rotating wind cowl
F	fenestrainon (single-sided & cross-ventilation)	RV	exhaust cowls/roof vents/roof cowls
FDS	Fire Dynamics Simulator	SC	Solar chimney
HVAC	Heating, ventilation, and air-conditioning	TW	Trombe wall
HTD	heat transfer device	VT	turbine ventilation
HRV	Heat recovery ventilation	WT	wind tower
IAQ	Indoor air quality	WC	windcatcher
		WW	wing walls
		WS	wind cowls/scoops

so that heat loss due to air exchange and energy-demanding can be minimized. However, a highly sealed space eliminates the supply of fresh air [11].

The natural ventilation system is considered an attractive solution for energy-saving buildings compared with air-conditioning systems. Although dependent on the outdoor weather conditions, natural ventilation still has good potential to offer satisfying thermal conditioning and indoor air quality (IAQ) without the reliance on mechanical systems [12–14]. Due to their potential benefits in economic ascendancy, encompassing mitigation of energy consumption, high durability, low noise level, and low carbon dioxide emission, they are increasingly being advocated as an alternative to mechanical ventilation systems [11, 15,16]. Even though the inherent shortcomings of natural ventilation systems depend solely on natural processes and are affected by temperature fluctuations and wind factors, its effects on energy conservation and human health cannot be ignored. Carlton et al. [17] and Chartier and Pessoa-Silva [12] have explored the significant correlation between ventilation rate and airborne infection. It was proven that natural ventilation systems could provide residents with a comfortable indoor environment while meeting those respiratory health requirements under the premise of optimal design and well maintenance. Simultaneously, it was speculated that the occupants prefer not to be wholly isolated from the outdoors with sound IAQ [18,19].

Air movement is caused by different power resources, including wind (as a momentum-induced airflow), buoyancy effect (produced by internal and external air density differences), or both of them [3], humidity difference, and mechanical power, which exchange stale indoor air and ventilates the interior spaces [20]. Typical natural ventilation systems with purpose-built openings can be classified into three categories [12,21], including wind-induced ventilation, buoyancy (stack) ventilation, and hybrid (mixed mode) ventilation. Intentional openings can be windows, doors, wind catchers, chimneys, and roof vent. Natural ventilation systems are sometimes included in passive cooling methods [16,22–27] to provide heat dissipation and heat gain operations. However, there are many uncertainties in the systems, especially under extreme ambient climate. The success of adequate natural ventilation relies on natural forces available, building features, airtightness, and occupant behaviors [28–30]. Oropeza-Pereza et al. [31] proved that passive methods could reduce the indoor temperature like the active refrigeration effect. It is explored the possible variation of indoor temperature caused by natural ventilation.

A thoroughly designed passive ventilation system exhibits different air distribution under climatic conditions, which can simultaneously have space heating and cooling functions. The necessary attempt is to apply an optimal integration of free heating/cooling strategies to reduce the burden of active systems that convert renewable energy into heat or electricity [12,32]. Numerous research works have been investigated in the literature regarding passive ventilation and have integrated systems for space thermal regulation. It is revealed the potential and effectiveness of the prospective implementation.

Although the independent passive ventilation approaches have been extensively studied involving controlling configuration parameters and methods for evaluating performance, the integration of two or more passive ventilation systems in a building has been less investigated and attempted. Due to the large volume and intricate design of modern buildings, it is almost impossible to achieve high performance and satisfactory energy efficiency with a single passive ventilation system. Therefore, it is necessary to provide the optimal combination of multiple passive strategies for appropriate energy-saving in ventilation systems at given locations. Besides, the purposeful integration of different passive ventilation strategies based on local climate conditions can show superiority in many aspects and significantly improve building energy efficiency, such as enhancing the performance and overcoming the shortcomings of different systems (*e.g.*, temperature adjustment, airflow rate, and moisture removal). Compared to those mechanical systems, natural ventilation systems are usually relatively cheap and easy to be installed. Consequently, the integration of different systems can then offer great potential to achieve the lowest energy consumption in a building with much better financial payback. Therefore, to guide the related practical implementations and optimization designs, an extensive literature review was, for the first time based on the best of our knowledge, to conclude the existing applications and then explore the future possibilities.

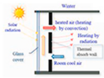
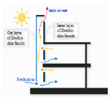
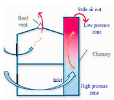
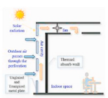
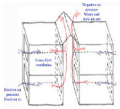
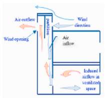
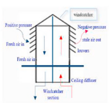
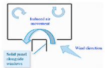
Therefore, the manuscript carries out an extensive literature review of existing studies of passive ventilation strategies, focusing on the different attempts made by researchers over the years. Section 2 highlights the objectives and methodology of this study. Section 3 reviews the typical independent passive ventilation system combined with their corresponding principles, whose research results are shown in Table 1. Section 4 reviews the research methods and evaluation indicators of passive ventilation systems, as well as influential parameters. tbl1Tables 1 and 2tbl2 summarize each independent system's performance and building response and its main advantages and disadvantages in practical application. Section 5 reviews the existing cases of multiple combined passive ventilation systems, and identifies previously uncombined systems, as listed in Table 3. Some applications to buildings and problems are discussed. Section 6 provides the potential application prospects and summarizes the proportion of articles in the existing integrated systems, whose percentage of articles is shown in Fig. 13. The conclusions of this research are drawn in Section 7.

2. Objectives and methodology

2.1. Objectives

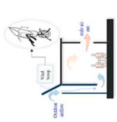
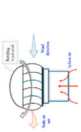
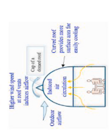
The objectives of this review study are to:

Table 1
Natural ventilation applications.

Natural ventilation Techniques	Performance							
	Typical natural ventilation systems	Schematic diagram and airflow pattern	Indoor temperature adjustment (°C)	Range of relative humidity [%]		Volumetric/mass flow rate (l/s, m [3]/s, m^3/h, or kg/s)[a]n under given scenario	Energy-saving percentage (%)	Analysis method
Thermal buoyancy-driven ventilation	Trombe wall		drop 2–17 °C with evaporative cooling [108,173]; increase around 1–2 °C [174,175];; reduce 9.1 °C [175]	28.3–28.8% [173]		0.01–0.02 kg/s [176]; 20–90 m3/h [177]	30–80% [20, 158,178–184]	Numerical study (CFD) and Experimental study
	Double-skin façade (Vent-skin walls)		rise 0.66–14.7 °C [128, 185–189]	50–95% [186,190]	1.351 [187,191,192]; 4 [193]; 2–11 with solar chimney [58];	0.27–0.36 m^3/s with PV [184, 194]; 54 m^3/h with fan [113]; 0.042–0.255 kg/s [20,186,188, 189,195–197]; 16.1–22.4 l/s/m [149]	14%–75% (with shading device) [113, 128,189, 198–200]	CFD [59,201]; Numerical study; Experimental
	Solar (thermal) chimney/ Roof solar chimney		Drop 1.0–3.5 °C [15,20,23,24, 44,47,97,100,103,107,185, 202,203]; 2.0–6.2 with water spaying roof [107]; 14 °C with water spraying; with EAHE drop 3.2–6.6 °C [204]; rise 7 °C [47];		2–6 [87,102,103, 205–209]; 8 [108] in coupling system of Trombe wall and water spraying system; 35–73 with wind tower [210]; 8–15 [206]	55–330 m^3/h [15,44,47,102, 103,202,209,211,212]; 50–374 m^3/h [47]; 0.0085–0.5 kg/s [184,213,214]; Roof solar chimney 0.08–0.15 $m^3/s/m^2$ [20,215] or 10–100m3/h [212]; 0.014 kg/s [216]; 0.18–0.33 m^3/s [217]; 2.3 m^3/s [207]; 0.25–0.39 m/s [218]; double air-channel solar chimney 0.1072 kg/s [219]; 0.75–1.4 kg/s [210];	EHD: 620; HD : 101 [31]; 12–50% [80, 81,128]	Numerical study; CFD; FDS; Experimental investigation
	Solar walls (unglazed transpired solar façade and glazed transpired solar façade)		unglazed transpired solar wall for space heating: rise 12–13 °C [20,185,220–222]		linear relationship between ACH and the solar intensity [87]	72–125 $m^3/h/m^2$ [222–224]	500–1000 kWh/m^2/year [222–224]	
	Atrium:		rise up to 1.5–5 °C [71,156, 225]; reduce 2.5–5 °C with solar PV [75]		linear relationship between the ACH and wind speed/direction [67];	15000 l/s with a strong stack effect [71,106]; 0.39–0.8 m^3/s [65]; 7.8–73.7 L/s per m^2 [106]; 600–1000 l/s [160,226]; 20–25 l/h [227]	40%-80% [228]	
Wind-induced ventilation	Wind tower		drop of 4–25 °C [31,44,45,120, 229–234]; reducing air temperature by 13% [235]; (with heat transfer device); reduce 5.2 °C with a SC and water spray [236]; reduce by up to 13.3 °C with evaporative cooling [237]; reduce 3.2 °C [238]	Increase of 19–22% [230,239] with use of wet columns; increase between 50% and 60% with evaporative cooling [229,237]; decline by 15% [240]	1.75–73 [82,119,193, 241–244]; 9 with SC and water spray [236]; 3–20 with evaporative cooling for two-storey building [244]	0.75 g/s [245,246]; 414 m^3/h [105]; 15.1 L/s/m^2 [83]; 0.3 m^3/s [231,247]; 4 l/s- 650 l/s [83,98,247–250] [43-45,143, 157,233]	[157] cooling energy reduction 43–61% [243] [31] EHD: 931; HD: 151; save 90% of the ventilation energy [236]	Field study [229, 240]; CFD [230, 251]; Wind tunnel testing; Experimental study
	Wind Catcher		Drop 2–5 °C [45,230,234,240, 252,253] [254]; With cool sink drop 12 °C [255]	Decrease 15% [240]; increase by 19% [230]	1.6–13.4 [256]	80–145 l/s [43,104]		CFD; Wind tunnel testing [234]; Field research [256]; Numerical study
	Fenestration — Single-sided ventilation				0.65–6.60 [257,258]	0.054–0.550 m^3/s [258]		
	Fenestration — Cross ventilation				5- 22 [257,259]		[260]	
	Wing walls				Induce fresh air supply up to 40% [43]; 0.54–5.9 [261]	the average indoor air velocity is 40% of the incident wind	20% [263]	

(continued on next page)

Table 1 (*continued*)

	Wind cowls/Scoops				velocity, while without a wing wall, it is only 15% [262] 100–260 l/s [264,265]		
	Rotating wind cowl/Turbine ventilators				20–300 l/s [43,266–271]; 270 m^3/h [272]; depending on size and wind speed [35]		
	Exhaust cowls/Roof vents/ Roof cowls			6 [273]	1764 m^3/h at wind speed of 2.5 m/s [43,274]; 490 l/s [273]; Various depending on size and wind speed [35]		Wind tunnel [273]
Heat modulation or amortization technique (Modify heat gains):	Nocturnal cooling applications (Night sky infrared radiation; Day-time ventilation: Shifting of day heat to night for removal)		reduced by up to 1.5–8 °C [11, 45,76,232,260,275–280]	10 [260,277]		EHD: 1918 [GW h]; HD: 312; HT/MT: 68 [31]; 11–90% [281,282]	

- Summarize the existing typical natural ventilation configurations and their foremost of research progress;
- Identify the current combination of natural ventilation technologies in the practical applications in buildings;
- Approach the applicability of natural ventilation or combined system on disparate buildings or under different climatic conditions; and
- Explore the future possibilities of integrating natural ventilation systems/technologies to enhance the performance or overcome their shortcomings.

2.2. Scopes

To provide an appropriate analysis, this review has been focused on the natural ventilation systems solely. High-tech natural ventilation systems with self-regulating involve control systems, and management techniques are excluded from the review, together with their integration with typical natural ventilation systems.

Furthermore, in addition to providing effective means of ventilation, some passive ventilation systems can also provide passive heating or cooling, reducing the overall heating or cooling load of buildings. Thus, the present review also looks at cooling/heating effects generated by the passive ventilation systems and techniques incorporated into a standard natural ventilation system to improve its capacities and extend service life.

2.3. Methodology

This study reviewed typical passive ventilation systems, and their combination undertook previously without limiting publication year. However, from the obtained literature, the related studies were published between 1980 and 2021. The research documentation search was mainly through four databases, including Science Direct, Scopus, Web of Science, and Google Scholars, to ensure better coverage. A combination of the following searching terms was used, including passive heating and cooling, natural ventilation or passive ventilation, building energy conservation, Zero Energy Buildings, building-integrated systems, or combined ventilation systems.

3. Principles of natural ventilation

As the passive ventilation strategies are the subject of extensive research, before exploring the potentials of the combined ventilation systems, it is necessary to present and recapitulate an overview of the individual natural ventilation system and the primary principles that cover existing passive approaches. The driven forces control the airflow pattern and the distribution of temperature and airflow through a building. According to the sources of pressure difference, natural ventilation means wind-induced, buoyancy-driven, and their combination.

3.1. Typical driven forces

3.1.1. Wind-driven force

A wind-induced system is a typical way to ventilate space naturally. Under the external wind, the distribution of windward static pressure increases, resulting in a positive or high-pressure region [33,34]. Vortexes may be produced on the leeward side, which forms a low-pressure or negative region. Under the pressure gradient, the air is driven from the domain with positive pressure to the region with negative pressure. The ventilation intensity is concerned with the area of air intakes/extractors and the magnitude of the wind force, as seen in Fig. 1. The volume control dampers can capture the wind at a high altitude and distribute through the building and moderate airflow.

3.1.2. Buoyancy-driven force

The ventilation driven by temperature gradient is called thermal

Table 2
A overall comparison of typical natural ventilation technologies according to the ten judgment criteria.

Major findings	Reference costs	Additional maintenance and operational costs	Simple Structure	Space requirement	Applicability under various scenarios	Heating effect	Cooling effect	Human behavioral factors	Transparency – Architectural design	Fire safety
Trombe wall		✓	✓	✓	✓	✓	✓	×	×	×
Double-skin façade (Vent-skin walls)	Standard 600 to 800 Euro/m^2; with openable exterior sashes 800 to 1300 Euro/m^2 [283]	✓	✓	✓	✓	✓	✓	✓	✓	×
Solar (thermal) chimney	501-1000 Euro [31]	✓	✓	✓	✓	✓	✓	×	×	×
Solar walls (Unglazed transpired solar façade, and glazed transpired solar façade)	NA	×	×	✓	✓	✓	✓	×	✓	×
Atrium	NA	✓	×	×	✓	✓	✓	×	✓	✓
Wind tower	501-1000 Euro [31]	✓	×	✓	×	×	✓	✓	×	✓
Windcatcher	501-1000 Euro [31]	✓	✓	✓	×	×	✓	✓	×	×
Single-sided ventilation (fenestration)	NA	✓	✓	✓	×	×	✓	✓	✓	✓
Cross ventilation (fenestration)	NA	✓	✓	✓	×	×	✓	✓	✓	✓
Wing walls	NA	✓	✓	✓	×	×	✓	✓	×	✓
Wind cowls/scoops	NA	✓	✓	✓	×	×	✓	✓	×	×
Air inlets/wind vent/turbine ventilators	NA	✓	✓	✓	×	×	✓	✓	×	×
Exhaust cowls/Roof vents/Air inlets/Roof cowls	NA	✓	✓	✓	×	×	✓	✓	×	×
Nocturnal cooling (Night sky infrared radiation)	0-30 Euro [31]	×	×	✓	✓	✓	✓	✓	×	×
Day-time ventilation	0-30 Euro [31]	✓	✓	✓	×	×	✓	✓	×	×

buoyance ventilation. One of the typical airflow paths can refer to Fig. 2. The intensity of the chimney effect is associated with the difference in air import and export height and the difference in the density of the internal and external air. When there is any heating source inside the building, the internal air temperature may exceed the external air temperature. The warm air rises to the upper part of the space, leading to an over-pressure compared to the outside environment. The air is then driven from indoor to outdoor. The neutral pressure plane (NPL) is an essential concept in calculating the pressure difference. The air pressure between inside and outside air reaches equilibrium at NPL. The NPL could vary from 0.3 to 0.7 of total building height. An overpressure above NPL exhausts the air through the openings, whereas a negative pressure below NPL drives the air into buildings [38] (see Fig. 2).

Besides, the airflow induced by the humidity gradient is like that of the temperature difference. Water vapor is relatively lighter than dry air. Buoyancy induced by humidity is only effective in those locations where the outdoor humidity is very low.

3.1.3. *Combined forces*

Two natural driving forces mentioned above usually act simultaneously, where sometimes one driving force could be dominant under a particular condition. As Fig. 3 illustrates, the combined forces may be mutually exclusive or compensate each other, depending on the incident wind angles and whether the internal or external temperature is high. The rate of airflow resulting from the combined effects can be calculated in a root-square function.

3.2. *Typical natural ventilation approaches*

3.2.1. *Single-sided ventilation and cross-ventilation*

The openable windows are commonly used vents of natural ventilation systems. As expressed in Fig. 4, single-sided ventilation refers to space with one opening connected with the external environment. Air exchange could take place through stack effect and wind pressure.

Naturally ventilated buildings require to be relatively narrow to allow the airflow to penetrate deeply into a building. The adequate depth of a single-open space driven by wind is twice the height from the floor to the ceiling. The adequate depth of the double-opening space driven by buoyancy is 2.5 times the height from the floor to the ceiling. Gan [42] derived a model based on CFD modeling to predict airflow patterns, temperature profile, and the mean age of air. The model can support an assertion of the efficient depth of air distribution in buildings. The results showed that the maximum depth for adequate air distribution in a single-sided ventilation space is concurrently determined by the opening dimension, internal heat gains, and external air temperature.

Cross ventilation is with purpose-built openings (two or more

Table 3
A summary of combined typical natural ventilation systems.

Architectural elements/other Systems		Natural Ventilation systems														
		Buoyancy-driven ventilation					Wind-driven ventilation							Hybrid solution		Heat modulation or amortization technique
		Trombe Wall (TW)	Solar (thermal) chimney (SC)	Double-skin façade (DSF)	Atria & Courtyard (A/C)	Solar walls with Photovoltaic module (PV)	Wind Tower (WT)	Windcatcher (WC)	Fenestration (Sigle-sided & Cross-ventilation) (F)	Wing walls (WW)	Wind cowls/ Scoops (WS)	Rotating wind cowl (RC)/ Turbine ventilators (VT)	Exhaust cowls/ Roof vents/ Roof cowls (RV)	Heat recovery ventilation (HRV) devices/ Heat transfer device (HTD)	Earth-air heat exchanger (EAHE)	Nocturnal cooling applications (NC)
Buoyancy driven ventilation	Trombe Wall (TW)		[24,49,108]											[183,305–316]		
	Double-skin façade (DSF)		[58,325]		[58,71]	[326]	[44,193,265]							[327]		
	Solar (thermal) chimney (SC)				[71,285]	[328]	[43,103,105,120,185,210,265,319,320,329]	[45,236,321]	[330,331]		[26]			[214,296–304,332]	[284,333,334]	[207,335]
	Atria & courtyard (A/C)						[44,322,336,337]						[71]			[71]
	Solar walls with PV															
Wind-induced ventilation	Wind Tower (WT)											[41]	[338]	[233,255,318,339–344]	[290]	[27,116,252,253,345,346]
	Windcatcher (WC)									[347]	[347]			[255,292,341]		[45]
	Fenestration (Sigle-sided ventilation & Cross-ventilation) (F)															
	Wing walls (WW)															
	Wind cowls/ Scoops (WS)															
	Rotating wind cowl (RC)/ Turbine ventilators (VT)															

(continued on next page)

Table 3 (*continued*)

Architectural elements/other	Natural Ventilation systems														
Systems	Buoyancy-driven ventilation					Wind-driven ventilation							Hybrid solution		Heat modulation or amortization technique
	Trombe Wall (TW)	Solar (thermal) chimney (SC)	Double-skin façade (DSF)	Atria & Courtyard (A/C)	Solar walls with Photovoltaic module (PV)	Wind Tower (WT)	Windcatcher (WC)	Fenestration (Sigle-sided & Cross-ventilation) (F)	Wing walls (WW)	Wind cowls/ Scoops (WS)	Rotating wind cowl (RC)/ Turbine ventilators (VT)	Exhaust cowls/ Roof vents/ Roof cowls (RV)	Heat recovery ventilation (HRV) devices/ Heat transfer device (HTD)	Earth-air heat exchanger (EAHE)	Nocturnal cooling applications (NC)
Exhaust cowls/ Roof vents/Roof cowls (RV)															

Note: The shaded part of the table is the duplicated pair-wise comparisons; In order to facilitate the legend annotation of Section 6, the full name of each type of system is abbreviated in parentheses. Those blank cells represent that no study has been found at the moment in the literature regarding the related combination, where future studies are suggested to confirm their viability in practice under various climate condition.

openings on the opposite walls) (see Fig. 5), using the prevailing wind for indoor ventilation. The recommended horizontal depth for cross-ventilation needs to be less than five times the floor-to-ceiling height of the space.

3.2.2. Wind-induced ventilation

Wind-driven ventilation can be realized through different systems, such as wind tower/catcher, roof vent, and rotating ventilator. These structures are usually installed on the roof level to enhance the interaction with the external wind. The airflow follows the pressure gradient and exhausts through purpose-built openings or the leeward side (see Fig. 6). The size and location of these openings and the distribution of internal walls show the high impact on promoting cross-flow. Khan et al. [43] summarized and classified different wind-driven ventilation techniques and presented their corresponding flow rates. Hughes et al. [44] retrospectively summarized the wind tower systems extensively and evaluated the development and integrating potentials of different cooling methods with the commercial windcatcher. Jomehzadeh et al. [45] reviewed previous studies on windcatcher from IAQ and thermal comfort perspectives.

3.2.3. Buoyancy-driven (stack) ventilation

In buoyancy-driven ventilation (see Fig. 7), an upward airflow is produced because of the thermal buoyancy under a temperature gradient. One of the attempts to utilization of stack ventilation methods is to develop solar heating and cooling technologies. Three prerequisites are generally needed to stack ventilation, such as relatively lower intakes and higher extractors and heat sources (internal or external heat sources). Solar-induced approaches employ direct or indirect solar energy to capture solar irradiance and convert energy into useable heat. Typical solar-driven ventilation systems which could be attached to the building envelope and mounted on rooftops [24], such as the solar chimney [46], Trombe wall, and double-skin facades (DSF), are in the nature of similar operational concepts using solar-induced thermal convection and buoyancy as they have openable channels that induce airflow circulation under the aid of insolation and preferable in temperate climates [20].

A schematic diagram of a solar chimney presented in Fig. 8 consists of a glass wall, an absorber, a tuyere, and a heat-insulating material. Air movement is typically affected by the intensity difference between indoor and outdoor, resulting from thermal gradient (naturally-driven convention) and wind (force convection) [47–50]. Thirugnanasambandam et al. [51] reviewed the thermal and ventilation performance and numerical models of solar-induced methods. It was indicated that air change per hour (ACH) depends on the chimney configurations (*e.g.*, inclination angle, aspect ratio, and inlet size) and solar intensity. Quesada et al. [52,53] summarized the studies on solar facades explored during the last ten years based on theory, experiment, development, and feasibility. It is also reviewed the transparent and translucent solar facades. Not only do solar facades absorb and reflect incident solar radiation, but they also transmit directly obtained solar heat to buildings.

The double-skin façade (DSF) as a heat protection method has become an accessible solution. However, challenges then arise due to the intricacy of thermal stratification, complicated airstream pattern, and the adaptability of DSF to different climatic scenarios [55,56]. Pérez-Grande et al. [57] explained the airflow mechanisms and the process of solar radiance transmission and the vertical temperature gradient through the façade layers. The solar incidence that enters through the outer skin is absorbed by the inner skin, which causes an emission of longwave radiation in various directions, resulting in air temperature increases in the air passage [58,59]. The heat interchange and airflow network involved in the DSF are described in detail in Refs. [60,61]. Excepting solar irradiance, wind characteristics play a pivotal role in the thermal and airflow behavior of the DSF. Wind generates different wind pressures around the DSF. When the wind effect is

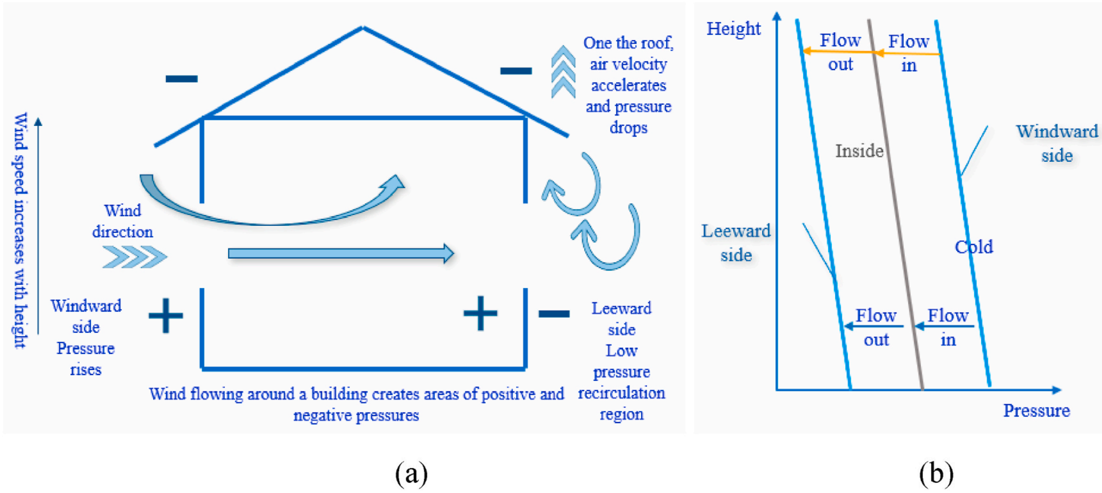


Fig. 1. (a)Wind-driven airflow (pressure differences result in air movement). Revised from Refs. [35,36]; (b)Wind action only with the pressure of equal magnitude on windward and leeward sides. Revised from [37].

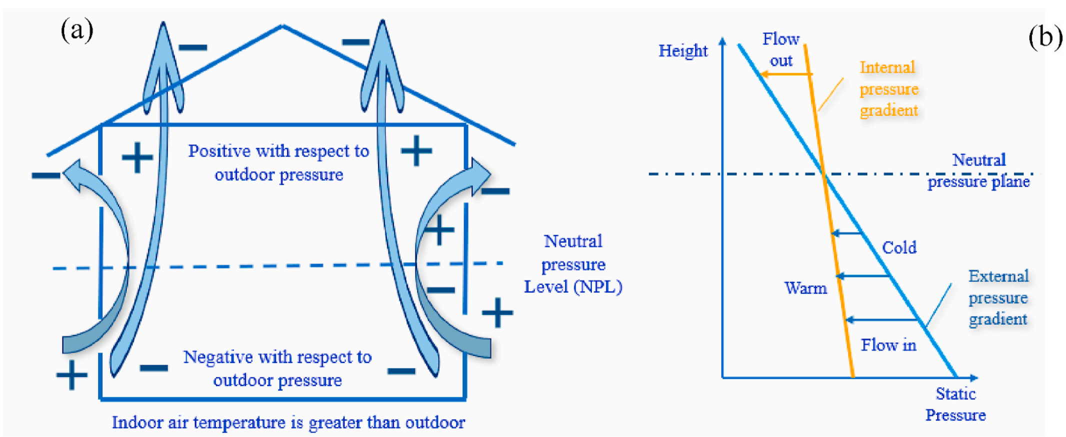


Fig. 2. airflow caused by the stack effect (density differences result in air mass movement). Revised from Refs. [35,36]; Stack effect only with neutral pressure plane [39].

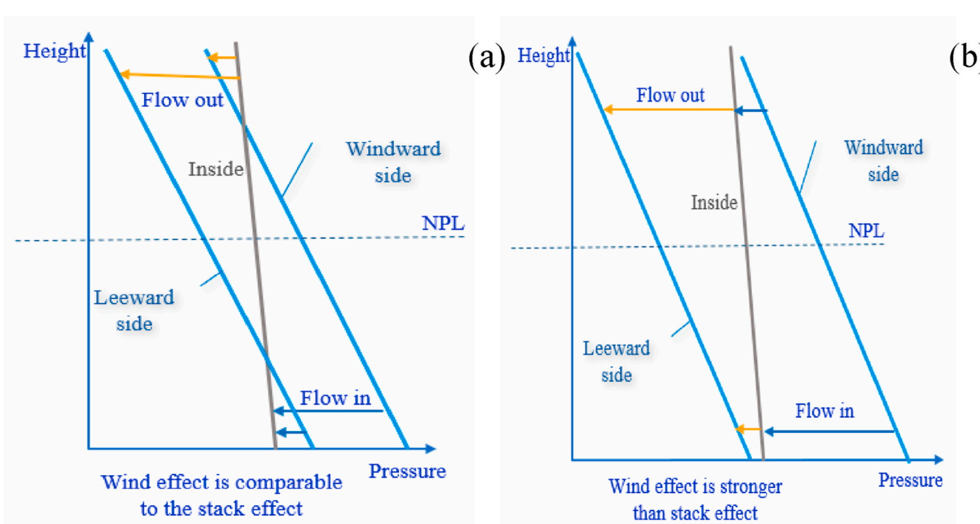


Fig. 3. The pressure gradient and airflow patterns of combined effects. Revised from [40].

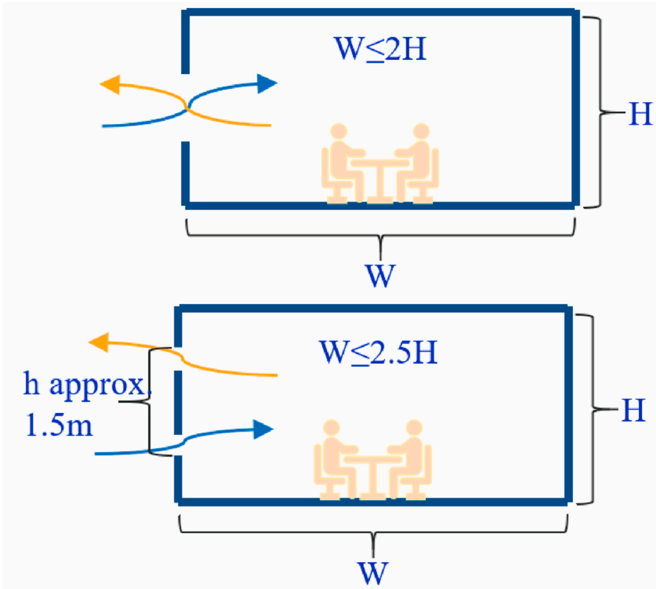


Fig. 4. Single-sided ventilation. Revised from Ref. [41].

considered in the study, the wind-driven will be the dominant force in driving air movement through the DSF layers [62,63].

Atria are typically embedded in buildings, thereby formed centerpieces with glazing space in buildings for natural ventilation purposes [43,64]. The air circulation through atria spaces is predominantly driven by buoyancy effects [65]. Holford and Hunt [66] advocated that raise the temperature of the warm air layer concentrated in the higher part of the space, thereby raising the air pressure of the upper layer. Expanding the depth of the heated air layer is attributed to the enhancement of stack ventilation.

Wind factors, however, can affect the stack ventilation positively or negatively. Horan and Finn [67] described the impact of external wind on the airflow rate inside a double-story office building under various wind speeds and wind directions through computational fluid dynamics (CFD) study. It is explored that the linear relationship between ACH and wind properties is evident. The energy efficiency of the atrium with the same geometry and glazing materials increases with the height of the building [66,68–70]. Moosavi et al. [71] explained how building designs differ according to the diversity of building function and explored the contributing parameters of atriums intending to obtain prudent designs of the atrium to refine the energy performance of buildings. However, when the excessive heat transfer from the atrium space to adjacent spaces in the hot season and the heat loss caused by the large glass curtain wall and continuous air stratification in the cooling season, the

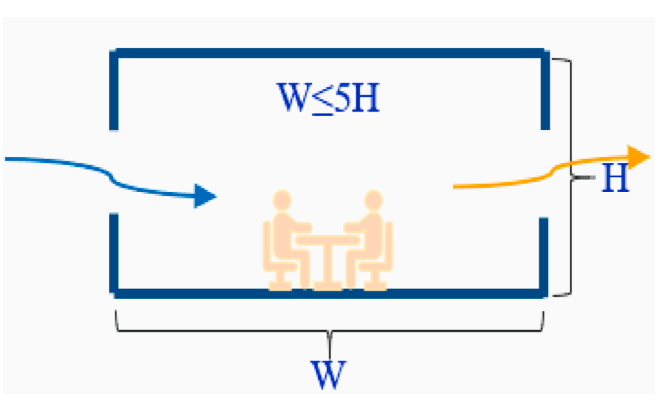


Fig. 5. Cross-flow ventilation. Revised from Ref. [41].

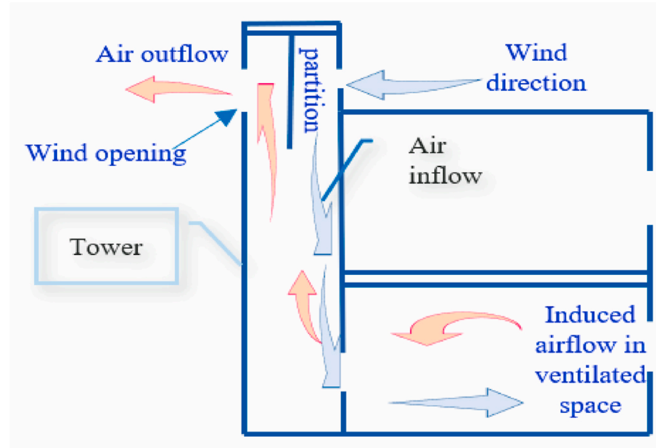


Fig. 6. Wind tower.

atrium may increase cooling loads to regulate thermal comfort [72,73]. Also, an unsuitable cavity depth design can cause the above defects [74].

3.2.4. *Hybrid ventilation*

Mix-mode ventilation is generally referred to as the coupling of mechanical and multiple passive ventilation in energy-saving buildings. The mechanical systems include forced ventilation (displacement) such as fan-assisted (extraction fans supplement ventilation rate) and heat exchanger [12], where they are only intended to use when natural systems are inadequate [75]. A constraint of natural ventilation is the high dependence on ambient climate. When the outdoor wind speed is too meager, the external temperature is too excessive, or the outdoor humidity is extremely high, the accessibility of natural ventilation could then be diminished. Furthermore, a stand-alone system tolerates the likelihood of excessive undulation in the ventilation rate. For example, Air change caused by the stack effect alone may not generate enough internal air movement in windless conditions.

In contrast, mix-mode ventilation systems extend natural ventilation practices in different building types and diverse climates [76,77]. They are commonly used to ensure a steady and persistent airflow rate. Yang and Li [78,79] compared three buoyancy-based ventilation schemes based on a ten-storey building model, including stack ventilation with/without an attached chimney and stack-based hybrid ventilation system. It is developed analytical models and conducted numerical simulations based on CFD, hereafter, obtained corresponding ventilation rates and derived energy performance equations. According to the theoretical analysis, the dimensionless expressions were derived for proposed systems, and the contributing factors were also identified.

4. Performance assessment and research methods

The critical factors of thermal and ventilation performance of natural ventilation systems, including airflow rate and temperature change, were concluded in Table 1. The cited literature comprises dissimilar investigation approaches to cope with different aspects. A comprehensive evaluation of the mentioned systems in tables is complicated. It has been recognized that a stand-alone natural ventilation system can typically offer around 20–50% energy conservation, counting on the system design and external climatic conditions. For example, a solar-assisted passive system was recognized to lessen air-conditioning average electrical consumption approaching 10–20% [80,81]. Ventilation rates achieved using the independent system usually cannot satisfy the overall ventilation requirements due to their dependence on the available ambient conditions [44,82,83]. Those solar-based natural ventilation systems highly rely on solar radiation, where a cloudy weather condition may hamper the performance during the period [84].

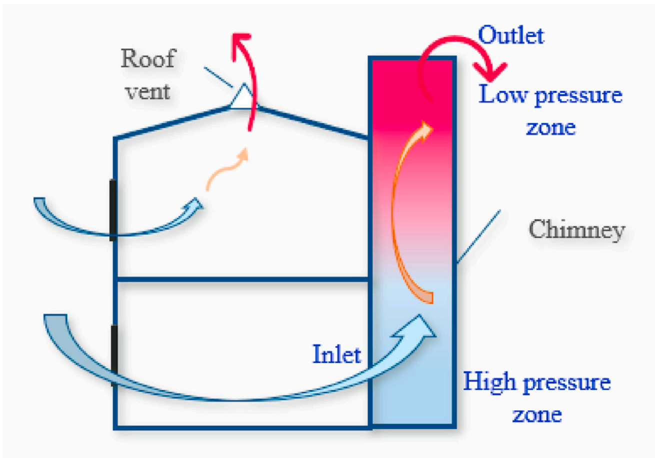


Fig. 7. Buoyancy-driven ventilation.

It is then essential for those solar-based systems to combine with systems not relying on solar radiation, such as wind-based systems [85]. That also emphasizes the significance of the combined natural ventilation systems in practical applications.

4.1. Research methods

The selected studies in the ventilation methods are generally based on experimental methods coupled with numerical simulations [15,86,87]. Two fundamental models are usually adopted for the detailed analytical and numerical analysis, including Bernoulli and Navier–-Stokes equation. Chen et al. [88,89] outlined those Computer-Aided

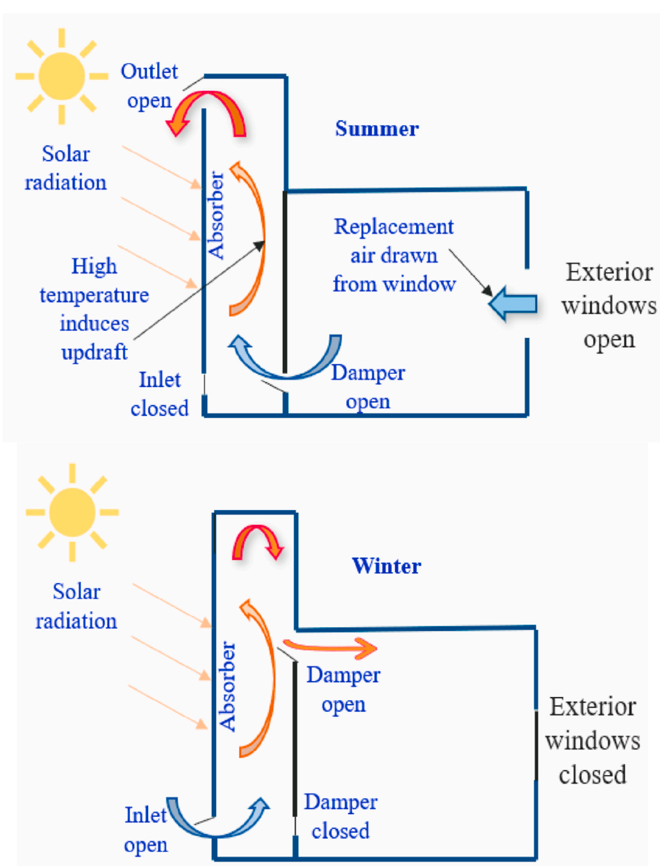


Fig. 8. Schematic of solar chimney. Revised from [54].

Prediction Models, including empirical models, small-scale experimental models, full-scale experimental models, multizone network models, zonal models, and theoretical models (usually related to CFD and analytical models). It is summarized the contributions of modern applications regarding the above simulation methods for practical design and research purposes.

Applications of CFD (Computational Fluid Dynamic) modeling is suited for simulating natural convection and relevant temperature variations or velocity distributions. Unlike analytical models, the development of the prediction capability of CFD modeling in modeling ventilation performance can contribute to preferable appraisals to address the referred issues in developing optimization strategies [90]. Simultaneously, CFD simulation allows researchers to verify additional structure cases in a limited time for optimizing the performance of structures. Varela-Boydo et al. [91]used CFD modeling to establish 204 scale models in order to explore the configuration of the air outlet and air passage for the best performance of the windcatcher. Compared with a one-dimensional approach, the CFD technique can capture the prevailing context of flow phenomena like reverse-flow, Laminar, and turbulent, by a multi-dimensional analysis [92]. Naraghi and du Sordet [93] examined a correlation for calculating the volume flow rate for a solar roof chimney with the support of controlling parameters obtained using CFD. Nguyen and Wells [94] used CFD simulation to predict the performance of solar chimneys with different configurations through two indicators: flowrate and thermal efficiency. Using Fire Dynamics Simulator (FDS), Shi et al. [95,96] developed an empirical model to predict the airflow rate through the air intakes under smoke exhaustion. It is examined the impacts that differ with regard to the interaction mechanism between the air inlet and room windows on the solar chimney performance. Zamora and Kaiser [97] evaluated the effects of wind-buoyancy-induced airflow characteristics on a solar chimney's ventilation performance. Su et al. [98] evaluated the volume flow rate of a commercial wind tower device according to different external wind velocities, using CFD, experiments, and far-field tests. The results critiqued that the buoyancy-driven flow shows an insignificant impact on the airflow rates of the wind tower at excessive outdoor wind speed.

4.2. Indicators of performance

4.2.1. Ventilation rate

Ventilation effectiveness evaluates the efficiency of the supplied fresh air commingled and distributed in the inhabited space [49]. The air exchange efficiency indicates the efficiency of the fresh air distributed in the space. Table 1 gives information regarding the performance indicators from existing studies. Ventilation effectiveness indicates the efficiency of the stale air removed from the space [27]. The air exchange efficiency is measured by ACH or flow rate through the building. ACH is a measurement of the air volume gains or losses of a space divided by the volume of the space [99]. If the air supply volume to the inner spaces is adequate, the interior temperature could infinitely approach the ambient temperature. In general, natural ventilation can produce a considerable airflow rate economically on account of the use of natural phenomena without the aids of traditional energy resources. The ventilation rate is affected by many factors, including the intensity of wind or stack forces, the wind direction, and the resistance of the flow movement. The uncertainties of natural phenomenon could result in the air change rate varying markedly. Moreover, the existence of uneven distribution of air movement to internal spaces which leading to either inadequate ventilation or over ventilation and excessive energy wastage.

The range of ACH values and the volumetric flow rate saw an apparent diversity in the same system in Table 1. This large fluctuation is due to different external conditions and research methods and the addition of different auxiliary systems to the same system. More specifically, ACH differs with regard to many design variables, such as structural geometry, number of residents, the use of insulation, windows, and building function [15].

For those systems that equip with a vertical cavity, the higher the vertical height is, the higher the amount of induced air ventilation rates will be [100]. For example, intentional shafts can create more considerable differences between top and bottom, increasing the airflow rate in a solar chimney, while the experimental results from Afonso and Oliveira [101] revealed that the chimney depth is more influential on the ventilation rate rather than its height. ACH will also increase as the intensified solar radiation and increased cavity depth [87,102]. Although wind-driven can generate more considerable air movement inside the building than buoyancy-driven, a constant airflow can be maintained with appreciate buoyancy design. Khanal and Lei [15] summarized the research of solar chimney in the past 20 years, especially for ventilation performance assessed by ACH and flow rate. It is argued that the previous studies were mainly divided into two research fields: one was to study the heat transfer process and fluid mechanics characteristics in the channel; The other is to study the flow and thermal behavior of the space inside the ventilated building.

On the other hand, wind-driven ventilation is peculiarly desirable in areas with relatively sufficient wind resources, and ventilation efficiency shows excellent diversity and heavily rely on local wind speed and direction. For example, an induced airflow rate of 140–330 m^3/h can be achieved at different ambient temperatures under solar radiation ranging from 200 to 1000 W/m^2 [103], while wind catcher supplies 106 and 145 l/s under direct wind with 0°and at wind speeds of 3 and 6 m/s, respectively. The air supplied was 106 l/s, and the air extracted was just over 80 l/s at a wind speed of 3 m/s [104]. Moreover, a wind tower could produce 414 m^3/h airflow rate, as shown in Ref. [105]. Furthermore, the configuration of the system can affect the ventilation rate profoundly. Rotating chimney cowls produced 35–90 l/s depending on cowl size and wind speed [43].

4.2.2. Temperature

The majority of the research on natural ventilation methods were related to passive cooling [106]. It was known that the temperature reduction based on wind-driven seems to be better than that of buoyancy ventilation under certain environmental conditions. For example, in the studies taken by Oropeza-Perez and Ostergaard [31] and Jomehzadeh [45], temperature droppings induced by a wind tower up to 12–25 °C, while solar chimney can achieve a decrease of the internal temperature by roughly 1.0–3.5 °C [107]. The main reason is that the pressures generated by buoyancy are relatively low. Nonetheless, in terms of the space heating effect, the buoyancy-driven system performs even better. In stack ventilation, the indoor air temperature and the amount of ventilation are coupling relationships, which can be expressed by a quantitative coupling equation. The specific calculation methods are not listed and described in this article.

4.3. Assessment and applicability

The initial intention of natural ventilation is to exhaust stagnant air, dilute indoor air pollutants, regulate thermal comfort, heat dissipation, and air flow displacement. The challenges of natural ventilation are the difficulties of achieving a consistent airflow direction and the variation of the ventilation rate due to inconstant driving forces. They could result in the possibility of a low ACH during unfavorable climate conditions. Also, a well-sustained negative pressure is challenging to achieve the required natural ventilation performance. Excepting the interferences mentioned above, it is still a convincing alternative to reduce the operating frequency of conventional ventilation systems by using an appropriate design or integrating ventilation. Owing to these problems, taking advantage of a combination system that minimizes energy consumption becomes attractive.

The comparison of natural ventilation can be undertaken following the general concerns of the literature in Table 2. Through extensive literature, ten judgment criteria were identified for the pair-wise comparisons of the existing natural ventilation systems. However, there is no general criterion for evaluating the merits and availability of systems based on their performance. For example, heating systems are to capture and store the heat gain and retain the thermal within the building, while cooling systems provide aeration-cooling or protect the building from direct solar radiation and accelerate air circulation to remove warm air. However, not each natural ventilation system can have the dual function of heating and cooling the space simultaneously.

Additionally, the advantages and disadvantages of different systems under a specific scenario can also be observed in Table 1. Give a few examples, the Trombe wall is excellent in space cooling and heating convenience, especially it can be combined with selected materials, various channels configurations, and different vents dimensions [84,108]. However, the related reverse heat transfer needs to be resolved for some cases [20]. Notably, the performance of the DSF on acoustic insulation and thermal insulation are significant. However, fire safety has become an obstacle to the widespread use of DSF. DSF is usually used in conjunction with shading or sheltered devices to reduce direct solar gains into occupant spaces [109–113]. As for the solar chimney, temperature and air velocity are increased with higher solar radiation intensity. The air channel can be heated by solar energy to drive the air movement to take away the internal heat to achieve the cooling effect [114]. The problem that needs to be solved in the chimney effect is how to prevent flow reversal effects [92,115]. Besides, it is generally considered that the solar chimney is not appropriate for regions with inadequate insolation or hot and humid climate since the air movement in SC is caused by intensifying temperature difference produced by direct or indirect solar gain.

In terms of wind-driven ventilation, different designs of systems are based on the same principle [116–118]. Wind tower shows excellent performance under hot and dry conditions [45,119–121]. Windcatcher performs exceptionally in achieving the desired IAQ and improving thermal comfort under a hot and humid climate [122]. Stagnant air is extracted from the intentional openings at the leeward side, owing to a negative pressure generated by the siphonic effect and stack effects [43]. A linear correlation was observed between wind speed and the extract flow rate. The suction effect of a wind-induced system depends on the prevailing wind speed and incident angle of the wind and the characteristics of cowls (regarding discharge coefficient) [67]. Thus, unstable and discontinuous wind and direction could limit the ventilation performance. The dependent variables with the most straightforward influence on ventilation performance and thermal performance are elaborated in the subsequent sections. These related causes affected different regions differently [23], and compromise may exist regarding thermal comfort level [123,124].

4.3.1. Building characteristics and thermal mass of building envelop

A close relationship has been found between the diversity of space geometry (*i.e.*, building typology and position of building openings) and the air circulation system. Through energy simulation software (*e.g.*, based on genetic algorithm, sequentially search technique particle swarm algorithm [125–127], and parametric study), researchers have conducted a series of case studies on approaching the impacts of structural characteristics on energy performance. The studies determined the optimal building features considering diverse parameters, such as facade type, opening area, building envelope, the height of different building parts, glazing type, building shape, the orientation of the windows, aspect ratio, and the windows-to-wall ratio [126,128–141]. Pacheco et al. [142] stated that the physical configurations of ventilated spaces could affect the supply of adequate air and thermal conditioning and moisture dissipation. Aflaki et al. [143] argued that reducing heat absorption from the environment is necessary to minimize energy loading. The study discussed the effect of architectural elements on ventilation performance in tropical climates, namely the building form, location, and size of building openings and building features (*i.e.*, orientation and layout).

Although numerous studies have been carried out on natural ventilation, their focus is much on the single room to simplify it. There are relatively few studies on natural ventilation performance in multi-chambers. It is essential to approach practice by shifting the focus from those simple cases to practical applications, even though they have many influencing factors. The research on the effect of hot-pressed ventilation in multi-chamber space can be divided into two categories: the multi-chambers located at the same level. The other is the vertical distribution of the chambers, that is, multi-storey buildings. As for the first case, Lin et al. [144,145] discussed how the interior geometry affected the ventilation flow and stated that the ventilation depends on the geometry and openings in the room and the size of adjacent rooms. The factors affecting the multi-floor space are relatively multitudinous. The multi-layer solar chimney with a vertical distribution model of three chambers was established by Punyasompun et al. [100] and validated by experimental data. Their study identified the optimal opening method for multi-layer solar chimneys. It verified that multi-layer buildings' indoor temperature using solar chimneys was 4–5 °C cooler than those without solar chimneys. Omrani et al. [146] summarized the evaluation methods and prediction tools of natural ventilation as a passive cooling strategy in the design process of multi-storey buildings.

Another consideration is the effects of diversity in configurations and dimensions of the passive system itself. Variables usually include the cavity width, temperature of the absorbing wall, internal air temperature, and chimney depth [93,147]. Shi and Chew [148] provided a review on summarizing the influences of geometric factors and design variables on the solar chimney performance. Mathur et al. [102] assessed the effects of employing a solar chimney to enhance airflow rate and validated the proposed mathematical model with experimental outcomes. A trade-off between the absorber inclinations and stack height was suggested. Besides, Barbosa et al. [59] comprehensively reviewed the relevant literature of DSF and summarized various factors considered by DSF in practical applications and their impact on DSF performance. In addition to environmental factors, it is emphasized that the single-layer space cavity depth [149,150], opening position, selection of internal and external skin materials, and the structural form of the cavity have a particularly significant impact on DSF performance. The conclusion shows that the narrow cavity is more conducive to the airflow generated by the buoyancy effect. The width of the cavity greater than 1 m is not conducive to the chimney effect, and it also leads to an increase in the internal space heat gain.

Based on the balance between the ventilation rate to remove heat from the indoor space and the heat transfer from the cavity to the residential zone, Radhi et al. recommend a cavity depth between 0.7 and 1.2 m [149]. Gan [151] undertook the simulation on the buoyancy-driven ventilation. It was found that the prediction of ventilation rate and heat transfer coefficient were affected by space and cavity dimensions, inlet location, and heat distribution ratio [152]. Because the atrium is an ancient and distinctive form of architectural structure, its performance and building compositions are closely related. Aldawoud and Clark [69] compared the thermal behaviors of atria and courtyards with similar geometry under four types of local climates.

The coupling of the thermal mass of the ventilated building to buoyancy-driven ventilation has also successfully attracted the attention of many researchers and conducted a lot of research and development. Yang and Guo [153] established a theoretical model to analyze the non-linearity of the coupling effect between the thermal mass of building envelopes and the buoyancy effect under an external heat source. The thermal profile and ventilation performance were discussed. Notably, it is analyzed the uncoordinated ventilation rate fluctuations under the coupling effect. Similarly, such a nonlinear coupling relationship was also studied by Yam et al. [154]. Their theoretical model is divided into two cases. One is when the ventilation rate is constant; another is when the ventilation rate is a function of the temperature difference between indoor and outdoor. The control parameters for thermal behaver expression in these two cases are different.

4.3.2. Location and climate conditions

The ambient variables are essential in producing airflow. Some desired flow patterns depend on the available climatic factors. Tejero-González et al. [123] assessed the effectiveness of passive techniques with a comprehensive climate analysis. Bhamare et al. [23] provided a review of passive cooling techniques, including solar control techniques, heat modulation technique, and heat dissipation technique considering the impacts of the climate factors.

While naturally ventilated buildings may experience an ideal outdoor environment offering driven forces appropriately, the performances are distinctly fluctuating and dependent upon external variables. Consequently, the theoretical prediction of airflow patterns rarely occurs consistently along with time-basis [71,123], which does not mean it cannot offer the required performance. Ambient variables are potential constraints in natural ventilation applications, such as solar intensity, wind intensity, temperature, and humidity. For example, wind towers visible in ancient buildings in parts of Arabia can suck in the high-speed wind. The air travels down through the tower and drives heat away from building the interior by providing a constant air current and circulation. Contrarily, as the movable wind direction changes in a specific time range, the pressure field around the building also changes accordingly. In the hot season, energy consumption for refrigeration purposes is significant. Take atrium, for example, Rojas [155] studied a five-story atrium in the Mediterranean climate condition, showing that protecting solar radiance can give rise to a 75% decrease in cooling demand.

In comparison, night ventilation contributes to a reduction of 10%. However, the application of atrium in the tropics could cause overheating problems, especially during the periods of intense insolation, the excessive heat transfer from the broad surface of the glazing components at the upper space of the atrium could be occurred [51]. Mahyuddin et al. [156] reviewed the performance of natural ventilation using different atrium configurations and components in buildings under different climatic conditions. By changing the physical features and adopting an evaporative cooling system, a field investigation of a building with atrium space in the tropics was examined in a tropical environment in which five modes are developed [71,157].

Besides, reducing energy consumption can also be realized by selecting different construction materials according to local conditions. Generally, insulation and thermal materials are employed in cold climates to reduce heat loss, whereas insulation and reflective materials are adopted to dissipate heat gain in hot climates [158].

4.3.3. Ambient temperature

As demonstrated in the literature, changes in indoor and outdoor temperatures directly affect the efficiency of natural ventilation systems. For example, in hot and humid climates, the impacts of surrounding thermal conditions on the temperature and air distribution through atrium space are more significant than the heat loads inside the space [106,159]. On the contrary, it is detrimental to employ the atrium system in scorching ambient temperatures (usually greater than 35 °C) [160]. If the temperature varies slightly between inside and outside, it can adversely affect the buoyancy-driven natural ventilation processes. Night ventilation contributes significantly to natural ventilation only when the exterior temperature drops obviously [27]. Nevertheless, the retardance of charging and discharging activities limits the performance and capacity of night ventilation on account of the reliance on the natural convection process and the dependency on structural thermal mass [161,162].

4.3.4. External wind

As one of the dominant driving forces, the external wind is critical in determining ventilation efficiency unless the building is fully sealed. Wind factors could also enhance the stack effect. Wang et al. [163] confirmed the influence of external wind on the optimal design parameters of wall-mounted solar chimneys. Since the additional wind driving force can avoid backflow in a larger cavity, the chimney gap should be increased by 0.2 m compared to the design size that only considers buoyancy driving. Simultaneously, the addition of wind reduces the air resistance to enhance the solar chimney's performance. For example, wind force can drive the fresh air in an atrium space by enlarging the positive pressure employed at the windward side inlet toward the wind. It also weakens the negative pressure on the leeward outlet. The pressure at the air intake may be varying from positive pressure to negative pressure according to the fickle wind direction. When there is a reverse airflow at the roof outlet in the atrium, the inlet opening turns into an exhaust port. It results in an unexpected descending air movement and then produces a suppression of the stack effect caused by plum from the heating source [164].

Many studies have investigated the interaction between external wind and natural ventilation systems [12]. For example, Gratia et al. [60] analyzed the influences of wind on air temperature distribution inside the DSF cavity. It is carried out that the temperature inside the glazing cavity of DSF can be 50 °C higher than outside when there is no wind influence; The temperature in the cavity is 30 °C higher than outside at a wind speed of 4 m/s. Gratia and De Herde [165] conducted a further study on the airflow pattern under the external wind. The results showed that, when the incident wind is perpendicular to the skin of the DSF, the airflows between the different floors are similar. In this case, the wind effect on the upper floors was significant than the buoyancy effect. In contrast, when the wind was blowing from the opposite direction, the air was extracted into the cavity on the lower floors. Saadataian et al. [166] emphasized the mechanisms of wind towers under the buoyancy effect and wind-driven flow. It argued that wind-driven flow is an essential variable in determining the ventilation rate when the wind source is adequate. Also, the study examined the attributes and configurations that can achieve optimal performance. Hughes and Ghani [83] presented a CFD simulation of a commercial wind tower. It is explored the effects of the variations of external wind on the capability of passive ventilation rate. Similarly, Jones and Kirby [167] also applied a semi-empirical model to determine the effects of the varying external wind features on the performance of the wind tower.

4.3.5. Solar radiation

Solar radiance is necessary to demand space heating during the cold weather and the encouragement of buoyancy ventilation during the hot season. Menchaca-Brandan et al. [168] affirmed the importance of accounting for radiative effects on airflow modeling, especially regarding the air temperature profile. It is pointed out that the ignorance of radiation results in the air temperature of occupant space is lower by 2–4 °C than the cases with the consideration. The air velocity was observed higher in simulations considering the radiation [169]. Hence, neglecting radiative heat transfer could bring an unreliable prediction of thermal comfort level. In other words, theoretical models or numerical simulations that omitting radiation may mislead the predictions of room temperature distribution. According to the research of an atrium, the solar radiance that penetrates through the glazing walls or roof has the primary role in producing thermal stratification in atrium space [170].

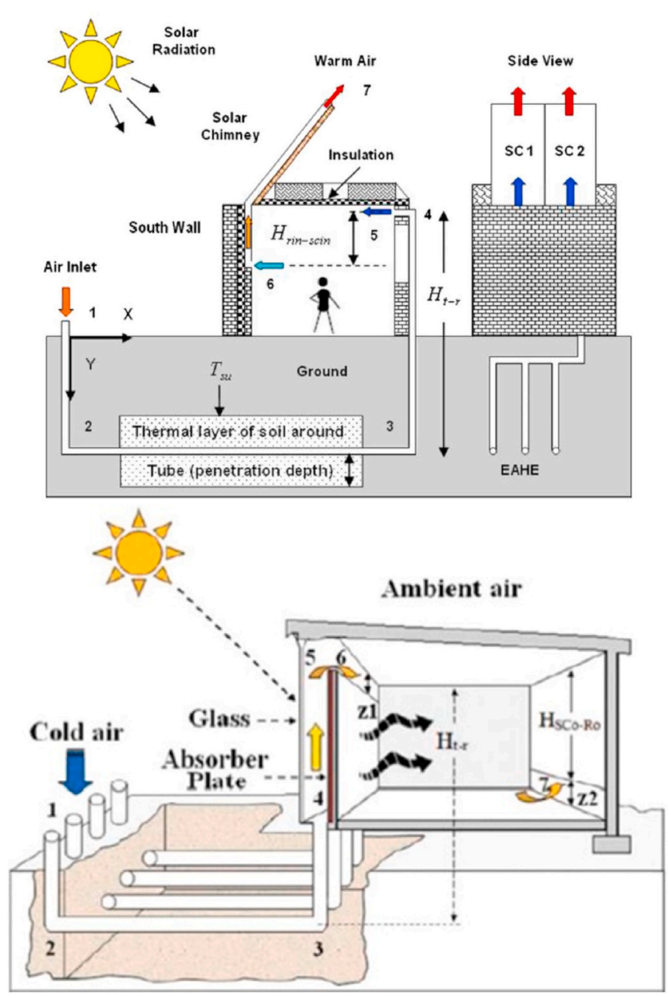


Fig. 9. Diagram of the combined earth-air heat exchanger and solar chimney/roof solar chimney [284,289,291].

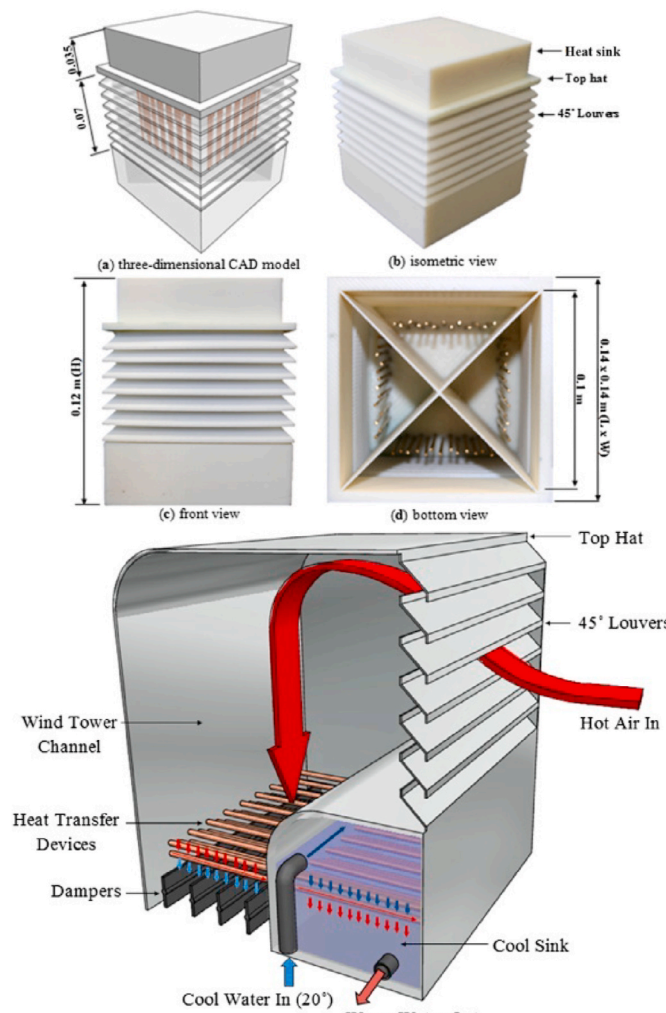


Fig. 10. A cooling wind tower/catcher incorporating heat pipes [255,318].

When the atrium/courtyard is exposed to extreme solar radiation for a long time, it places a severe problem on the energy conversation [171]. The overheated air was conducted into the adjacent spaces, which lead to extra energy consumption to avert thermal discomfort.

Furthermore, the concurrent influences of solar radiance and external wind on the same natural ventilation system were also compared by some studies. For example, Shi [85] investigated the interaction of solar chimney with both solar radiation and external wind under different wind angles (the angle between the incident wind and outward normal of the wall with the window) numerically and theoretically. A windward situation ($0^\circ < \alpha < 90^\circ$) was suggested, but it was surprising to know that the leeward scenario with $\alpha = 180^\circ$ presents a narrow effect on the performance of the solar chimney. The study affirmed solar chimney performance utterly dependent on the external wind rather than solar radiation and developed a mathematical model to predict the critical wind velocity.

4.3.6. Relative humidity

There are not too many direct studies on addressing the influences of relative humidity on natural ventilation performance. Humidity and condensation prevention are two considerations related to thermal comfort. Insufficient ventilation rate may result in more significant indoor relative humidity and moisture accumulation. Simultaneously, the significant increment in relative humidity will lead to a diminution in airflow rate at the chimney inlet and outlet [172]. Besides, the high relative humidity could also lower the efficacy of a passive cooling system [123]. The quantitative influence and how the relative humidity affects the natural ventilation systems can be critical for future works.

5. Combined technologies

5.1. Practical implementations

Table 3 summarizes the different combined passive-assisted ventilation systems in a building to enhance ventilation and thermal performances. It was known that relying on a single natural ventilation system may result in both under and overventilation relative to a design objective. The combined approaches of passive ventilation systems as an economical solution are then embraced. The two driving forces of a natural ventilation system that produce air circulation vary randomly. Moreover, the difficulties in controlling natural ventilation, with airflow being unpleasant in some places and stagnant in others, result in not working as expected. Therefore, the interruption in regular operation may occur during unfavorable climate conditions.

Integrated approaches are advised appreciably economically. When natural ventilation alone cannot meet the required ventilation performance, the scheme of alternatives may be considered. Energy consumption would considerably be reduced by adopting multiple passive strategies [187]. Moreover, the implementation of the practical corporation of passive technologies needs to account for the functions of the buildings.

Since buoyancy-driven natural ventilation systems with vertical air shafts can be easily accommodated into a building structure, they are more accessible to integrate into buildings and work with other natural ventilation facilities to induce high air ventilation rates. The buoyancy provides adequate driving forces to extract the stagnant air from the buildings under intensive solar radiation. By a coordinated integration of components, DSF, solar chimney, and atrium can achieve high-quality feasibility. A few studies [24,49] have outlined the solar chimneys incorporated with selected systems to enhance ventilation performance. The recommended systems include Trombe walls, earth to air heat exchangers, solar roof collectors, evaporative or adsorption cooling components, and the active solar systems of solar chimneys. The research indicated the optimization and control strategies of such coupling systems deserve further study under various climatic scenarios. Likewise, the atrium can collaborate with the solar chimney or double-skin facade. Implementation of incorporative ventilation techniques may break the limitations of building design. For instance, it is generally recognized that deep surrounding spaces place an obstacle for the buoyancy ventilation, leading to insufficient buoyance effect to drive the air pass through a remote district. Moreover, it is observed that using buoyancy-only ventilation models shows deficient effects on the thermal conditions in extreme climates [24,49,71,102,284].

Moreover, solar-assisted components integrated into stack ventilation are an efficient way to refine the performance of passive ventilation [49], contributing to the enhancement of the capability of integrated systems. Hussain and Oosthuizen [285] examined the coupling of the atrium and solar chimneys with diverse geometric configurations. It was affirmed [71] that the atrium scheme, coupled with a solar chimney, could be viable to improve the buoyancy effect [40]. It revealed that the application of atrium independent buildings is efficient in temperate climates with a low impact of thermal stratification [58]. Chan et al. [184] reviewed the previous studies on passive solar technologies for regulating space thermal comfort and indoor environment. The pros and cons of each technique were discussed. It is believed that a combination system that is compatible with space heating and cooling is an acceptable solution for improving natural ventilation.

The role of combined systems in a building can be summarized as follows. First, the combination of multiple systems can compensate for inherent defects in the independent system or instability. Secondly, to achieve constant space ventilated availability, the coupled systems are capable of enhancing the ventilation under various climatic scenarios through thermal management (temperature regulation and heat storage) to reduce undesirable temperature fluctuation. Thirdly, once one of the combined systems fails to operate properly under adverse climatic conditions, the other system can continue working that can then temporarily replace the failed system to fulfill the thermal requirement. Alternatively, provide the driving force needed by another system to create conditions conducive to operation. These several aspects were further elaborated in the following several paragraphs.

Firstly, the combined natural ventilation systems can offer advantages that cannot be achieved through a single system. For example, a single system cannot guarantee a stable performance due to uncertain climate, so the combined form that can provide enhancement of ventilation performance under a stable heat exchange becomes a practical strategy. Employing pre-cooling/pre-heating air from the earth-to-air-heat exchanger (shown in Fig. 9) is an innovative application of mix-mode ventilation to improve thermal and ventilation performances for space cooling/heating [286]. An earth-air heat exchanger (EAHE) is a technique to circulate the air in the building employing pipes buried at a particular depth underground, utilizing soil beneath the ground as a heat sink to offer an undisturbed constant temperature source [284,287]. Because of the passive nature of the operation, the implementation of EAHE is still primarily affected by surrounding conditions, such as ambient air temperature, groundwater level, soil type, and outdoor relative humidity. When the soil is thermally saturated, the energy transfer between the soil and the air does not occur, and the temperature gradient between the soil and the air is approaching zero [288].

The traditional EAHE is driven by a fan, contrary to the original intention of low-energy building design. Alternatively, the idea of integrating EAHE with buoyancy-based ventilation systems could be the solution to eliminate the use of fans and reduce energy consumption and peak cooling demand in the hot season. Maerefat and Haghighi [284] proved that the proposed EAHE-SC system could achieve thermal comfort in a harsh environmental condition by making an appropriate modification to system. A schema of the system is illustrated in Fig. 9. The heat source for the stack effect is mainly provided by the solar chimney, while the EAHE system relies on the soil to provide the cooling effect. Li et al. [289] verified that the significant cooling capacity of the coupling system could make indoor temperature 10–13 °C lower than the outdoor temperature. Wei et al. [286] developed a quantitative model of EAHE and the buoyancy generated by the heat source inside

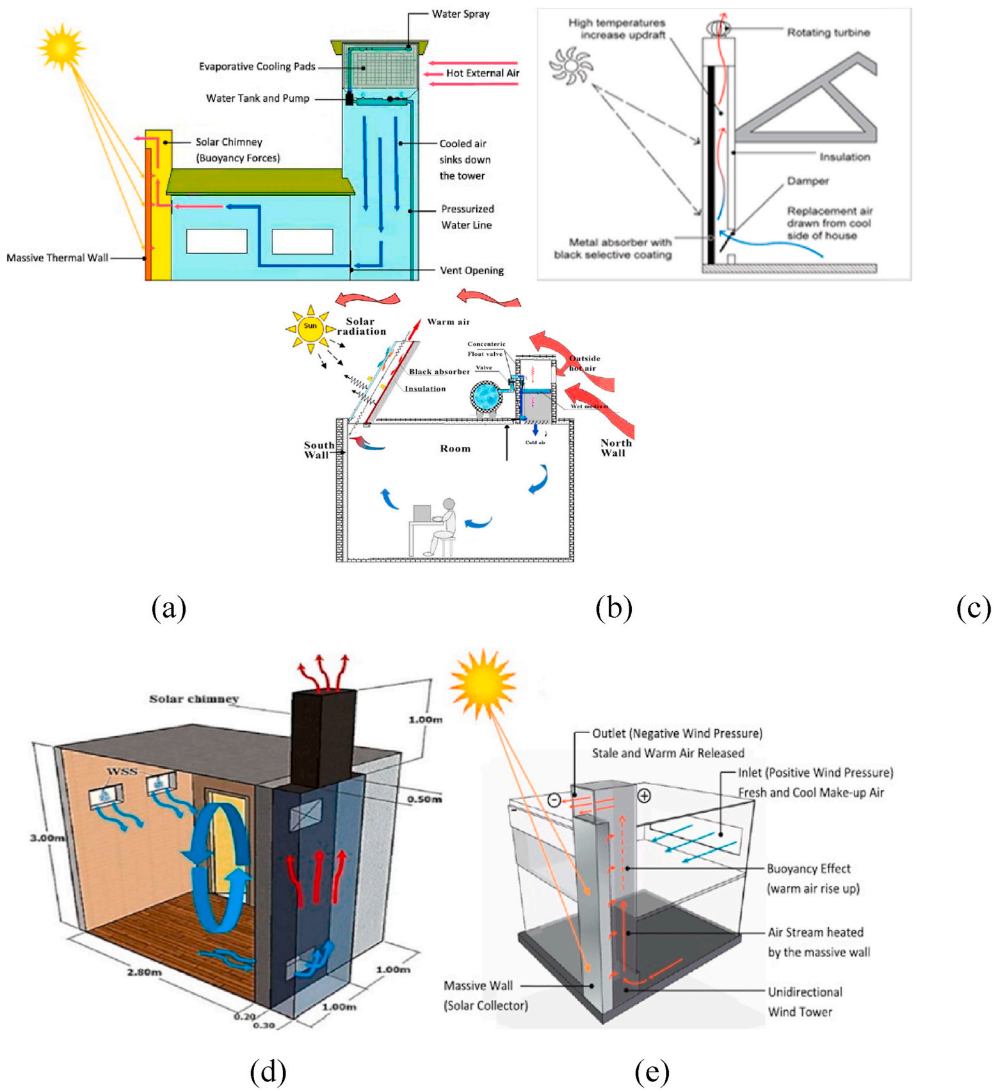


Fig. 11. Diagrams of a coupled system with different natural ventilation systems: (a) Conceptual design of a wind tower integrated with a solar chimney [44,120]; (b) Combination of a solar chimney and a Turbine ventilator (Source: Green Builder Solar Guidelines (Residential)); (c) A solar roof chimney integrated with an evaporative cooling wind tower [320]; (d) Schema of a Trombe wall coupled with and a solar chimney and a water spraying system [108]; and (e)wind tower integrated with solar chimney [44].

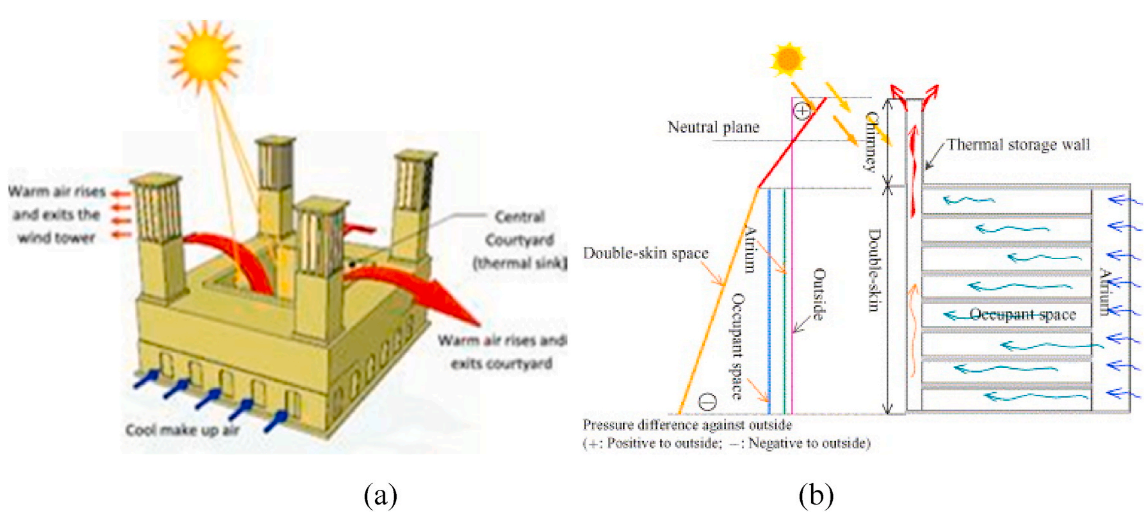
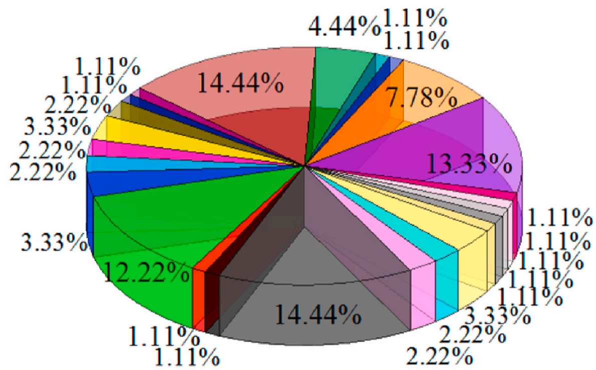


Fig. 12. (a)A schematic of integrated wind towers and a courtyard [44]; (b)a diagram of an atrium integrated double-skin façade with solar chimney [58].

the space, considering the nonlinear coupling relationship of the combined effect.

Additionally, the coupling of wind-based ventilation and EAHE can also provide the driving force for airflow in EAHE. Benhammou et al. [290] developed a mathematical model to investigate the performance of a windcatcher coupled with the EAHE and evaluated the thermal



Legends table

Combinations	TW	SC	DSF	A/C	PV	WT/C	F	WW	WS	RC/VT	RV	HRV	EAHE	NC
TW		SC-TW	NA	NA	NA	NA	NA	NA	NA	NA	NA	TW-HRV	NA	NA
SC			SC-DSF	SC-A/C	SC-PV	SC-WT/C	SC-F	NA	SC-WS	NA	NA	SC-HRV	SC-EAHE	SC-NC
DSF				DSF-A/C	DSF-PV	DSF-WT/C	NA	NA	NA	NA	NA	DSF-HRV	NA	NA
A/C					NA	A/C-WT/C	NA	NA	NA	NA	A/C-RV	NA	NA	A/C-NC
PV						NA	NA	NA	NA	NA	NA	NA	NA	NA
WT/C							NA	WT/C -WW	WT/C-WS	WT/C-RC/VT	WT/C-RV	WT/C-HRV	WT/C-EAHE	WT/C-NC
F								NA	NA	NA	NA	NA	NA	NA
WW									NA	NA	NA	NA	NA	NA
WS										NA	NA	NA	NA	NA
RC/VT											NA	NA	NA	NA
RV												NA	NA	NA

Fig. 13. Research share of the cross combination of natural ventilation systems (TW – Trombe wall; SC – solar chimney; DSF – double-skin facade; A/C – atria & courtyard; PV – solar walls with photovoltaic module; WT – wind tower; WC – windcatcher; F – feneestrainon (single-sided & cross-ventilation); WW – wing walls; WS – wind cowls/scopps; RC – roating wind cowl; VT – turbine ventilation; RV – exhaust cowls/roof vents/roof cowls; HRV – heat revoery ventilation devices; HID – heat transfer device; EAHE – earth-air heat exchanger; and NC – nocturnal cooling applications).

performance of the integrating system in a hot and humid climate. Alternatively, there is a view that the system is not suitable for residential buildings due to the demand for space and the high price.

Secondly, temperature stability is a prerequisite for providing continuous ventilation. There is an increase in the application of the heat recovery ventilator to reduce the heating and cooling demands. A passive ventilation system with a deep cavity and thermal mass structure provides ideal storage space for the installation of heat transfer devices (see Fig. 10). The heat emitted by the building can be used as a heat source or radiator that depends on the ambient circumstance. Heat recovery ventilation (HRV) devices, such as heat pipes [292], phase change material (PCM), rotary thermal wheel, and fixed plate heat exchangers [7,8], are integrated components in enhancing ventilation performance. Some studies have reviewed existing heat recovery equipment to explore the potential and important considerations of incorporating heat recovery devices into passive ventilation systems [7, 8].

Sensible and latent heat are two classifications of thermal energy, which could be continuously recovered by the heat recovery devices. Sensible heat refers to the heat of dry air. The heat recovered by latent heat comes from the moisture in the airflow. Devices capable of recovering sensible and latent heat are preferable for integrating into the passive ventilation system. Heat pipes (see Fig. 10) and rotary thermal wheels are considered the most promising integrated technology because of excellent thermal efficiency and low-pressure loss throughout the heat recovery equipment [7]. In order to maintain a sufficient airflow rate, a low-pressure loss is expected. Besides, several disadvantages limit the applications of heat recovery. Take rotary thermal wheels for an instant, and they are susceptible to air short-circuiting. In this case, air flowing in one direction will be recirculated in an unexpected direction.

Thirdly, a large number of studies researched phase-change materials (PCMs) employed in passive ventilation systems as it is readily incorporated into the building. PCM can be integrated either into heat modulation or amortization technique (*i.e.*, modify heat gains) or heat dissipation technique (*i.e.*, remove internal heat). Geetha et al. summarized and discussed the applications of passive cooling techniques with and without thermal storage components and collected relevant performance reports for each technique [11]. The thermal mass containing PCMs applies as thermal storage applications are opposed to instantaneous [293]. During the phase transition, it is better to keep the PCM temperature relatively constant. Coupling thermal mass and PCM makes it useful to keep the space at the desired uniform temperature and significantly reduce the cooling load in milder weather conditions, especially when PCM is combined with night ventilation [294,295].

Since solar chimney, Trombe wall, and windcatcher are attached to the building envelopes structurally, and PCM can entirely replace the thick concrete external wall due to its superior energy storage ability and ease of compatibility with most building elements. Quite a few studies have investigated the consolidation of PCM in the absorb/storage wall of a solar chimney [296–304] or a Trombe wall [305–316] for building ventilation applications. Waqas and Din [317] provided a review of the passive cooling building using PCM as cold storage. Use the cool air to solidify the PCMs and extract the stored coolness during the hot day. It has been claimed vital challenges and impacts facing the passive system's design, which also provide a wide range of the PCMs. Vargas-Lopez et al. [303] presented a wide range of transient mathematical models of SCs with/without PCMs. The limitations and advantages of each model were explored. It is further derived a new theoretical model for a double-channel SC with PCMs.

Fluctuations in solar radiation yield to solar chimney instability. In the absence of insolation, the thermal efficiency of the solar chimney will decrease sharply. At this time, PCMs as thermal storage mediums will provide heat supplement and heat exchange for the system [296]. The evidence revealed that a solar chimney coupling with PCM could extend the ventilation hours without insolation, notably contributing to ventilation effort during the night time. Calautit et al. [233] obtained a temperature reduction of 9–12 °C achieved by wind tower with a heat transfer device in hot and dry climatic conditions. Xaman et al. [214] performed a conjugate heat transfer analysis under transient conditions for a solar chimney with three different absorbing materials (*i.e.*, concrete, PCM, and copper plate) on the warmest day in Madrid, considering the gains and losses of convection and radiation. The transient numerical simulation proofed that the mass flow rates and thermal efficiency values of the solar chimney with a PCM are higher than concrete but lower than a copper plate.

Fourthly, to cope with the inadequacy of the stand-alone system in natural heating/cooling, a benefit of coupling systems is that, when the operating capacity of one system is restricted, the other system can still operate normally. Wind-buoyancy ventilation is a strategy adopted to obtain the desired level of thermal comfort and constant naturally ventilated operation [159]. Since relying on a single chimney effect cannot provide sufficient ventilation, the weight of wind ventilation increases. Wind-driven and buoyancy-driven are not mutually exclusive in some cases, and the wind can even contribute to the chimney effect. When solar radiation is insufficient, the exhaust airflow rate can be supplemented by a fan. Meanwhile, the wind-driven devices could provide a supplementary ventilation rate.

The efficiency of the combination of the two driven forces is subject to the interaction between wind and buoyancy effect, which results from many variables, such as flow patterns, incorporated forms, and opening dimension and position. The studies [44,45,319] outlined that the windcatcher can be coupled with evaporative cooling systems, solar chimney, and a courtyard (see in Fig. 11(a), (c), and Fig. 12). Abdallah et al. [320] presented a coupled system with a solar roof chimney and a wind tower, as shown in Fig. 11(c). The integrated system achieved a volume flow rate of 414 m^3/h and a decrease of 10–11.5 °C at room temperature. Besides, a traditional Trombe wall may lose much heat at night due to its low thermal resistance. It might also act as a heat source under a hot atmospheric condition and cause overheating in a well-insulated building [158]. Rabani and Kalantar [108] proposed a newly designed coupling system of the Trombe wall and solar chimney with a water spraying system, as shown in Fig. 11(d), to enhance cooling capacity. It is appraised the cooling capacity of the system numerically under the desert climate. It explored that the mass flow of 10 l/h and ACH approaching eight could be achieved by the combined system. It is also proved that the change in outdoor relative humidity just slightly affects the air velocity and ACH. As the temperature difference between the indoor and the cavity decreases, the average air velocity and ACH in the channel will decline.

Meanwhile, the thermal effectiveness of the system can be improved by roughly 30% by a water spraying system. Ahmed et al. [13] reviewed the ventilation performance of Single-sided and cross-ventilation, Windcatchers, and Solar chimneys in a warm climate environment and evaluated both thermal comfort and IAQ. The study proposed that combining SC or windcatchers with water evaporation cooling is the best solution to achieve the cooling effect and ventilation efficiency in hot and dry climates.

Nowadays, the concept of a solar-wind tower system employed in a naturally ventilated building has been studied by various researchers numerically and experimentally, as seen in Fig. 11(a)&(e) [120,210]. By thermal gradients and incident wind, the enhancement of flow convection can be produced. The glassing cover of a solar chimney (see Fig. 11 (e)) is heated by solar radiation and warms the air across the channel. After that, warm air rises and exhausts from outlets and draws fresh air through the openings [47]. Some researchers argued that the application of solar chimney integrated with windcatcher might be the solution when there is not a desired wind [321]. In other words, the thermal efficiency of a solar chimney is comparatively higher when encountering inadequate incident wind [103]. A wind tower could generate a mass flow rate roughly of 0.75 kg/s at a wind speed of 1.0 m/s, while the solar chimney assisted system was capable of producing up to a 1.4 kg/s airflow rate at 700 W/m^2 solar intensity [210] and a reduction of air temperature up to 15 °C for the combined system [120]. Bansal et al. [210]developed a steady-state mathematical model of an integrated system with a solar chimney and a wind tower to ventilate for a three-story building. An individual wind tower generated only 20 ACH compared to 60 ACH produced by the integrated system. Hughes et al. [44] provided a wide-ranging review of wind tower evolution and evaluated the potential of the combinations. Nouanégué et al. [321] investigated solar-wind tower systems numerically. The impacts of influential geometrical parameters on the ventilation and thermal performance of the solar chimney were identified.

The combined structure of the Wind tower-Atria/courtyard is a traditional architectural style in a hot and dry area, as illustrated in Fig. 12(a). The air in the courtyard was heated by solar radiation during the day, and the air movement occurred due to the stack effect, resulting in air circulation between adjoining spaces. In contrast, the courtyard is operated as a heat sink that washes away the stale warm air in the room and fulfills coolness to the adjacent spaces during the night time [322]. Since Atria is a long-standing ventilation system, there is much research on adding additional systems to its structure. The combination of the atrium with a solar chimney and a DSF can benefit from intensive solar radiation, as seen in Fig. 12(b). The interactively support between components could address the insufficiency of the buoyancy force [58].

Similarly, the research on solar chimney has never stopped. In addition to the related research mentioned in Sections 4 and 5, Jafari and Poshtiri [9] established a solar system composed of a solar-driven adsorption chiller, integrating a solar chimney and a cooling channel. The proposed system is simulated analytically, and internal temperature, relative humidity, and ACH are examined. The effects of different contributing parameters on air temperature and ACH were evaluated as well.

Finally, combining building design optimization strategies with passive design can provide a more comprehensive and useful energy-saving scheme for the conceptual design and hypothesis stage. Stevanović [32,323] extensively reviewed the previous studies on passive solar design strategies based on numerical simulation. The review also introduced the optimization methods available and software packages employed widely, focusing on the building forms, opaque envelope components, glazing types, and shading devices.

5.2. Problems and improvements

Since constraints vary according to the diversity of the modeling conditions and controlled experiments under various climatic conditions, it is challenging to draw comprehensive and in-depth conclusions of integrating systems performance. Consequently, it is intricate to rely on previous research achievements to summarize objectively and practically in detail.

According to the studies mentioned above, most of the combined systems exist in systems based on the principle of buoyancy-driven, while only a small amount of studies dealt with the cooperation of wind-driven and buoyancy-driven due to the complexity of airflow mechanism. The effects of wind on airflows, especially on the coupling of natural ventilation systems, are remarkable. Yusoff et al. [324] revealed that the influence of wind on the airflow rate might be favorable or unfavorable, depending on the location of the inlet/outlet vents. Simultaneously, the airflow path, ventilation rate, and temperature change are affected by the inherent characteristics of the system itself and the uncertainty of natural conditions.

Although combined passive systems are widely regarded as an effective strategy for sustainable buildings, there is currently no general criterion to summarize and rank them in line with their performance. It is then necessary and critical to conduct more experiments towards the coupling of natural ventilation systems to solve commercialized disputes in their implementations [24]. The strengths of natural ventilation come from the capability of providing a desired air change rate economically, with a straightforward structure. Despite the existence of significant fluctuations in the air-change rate, buildings with thorough designs and proper operation can realize the desired ventilation and thermal performance by natural forces under ideal climate conditions.

Additionally, thermal bridge breaking of glazing materials and condensation phenomena may occur in either cold season or hot and humid climates. Since natural ventilation systems lacking dehumidification and temperature control, these risks may compromise the durability and longevity of buildings. Since the natural ventilation system is mainly driven by wind and thermal buoyancy, fire protection issues in most NV systems have not been resolved. Only a few studies have contributed to early smoke exhaustion [348–351]. For example, Cheng et al. [349] determined the typical factors affecting natural ventilation and fire safety performance based on a solar chimney. A world-first solar chimney was also implemented in a real practice considering energy conservation and fire safety in Melbourne of Australia [352]. Although these studies have confirmed the viability of solar chimneys in energy-saving and fire safety, more studies are critically needed to prepare them for practical usages in real buildings regarding their dual functions. Yang et al. [351] established a quantitative model to study the convection between a vertical shaft and adjacent spaces via parametric studies, especially when the heated current flows from the spaces into the cavity with a lower temperature. The developed model can predict the vertical distribution of temperature and pressure, mass flow rate, NPL position, and the critical conditions for the transition from single flow to two-way flow. Sensitivity studies were used to analyze a series of parameters that affect the buoyancy effect, such as chimney configurations, the physical characteristics of the air, and the convective heat transfer coefficient.

6. Recommendations and implementations

Ventilation enhancement methods have been dedicated to analysing the performance of natural ventilation systems numerically and experimentally by many studies. Although previous research has focused on the functional evaluation and optimization design of single systems, there are very few papers on the centralized classification of passive ventilation systems and the comprehensive review of existing combined systems. In order to achieve a comprehensive natural ventilation survey and advance the exploration of combined systems, this study records in detail the various attempts made by researchers in natural ventilation over the past 20 years, especially the combination of passive systems and their performance.

6.1. Research progresses on combining natural ventilation systems

A list of natural ventilation technologies and their combination in the single building were reviewed and analyzed, together with their applicability, advantages, and disadvantages in the previous sections. Fig. 13 intuitively shows the share of different combination systems in the research over the years. The following observations can be derived and concluded after the review study. The combination of buoyancy-driven ventilation and wind-driven ventilation is the most common method. Especially the combination of solar chimney and wind tower/catcher, occupying 14.44%. The Tromble wall-HRV combination, which has the same share, has also been numerically simulated and visualized test by many researchers. The secondary research areas are similarly concentrated on combining the HRV system and ventilation facilities with thermal mass, namely SC-HRV and Wind Tower/Catcher-HRV, respectively, occupying about 13%. The third research area is related to nocturnal cooling applications. The radiation effect of day and night can form a natural temperature difference between inside and outside, which can be used by almost any natural ventilation system. Meanwhile, night ventilation is a relatively important sector in the field of natural ventilation.

The ancient ventilation structures, such as the combination of Atrium and wind towers/catchers, which are still used today, constitutes the fourth research area. With its excellent thermal insulation and transparent appearance, the double-skin façade has gradually become a new research focus. It is combined with the solar chimney or the wind tower/catcher system, which also has an intermediate cavity, to enhance the buoyancy effect and promote the airflow in the cavity. This combination not only promotes building ventilation but also reduces cooling and heating demand. The remaining system combination forms are sporadic due to the small volume of the ventilation facilities and their restricted ventilation capacity.

6.2. Current challenges and future works

The following suggestions can be provided by reviewing and summarizing the combined mode of the passive ventilation systems above. Due to its complexity and lack of theoretical models, the majority of previous studies are without detailed parametrical results or merely focuses on the validation of analytical models in corresponding experiments. Some studies examined the ventilation capacity and thermal performance of a stand-alone ventilation mode under specific climatic conditions [114,147]. The primary considerations in the improvement of the performance of natural ventilation approach include introducing different configurations of systems (*e.g.*, configurations and geometries of systems, stack height, the inclination angle of a solar collector and cavity depth), and structural dimensions (*e.g.*, building mass, window to wall ratio), as well as the parameters affected by external and internal variables [353], such as the solar absorptance of the thermal mass [48], and heat transmittance and solar reflectance of glazing materials [59], and ambient conditions (*e.g.*, solar insolation, wind velocity, and direction) [48,353]. For example, many mathematical models have been proposed to predict the performance of a solar chimney based on the above variables [96,102,218,354–356]. Some studies also focus on the correlation between the calculated airflow rate or thermal performance and the variables used based on the parametric analysis [22,29,45]. It is suggested to develop the parametric analysis by considering more contributing variables in future work.

Secondly, according to the leading indicators (temperature and volume airflow rate), buoyancy-driven ventilation is mainly affected by solar radiance and ambient temperature, while wind speed and direction strongly influence wind-driven ventilation. The stack performance predictions are relatively reliable at the design stage [357]. Conversely, It is difficult to predict and control the potential performance of wind-driven ventilation due to its stochastic characteristics [358]. Although wind-induced force can generate a more considerable airflow rate inside the building than the buoyancy effect, air flow could remain constant with proper buoyancy design. The stack effect tends to be less intense. Thus, the wind-induced force requires compromise with buoyancy force for better collaboration in designing integrating passive systems, especially for districts with low internal and external temperature differences [359]. When combining such systems, a thoughtful investigation is required to avert the unpredictable delivery of air flow.

Thirdly, a thoughtful attempt was made on design considerations of the combinations over the year. Most of those previous studies were found concentrating on one-story buildings. With the growth of population, constructors tend to build multi-storey buildings instead. Therefore, either the solar chimney or DSF is an attractive solution for a multi-story structure. Besides, the components with the function of temperature regulation and exchange are well integrated into existing ventilation systems. Studies include the use of EAHE based wind tower/solar chimney and PCM based Tromba wall/solar chimney/wind tower to improve ventilation performance and thermal performance. The proposed combination has been developed numerically and examined experimentally under a controlled environment. In 2D ventilated rooms in contact with cold external environments, the heat transfer of natural convection and surface radiation has been studied numerically [114]. The authors explored the noticeable dependence of thermal performance on the geometrical features of solar chimneys and external variations [114]. Due to the increase in building volume, multiple combination systems will become a development trend in energy-efficient buildings. Salari et al. [328] presented a numerical study of a compound rooftop solar chimney with the PV module and PCM and compared the performance of the proposed system with a conventional SC, an independent PV module, an SC-PV system, and an SC-PCM system. The proposed system shows superiority in power generation under a subtropical climate. In order to achieve more significant building energy savings while meeting the building's internal cooling and ventilation requirements, Elghamry and Hassan [334]also used the power generation capacity of PV to propose and examine a combination of three systems called a geothermal tube-chimney-PV system. The experimental results show that the new system can increase the room temperature by 6.4 °C and generate a forced air flow at 0.0184 m^3/s.

Moreover, as the influencing factors of the combined system increase significantly, it is necessary to carefully and consider as many influencing factors as possible when predicting system performance, instead of blindly combining according to the performance advantages of each system. Taking SC-HRV for example, the performance of the coupling of a solar chimney and heat recovery devices was investigated in Ref. [292]. Using a solar chimney with different glazing materials to warm the air in the cavity, the ventilation rate increases under a higher cavity air temperature. When the model added heat pipes to try to recover the thermal energy in the air, it was found that the buoyancy effect was reduced, thereby limiting the ventilation rate. It also suggested that the buoyancy effect drives the passive ventilation often requires external wind assistance to drive the airflow to the required volume flow rate.

Furthermore, studies on the coupling between different passive ventilation systems are still insufficient. The effort in future works includes the need for parameterization studies. The influences of different kinds of parameters affecting the performance of natural ventilation systems on combined passive systems could be further investigated. Due to the limitations of research methods and experimental conditions, although some combination modes' effectiveness has been practiced, it has not been possible to obtain a universal combination mode of passive ventilation approaches and recognized accurate prediction methods. Fig. 13 and Table 3 show that the leading integrated natural ventilation systems existing are solar chimney-wind tower systems, wind tower-courtyards/atrium systems, and atrium-SC-DSF systems. The airflow mechanisms of integrating techniques, along with their corresponding capabilities and applicability, are discussed in the relevant literature. However, there are significant differences between the predicted results and experimental data of passive ventilation systems mentioned in the selected literature summarized in Table 1. Additionally, another direction that deserves attention and effort is the coupling of the thermal mass of the building itself with buoyancy-driven ventilation. Yang and Guo [153] have proved that the ventilation rate is coupled with the indoor air temperature. Such interaction, which in turn, will change the internal temperature and ventilation rate in thermal pressure ventilation.

It worth mentioning that the applications of integrating the evaporative cooling device with natural ventilation systems to improve thermal conditions and reduce the energy demand of ventilation and cooling [24,45,237,244,337,360] exist in numerous case-studies. Since most of such a system uses water as a medium, it is not sustainable for water-scarce areas. Besides, it was barely noticeable to see some ventilation devices, such as wind scoops, turbine ventilators, and roof cowls, applied into the integrating system. Even though they are capable of obtaining the desired IAQ for a single room, the combined applications may not be practical in high mass residential buildings due to their limited ventilation capacity. Such widgets are often incorporated as appendages into more extensive forms of systems that are also driven by the wind, like wind cowls/scoops, in conjunction with wind towers [264].

Last but not least, to obtain a green building and optimize the building's structure and the equipment that adjusts the indoor environment, sustainability, and the low-cost design process also receive research attention. Using refined Building information modeling (BIM) models to simulate and analyze buildings is one of the most promising methods in the architecture, engineering, and construction (AEC) industry [361]. BIM performs pre-operation and physical simulation of buildings by integrating different simulation software, which can comprehensively analyze architectural lighting (*i.e.*, Ecotect), wind environment (*i.e.*, Ansys Fluent), structural loads (*i.e.*, Abaqus) to form an intuitive three-dimensional architectural model. BIM makes the designed structure more intuitive. After continuous simulation verification, the architectural plan's optimal design is reached, outlined using BIM software to evaluate green buildings and BIM functions in practical applications. Combined the three-dimensional collaborative design under the BIM with the investigation of green buildings, make full use of the richness of BIM information and the foresight of physical simulation of green buildings, provide a scientific basis for architectural design, and provide designers with strong technical support [362,363].

7. Conclusions

This study investigates the current development of combined passive ventilation approaches used in low-energy buildings and their applicability. A review of combined natural ventilation systems was taken before the typical stand-alone systems were briefly introduced. It was observed that the combined natural ventilation could offer several advantages over those single system, including achieving beyond the existing performance by the single system (*e.g.*, employing pre-cooling/pre-heating ventilation to overcome the extreme weather conditions), maintaining the indoor temperature stability (*e.g.*, thermal mass for heat storage), realizing heat energy recovery (*e.g.*, heat pipe and rotary thermal wheel), overcoming the inadequacy of single system (*e.g.*, combined solar- and wind-basis driven ventilation), and providing a more comprehensive and useful energy-saving scheme (*e.g.*, tailored based on building characteristics and weather conditions).

However, the studies on the coupling between different passive ventilation systems are insufficient. Several directions are suggested in future works. One of the main focuses in previous studies is to achieve optimal design, where the focuses are on the configuration of ventilation systems and the building's responses. As the performance of the natural ventilation system is based on many parameters, it is then critical to consider a systematic analysis and the correlation between performance and parameters to figure out the impacts of ventilation capacities and thermal comfort improvement and to realize a stable and durable function of the practices. The paramount combination of systems is buoyancy and wind-basis, where a thoughtful investigation is indispensable in order to avert the unpredictable delivery of airflow, such as through the manipulation of external wind forces. Besides, most of the previous studies concentrate on one-floor buildings or stand-alone systems. The related research focuses should also be shifted to follow multi-storey buildings under the rapidly growing population.

Moreover, more theoretical studies are critically needed in combined passive ventilation systems as the coupling systems face barriers in practical applications. For example, most of the combined systems are based on the principle of buoyancy-driven. Simultaneously, only a small amount of studies deals with the collaboration of wind-driven and buoyancy-induced owing to the complexity of air mechanism. No guideline was found to arrange these natural ventilation systems in terms of performance and applicability for their practical selections and usages. The thermal bridge breaking in cold winter and condensation in summer may compromise the natural ventilation performance, durability, and longevity.

Furthermore, passive ventilation is heavily dependent on local climate conditions, experimental settings, and prediction methods of performance, bringing great difficulties to the quantitative comparison between different passive ventilation combinations. However, parallel comparison can be used as future work, which requires visual testing under more climatic conditions and requires additional simulations for verifying the correlation among parameters or eliminate irrelevant factors.

Notes: The unit of m [3]/s/m^2 represents the volumetric airflow rate per square meter of the absorption wall; Nomenclature: Solar wall: Solar-assisted passive systems incorporating Building-integrated photovoltaic; Hot humid (HH), extreme hot humid (EHH), hot dry (HD), extreme hot dry (EHD), hot temperate (HT), mild temperate (MT).

Note: √represents advantages, while ×means the disadvantages or limitations of natural ventilation technology. It should be mentioned that the related judgements are based on the results from literature review which may not represent the overall facts.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was supported by the Australian Government through the Australian Research Council (DE200100892; DP190100559).

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