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Single-Sided Natural Ventilation in Buildings: A Critical Literature Review

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Abstract

Natural ventilation nowadays has been paid great concerns due to its zero carbon emission and good performance on the human health. In engineering applications, cross ventilation driven by winds has been frequently restricted in building clustered cities. Instead, single-sided natural ventilation becomes an alternative mode in wind driven natural ventilation strategies for clustered urban buildings. This research has reviewed the former published researches on single-sided natural ventilation in terms of the classification, features, influence factors, investigation methodologies and evaluation indices/parameters. Existing researches on a novel ventilation mechanism of single-sided natural ventilation—"pumping ventilation" have been comprehensively reviewed, which could be a promising ventilation strategy of single-sided natural ventilation. This critical review demonstrates that single-sided ventilation has raised increasing concerns of researchers. In current and future investigations, different methodologies and other advanced technologies should be coupled together to promote the predicting capability of single-sided ventilation. This review could facilitate the fundamental researches and engineering applications of natural ventilation in modern urban buildings.

Keywords

Single-sided ventilation; Pumping ventilation mechanics; Ventilation rate; Turbulent fluctuations.

Main text

1. Introduction

Modern people spend more and more time living and working indoors. An increasing requirement of indoor thermal comfort and air quality thus leads to a large energy consumption by heating, ventilation and air conditioning (HVAC) systems. It was reported that buildings contribute around 40% of the total global energy consumption and more than 30% of CO_2 emissions [1]. HVAC systems were reported to consume about 50-60% of the total building energy [2]. In order to reduce building energy consumption and CO_2 emissions, natural ventilation (NV) has become a preferred alternative to provide desired indoor thermal comfort, especially in temperate and tropical climates [3].

1.1 What is Natural Ventilation?

Ventilation of buildings is aimed to supply the outdoor fresh air into a building and also to circulate the air inside the building. In contrast to Mechanical Ventilation (MV), NV uses natural forces to drive the outdoor air into a building. Two kinds of dominant natural forces are the wind pressure and buoyancy forces. The buoyancy force is generated by density difference between indoor and outdoor air, which is usually induced by difference in temperature or moisture [4]. Air infiltration is the unintentional airflow into a building driven by both natural and mechanical forces through unintentional building leakages, whereas NV is the intentional air induced by natural forces, supplied into a building through windows, doors or other artificial openings.

NV may be considered as a simple procedure that open the windows and just let air flow into the building. In fact, NV is not that simple. Some fundamental questions have to be figured out while studying NV: (1) which is the available natural force (wind pressure, buoyancy or their combination); (2) how to promote natural ventilation in order to meet ventilation requirements; (3) how to ensure that the use of NV will not negatively affect other performance aspects of the building, e.g. pollutant dilution, security, thermal and humid comfort, noise control or even privacy; (4) how to integrate NV with cooling, heating, lighting, façade design and other needs; (5) whether NV still can be used in haze weather when outdoor air are polluted; etc.

To conclude, designing NV is considered to be much more difficult than MV as the natural forces can vary both spatially and temporally [5].

1.2 Why Natural Ventilation?

Despite the difficulty of designing and investigating, NV is gaining increasing popularity in the sustainable city strategy, especially in the development of zero/low carbon buildings [6].

NV can be widely accepted and utilized due to the following advantages:

- The operational (no electricity is consumed) and maintenance (no mechanical devices need to be maintained) costs of NV are generally much lower than those for MV systems **(economical)**;
- When the natural forces are strong and the opening strategies are well arranged, NV can offer "transient very high ventilation rates" for summer cooling and one-off complete removal of indoor contaminants which cannot be achieved by conventional mechanical ventilation **(efficient)**;
- Occupants are able to control their local wind and thermal environments by opening or closing the adjacent windows, which helps to improve their individual satisfaction of the indoor environment **(occupant-friendly)**.

1.3 Natural Ventilation Strategies

Considering different dominant driving forces, NV can be divided into wind-driven ventilation [7] and buoyancy-driven ventilation [8] or a combination of them [9].

NV is commonly categorized into three strategies according to opening locations, namely cross ventilation (CV) [7], corner ventilation (CRV) [112], stack ventilation (SV) [108] and single-sided ventilation (SSV) [10], as shown in Fig. 1.

CV occurs when openings are mounted on two different façades of a building. Airflow enters from the upstream opening, flows through the indoor space and exits through the downstream opening (Fig. 1(a)). CV is usually wind driven, induced by pressure difference between the two openings on the opposite wall [11]. CRV is similar in character to CV and is driven by the wind pressure difference between two openings on the adjacent façade (Fig. 1(b)). SV is usually buoyancy-driven, induced by temperature difference between the warm indoor air and cool outdoor air (Fig. 1(b)). Similar with CV, SV also requires at least two openings, which, however, must be located at different heights. Airflow moves in from the bottom opening, replacing the warmer and polluted indoor air, and out from the top one [12]. In contrast to CV and SV, SSV occurs when all openings are in one building façade, regardless of opening number (one or several) and of opening position (Fig. 1(c)). SSV is not necessarily wind-driven. It can also be driven by buoyancy or a combination of them especially when the openings are mounted at different heights [9].

1.4 Why Single-sided Ventilation (SSV)?

It is widely accepted that CV usually achieves much larger ventilation rates than SSV especially for wind-driven ventilation due to a larger pressure gradient between the windward and leeward facades [56]. Recently, it was also reported that ventilation rate of CRV is also sufficiently higher than SSV both in mean and turbulent ventilation rates [112]. SV can take the advantage of both wind pressure and buoyancy forces and thus contributes to relatively higher ventilation rate [15].

However, rooms on different facades of the same floor are often isolated from each other due to the large number and compact arrangement of both residential and commercial buildings. Hence, CV, CRV or SV strategies are often restricted in urban buildings [13]. Though there are some special ways to enable CV in urban buildings if the internal partitions, such as door gaps are properly designed, these designs are still not very common in most urban buildings. As a result, in urban buildings without internal designs which enable CV, SSV becomes a feasible choice for the natural ventilation of urban buildings [9].

1.5 Objective and Methodology

The documentation search was conducted in May of 2020, mainly through web of science and Google Scholar to ensure a good coverage. Keywords used for the paper searching include "single-sided/single side/one side", "ventilation", "single/one opening" and "single/one window". To narrow the search scope, several steps were conducted. In each step one keyword was used, i.e. "single-sided ventilation", "single side ventilation", "one side", "single/one opening", "single/one window". Only papers with a detailed study on SSV would be selected in each step. During the above several steps of searching, papers selected in each step were totally 74 papers found to focus on SSV, which have been reviewed in this study. Among these papers, 27 papers were published before 2010 (1976-2010) and 47 papers were after 2010 (2011-2020) (Table 1). An increasing number of studies on SSV reveal that more and more attentions have been paid to SSV.

On the other hand, there has not been any review article about SSV found in this database. It suggests that both researchers and architects (or building engineers) have not fully realized the importance and potential of SSV. However, a literature review on SSV is significant for a systematic and comprehensive understanding of SSV.

This paper thus aims to make a critical literature review of existing studies on single-sided natural ventilation and to proclaim its academic and application value.

2. Single-sided Ventilation (SSV)

2.1 Classification of SSV

SSV can be dominated by wind pressure, indoor-outdoor temperature difference or a combination of them, even if there is only a single opening [14].

SSV is commonly classified according to the opening/window numbers on a same façade, i.e. SS1 (single-sided ventilation with one opening) and SSn (single-sided ventilation with multiple (n) openings). In SS1, the air has to enter and leave the indoor environment through the same opening. The ventilation rate of SS1 is usually very small and, in most circumstances, principally attributed to the fluctuations of wind pressure across the opening. The SSn ventilation rate was found to be larger than that of SS1 even for the identical total opening area [15]. SS2 (single-sided ventilation with two openings) was the most studied configuration among SSn since the common airflow characteristics of SSn can analogously be represented by SS2 [9, 16-22]. A brief review on SS2 studies can be referred in Table 2. In terms of wind-driven SS2, it was found that SS1 usually has higher-frequency turbulent fluctuation (around 0.1 Hz) while the turbulent fluctuations in SS2 have much lower frequency (about 0.008 Hz) [16]. The low-frequency turbulent fluctuations could contribute more significantly to the air exchange than high-frequency fluctuations, thus the influence of fluctuating velocity component should be considered when predicting the air exchange of SS2 [21]. SS2 ventilation rate is sensitive to the incoming wind angle and can be notably promoted by increase of the window separation [20, 22]. For a special wind direction that is parallel to the openings, i.e. the shear ventilation, the ventilation rate is independent of the wind speed, opening area and location [19]. If the two openings of SS2 are mounted at different heights, buoyancy force will also effectively contribute to the air exchange. The buoyancy and wind pressure force could have opposing effect between each other

[9] and interaction of the two driving forces could be significantly affected by the street canyon aspect ratio in the urban climates [17]. Due to the turbulence features of SS2, different predicting models showed a large variation of ventilation rates and thus enhanced prediction models should be proposed [18].

2.2 Features of SSV

Driving Forces of SSV

As mentioned in Section 2.1, both wind pressure difference across the opening (wind) and temperature difference between indoor and outdoor environment (buoyancy) can be the dominant driving force of SSV. The indoor-outdoor temperature difference usually shows continuous variation with time and does not include large fluctuation components. The wind force which, nonetheless, naturally comprises of mean flow and unsteady turbulent fluctuation, contributes to the complexity of the airflow characteristics, making the wind-driven SSV much more difficult to predict than the buoyancy-driven SSV [23].

The dominant driving force of wind-driven SSV depends on the incident wind angle, i.e. wind direction.

When the incident wind is normal to the opening (i.e. windward ventilation), the airflow fields at the opening will be generally stable and the turbulent fluctuation is relatively much lower. The impinging mean wind flow with large momentum (large positive wind pressure) thus becomes the dominant contributor to the SSV ventilation rate (Fig. 2(a)).

If the upstream wind direction is parallel to the opening (i.e. lateral ventilation or shear ventilation [24]), the airflow fields at the opening are unsteady and highly turbulent. In this condition, the SSV ventilation rate mainly attributes to the unsteady fluctuation in the shear layers around the lateral opening (Fig. 2(b)).

For SSV with only leeward openings (i.e. leeward ventilation), the sheared boundary layers and vortex shedding lead to a large mean recirculation vortex with negative pressure at the building wake which becomes the dominant driving force of

SSV ventilation rate [25]. The intensity of turbulent fluctuations falls in between the shear and windward ventilations. (Fig. 2(c)).

The various and complicated driving mechanisms hence make it quite difficult to predict and investigate SSV precisely and efficiently.

Difficulties in Predicting SSV

As discussed before, turbulent fluctuations can play an important part in affecting the airflow field characteristics and air exchange of SSV in most wind directions.

The large amount of turbulent fluctuating flows across the SSV opening/openings enter the building and make the indoor airflow fields far from steady [23]. The indoor velocity and pressure inherit the large turbulent time-depending fluctuations, making it difficult to predict and evaluate the flow fields with only spatial or temporal averaged values.

Ventilation due to turbulent fluctuations mainly has four different physical mechanisms [26]: (1) Continuous and variable flow across the opening; (2) Pulsating flow; (3) Eddy penetration; (4) Molecular diffusion.

Continuous airflow refers to the bulk unsteadiness of the flows continuously ventilating a room due to the turbulent fluctuations induced by variations in external wind conditions. Pulsating flow commonly has two different forms depending on the location and number of openings. When the external wind pressure at all openings are equal (e.g. two openings are located symmetrical about the centerline of the building) or there is only a single opening, the temporal variation of the external pressure can make an opening perform as an inlet or outlet depending on the positive or negative pressure difference between indoor and outdoor environment (Fig. 3(a)). When the pressure difference exists and changes between two or more openings, the airflow direction through openings can alternate periodically (Fig. 3(b)), which is the other form of pulsating flow. For large openings, along the length of which significant pressure variations often occur, ventilation can be contributed by the penetration of turbulent eddies usually with sizes smaller than that of the opening. For shear ventilation in which wind direction is parallel to the window, since the mean flow can hardly enter the room from window, eddy penetration could be the main contributor to the indoor-outdoor air exchange especially for a large opening [39]. Fig. 4 shows the diagram of eddy penetration. Molecular diffusion is a microscale ventilation phenomenon which has no direct relation to pressure variations of the ventilating flows.

The prediction of SSV ventilation rate is even more challenging than that of the airflow field. Many early studies used to predict SSV ventilation rate based on the mean pressure difference across the openings [14], which neglected that fluctuating pressure difference could also contribute a certain part to the SSV ventilation rate. Some other studies took the consideration of the turbulence effect by dividing the SSV ventilation rate into mean (steady) and unsteady (fluctuating) parts and calculating them respectively [16, 20]. However, it is not easy to quantify the turbulent effect by a single linear model before the mechanisms of turbulent air exchange through SSV openings can be clarified.

3. Influence Elements of SSV

Former published investigations on SSV have taken into consideration mainly two types of influence elements on SSV, namely the environmental elements and the architectural elements.

3.1 Environmental Elements

The environmental elements commonly refer to the upstream/ambient wind condition. For buoyancy-driven ventilation, indoor and outdoor temperature difference is also a significant factor.

Upstream Wind

Many previous researches studied the effective elements of upstream wind on SSV, such as wind speed and direction [27-30, 32-59], and turbulent fluctuations [23, 25, 31, 42, 56] in the upstream wind. Upstream wind speeds and directions were the most studied upstream wind elements. For the 41 previous studies reviewed on the effect of upstream wind elements on SSV in Table 3, only 2 of them did not include wind speed and direction effects.

The increase of upstream wind speed can directly promote the SSV ventilation rate especially in impingement airflow where mean pressure difference across the window dominates the air exchange [25, 27, 29]. If the buoyancy effect is considered, the SSV ventilation rate generally increases with increasing wind speeds as long as the wind and buoyancy do not act as counteracting forces [50, 54, 57]. Specifically, the ventilation rate increases with wind speed for negative indoor-outdoor temperature differences (indoor < outdoor) and shows nonlinear correlation with wind speed for positive indoor-outdoor temperature differences (indoor > outdoor) [50].

However, the importance of wind speed effect fundamentally depends on the wind direction. For wind-driven ventilation, the ventilation rate is relatively steady for windward ventilation and unsteady for shear and leeward ventilation [25]. The maximum ventilation rate occurs for the windward opening with an oblique wind direction in which case the external air can easily enter the building through the opening. The ventilation rate of shear ventilation rate is generally lower than the windward and leeward ventilation but the ventilation rate of leeward opening is slightly larger than the windward opening when the wind direction is perpendicular to the opening face [20, 24, 46, 51]. As mentioned in Section 2.2, the eddy penetration is a main contributor in shear ventilation and the eddy penetration could be zero for windward opening when the wind direction is normal to the opening due to zero parallel wind velocity [39]. When the buoyancy effect is considered, the dominant driving force will alternate between the wind pressure and buoyancy forces for different wind directions [34]. The wind direction was also found to have an impact on the variation of SSV ventilation rate with different window types [44, 48]. Therefore, some researchers have emphasized the significance of wind direction on the SSV and claimed that the wind direction should be considered when evaluating the ventilation performance of SSV [36]. However, compared with the aforementioned isolated cases, the influence of wind direction on the SSV ventilation rate will be much weaker in the building array cases [49].

The importance of turbulent fluctuations on SSV was also emphasized in the effect of the external wind in addition to the wind speed and direction [23]. The relation between SSV ventilation rate and turbulent intensity around a full-scale building was tested by Gough et al. [56]. It was found that the prediction accuracy for wind-driven SSV ventilation rate in high turbulence of empirical models could be improved by including turbulent intensity as a multiplicative factor in the equations. In addition, it was also proved that proper profiles of turbulent kinetic energy should be adopted when predicting SSV by CFD simulations [42].

Temperature Difference

The temperature difference between indoor and outdoor air is a vital element directly affecting and dominating buoyancy-driven SSV. The effect of temperature difference matters in SSV when the ventilation openings are provided at different heights, which can also promote the ventilation rate of SS2 or SSn. For SSV driven by a combination of wind and buoyancy, the dominant driving force will alternate between wind and buoyancy depending on the relative strength of indoor-outdoor temperature difference and wind pressure [34]. Table 4 shows a summary of papers on the influence of the temperature difference on SSV. When increasing the indoor-outdoor temperature difference, the buoyancy force could replace the wind pressure force to be the dominant driving force of SSV [34]. Positive indoor-outdoor temperature difference will make the wind pressure force and buoyancy force become two opposing forces and consequently reduce the ventilation rate whilst the negative temperature difference would result in synergy between the two forces [50]. It was reported that the influence of temperature difference would be reduced by the turbulent diffusion of the wind especially in leeward ventilation [37, 40]. In high-density urban climates, the buoyancy force was measured to be more significant than wind pressure, indicating that the temperature difference plays a vital role in this condition [10]. However, temperature difference does not produce an obvious impact on the basic characteristics of thermal flows and concentration distribution inside the building [62].

3.2 Architectural Elements

The architectural elements refer to both the effect of opening and building configurations. Previous studies have considered various architectural elements' influence on the airflow field and air exchange of SSV, including the number/area, location, geometry and arrangement of openings, the building facade design and the surrounding buildings etc. A summary of studies on the influence of the architectural elements **is** illustrated in Table 5.

Opening number/area

The effect of opening number on SSV is remarkable. The air exchange of SS2 or SSn is better than SS1 even when the total opening area are equal [15]. Hence, it is better to open more windows if a large ventilation rate is required. The impact of opening size is commonly similar with that of opening number since both elements usually promote the SSV ventilation rate by increasing the total opening area [16, 28, 60, 61]. However, larger opening areas do not always contribute positively to the ventilation rate. For SS2 with leeward ventilation, increasing the opening area even has a negative effect at very large opening porosity [75].

Opening location

The influence of opening location is far from obvious since the position arrangement can be quite complex. For wind-driven SS1, the vertical position of the opening has a significant impact on the ventilation rate and the ventilation rate will decrease when the opening gets far from the ground due to the pressure decrease along the height [39]. In the cases of SS2 or SSn, the relative horizontal position between openings, namely opening separation, will take a role in affecting the SSV ventilation rate. A large opening separation has been found to be able to promote the ventilation rate in small and medium sized buildings especially in windward or leeward ventilation [15, 20, 22].

Opening geometry, type and arrangement

In modern architecture, various kinds of opening geometries have been designed for different purposes and in recent years an increasing number of studies have taken an interest in the effect of opening geometries on SSV. For a concern of aesthetic design, typical openings used to be designed into many different shapes, e.g. square, round, polygon etc. Windows in modern architecture can have smarter and more delicately designed types, such as louvers [48], over hung, bottom hung, and side hung [44]. It was found by Wang et al. [44] that the influence on SSV ventilation rates of various window types varied greatly with different wind directions. Wang et al. [54] also studied the effect on ventilation performance of six common window types in residential buildings, i.e. the vertical slide window (VSW), tilt window (TILT), awning window (AW), horizontal pivot window (HPW), turn window (TURN) and vertical pivot window (VPW). It was found that the sensitivity of ventilation rates to the ambient wind for various window types were quite different. The HPW and VPW types showed the best ventilation performance whereas the TILT type had the worst. In addition, the influence of different window types on the indoor thermal profiles, velocity and its fluctuations was significant in wind and/or buoyancy driven ventilation. However, whether the effect of different window types is more significant than shape or geometry in SSV is still an interesting problem that remains to be addressed in further SSV studies.

Building façade design

Façade designs refer to balconies [35, 41, 74], wing walls [58] and other special designs including guide vanes [21] and flow deflectors [71]. These façade designs disturb the pressure distribution on the building façade which can determine the ventilation rate for both wind and buoyancy driven natural ventilation [76, 77]. According to literature, balconies were the most considered in the design parameters of the building façade. It was reported that the balconies can significantly change the outdoor flow field near the building façade and proper designs of balcony configurations are able to enhance the ventilation rate of SSV at normal wind angle [35]. For a multistory building with many different units, the presence of balconies can intensify the interunit dispersion of infectious respiratory aerosols by creating “dispersion channels” to increase the re-entry ratios [41]. The building depth size is a dominant parameter of balcony geometry. The effect of balcony depth on mean indoor air velocity depends heavily on the orientation of buildings. It was also found that the smaller balcony depth made the indoor air distribution non-uniform and unstable [74]. Therefore, building façade features such as balconies, are required to be properly designed for better natural ventilation performance.

Surrounding buildings

In urban areas, the influence of surrounding buildings or structures should not be underrated. From the literature review, the locations and distances to the target building of surrounding buildings have been studied. The effect on the SSV of target building can be quite different when the surrounding building is in the upstream direction compared with that in the downstream direction. The distance between interference building and the SSV target building has a significant impact on the airflow field and air exchange around and across the target building [21, 49, 56, 75]. At neighborhood scale, street canyons have always been considered as basic units in terms of urban ventilation. In this case, street canyon Aspect Ratio *AR* (averaged building height *H*/street canyon width *W*) becomes a dominant influencing element. The vortex number is increased when *AR* gets larger (Fig. 5). The interaction between vortices can create an opportunity to promote the turbulent ventilation of the SSV if AR is not too large [17, 73]. However, though not included by far in the studies of SSV, many other urban morphological indices should also be accounted for when SSV in investigated in the urban environment. Urban morphological indicators selected in SSV study should be commonly considered in urban planning and be closely related to the wind flow field characteristics. Some typical indicators include Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Building Density (BD), Mean Building Height and its coefficient of variation, among which FAR and BCR are the most commonly used [113]. FAR refers to the ratio of the total building floor area in a district to the site area. BCR is the ratio of the total area of the building footprints to the site area. These urban morphological indices play a vital role in the wind field construction inside and outside the urban buildings and thus need to be included when surrounding buildings are considered in SSV study.

Fig. 6 shows the proportion of different influencing elements considered in the SSV papers. Over half of the studies included environmental elements, in which upstream wind was the most frequently studied element, revealing that it has been regarded as the dominant influencing factor of SSV.

4. Methodologies of Investigating SSV

According to literature, existing methodologies utilized to investigate SSV can be concluded into experiments, empirical models, airflow network models and CFD simulations.

4.1 Experiments

Both reduced and full scale (field) experiments have been widely adopted to the study of SSV. According to literature, many studies have used field measurements on SSV investigations [10, 18, 32, 37, 43, 47-49, 52, 53, 55, 56, 70, 74, 84]. Field measurements take an advantage of real outdoor environments and have no worry about the invalidity caused by the similarity criterion and flow characteristics independence, which are predominant concerns for reduced-scale experiments.

However, field measurements are not always applicable. In some situations, reduced-scale measurements could be a superior choice. Firstly, field measurements are not practical in the design stage [84] and reduced-scale experiments can be more cost- effective. Secondly, sometimes there is potential concern including unusual incident wind, terrain and surroundings [97]. For SSV or other NV studies, formation of atmospheric boundary layer in labs could be a difficult task. Early-stage experiments used to create incident wind flow by using a variable-speed fan [27]. Some researchers chose water to reproduce an atmospheric environment [17]. On one hand, water tank experiments cost much less than wind tunnel experiments (WTs). On other hand, since water has much smaller kinematic viscosity than air, water tank experiments can more easily achieve higher Reynolds numbers as that in the real scale. Nevertheless, since water has different viscosity with air, the dynamic similarity should be paid enough attention. As technology develops, WTs has been increasingly utilized to predict flow field and ventilation of SSV [18-20, 22, 24, 28, 32-34, 36, 53, 65, 78, 80]. Many existing WTs have been applied to validate and develop the theoretical empirical equations [18-20, 24, 33, 34, 88], especially for certain depending coefficients in the calculation equations, such as the discharge coefficient (C_d) in the orifice equation [24]. In addition, the reliability and accuracy of numerical simulations were also predominately verified by WTs [22, 28, 32, 36, 78, 80]. WTs have significant advantages compared with other reduced-scale experiments. A boundary-layer wind tunnel can produce a similar inflow boundary layer as the real atmospheric boundary layer and achieve many unusual inflow wind conditions [97]. Though these reduced-scale experiments are more cost-efficient and convenient than field experiments, they still have an inevitable disadvantage. It was reported by Menchaca-Brandan et al. [109] that water or WTs can hardly predict the influence of radiation or convection heat transfer between the walls and the indoor air flows.

4.2 Empirical Models

Empirical models for predicting SSV can be quite different depending on the driving forces.

(1) Wind-driven SSV

By far two different theories have been tried in the form of empirical models to predict SSV. One is "the pulsation theory" proposed by Cockroft [27], estimating the airflow rate by combining the fluctuating wind pressure and the opening area. The pulsation theory can be expressed as a standard orifice equation:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where Q is the instantaneous ventilation rate (m^3/s), C_d is the discharge coefficient of the opening, A is the opening area (m^2), ΔP is the pressure difference opening and indoor environment (Pa) and ρ is air density (kg/m^3).

Another one is "the mixing theory" presented by Warren to solve the airflow rate dominantly contributed by the eddy penetration [86]. In this theory, it is hypothesized that a mixing layer with velocity distribution develops alongside the single opening (Fig. 7) and the air exchange rate through the opening is proportional to the external free stream velocity and the opening area [85]. Consequently, the bulk ventilation rate across the mixing layer can be simplified as:

$$Q = CAU_L \tag{2}$$

where C is a coefficient, A is the opening area (m^2) and U_L is the external free stream velocity (m/s).

The aforementioned two theories have become the basic guidelines for the following researchers to predict wind-driven SSV. According to literature, earlier studies inclined to use of pulsation theory to calculate the ventilation rate [16, 23, 27, 31, 64, 83]. “The mixing layer theory” was also widely adopted by many researchers [80, 81, 85] due to its simplicity on calculating the ventilation rate.

Wang et al. [39] later developed a semi-empirical model combining both of the two basic theories to calculate the ventilation rate due to mean airflow and the fluctuating ventilation rate contributed by pulsating flow and eddy penetration, respectively. The model can be concluded as follows:

$$\bar{Q} = \frac{C_d l \sqrt{C_p} \int_{z_0}^{h} \sqrt{z^{2/7} - {z_0}^{2/7}} dz}{z_{ref}^{1/7}} \bar{U} \tag{3}$$

$$\sigma_q = \sqrt{\sigma_{q_e}^2 + \sigma_{q_p}^2} \tag{4}$$

$$\sigma_{q_p}^2 = \left(C_d l \sqrt{C_p} \int_{z_0}^{h} \sqrt{z^{2/7} - {z_0}^{2/7}} dz / z_{ref}^{1/7} \right)^2 \sigma_u^2 \tag{5}$$

$$\sigma_{q_e}^2 = C^2 A^2 \bar{U} \int_{\bar{u}/l}^{\infty} S(\tilde{n}) d\tilde{n} \tag{6}$$

where

$\bar{Q}$ = ventilation rate due to mean airflow

z = Z position

z_0 = Z position of the neutral plane

C_p = pressure coefficient

$\bar{U}$ = mean speed

σ_q = fluctuating ventilation rate

σ_{qp} = fluctuating ventilation rate due to pulsating flow

σq_e = fluctuating ventilation rate due to eddy penetration

S = power spectrum

n = frequency

$C = C_d \sqrt{C_p}/2$

Later, Wang et al. [43] modified and improved the semi-empirical model to calculate the SSV ventilation rate across different window types, i.e. hopper, awning, and casement windows. The prediction accuracy of their model was within an error of 25% compared with full-scale measurements.

(2) Buoyancy-driven SSV

The first empirical model was introduced by Warren and Parkins [87] to calculate the ventilation rate of SS1:

$$Q = \frac{1}{3} C_d A \sqrt{\frac{(T_i - T_e) g H}{\bar{T}}} \tag{7}$$

where T_i and T_e are the air temperature inside and outside the building, H is the window height and $\bar{T}$ is the average of T_i and T_e.

(3) SSV driven by both wind and buoyancy forces

De Grids and Phaff [88] were the first to propose an equation considering both wind and buoyancy effect, as well as the contribution of turbulence near the opening:

$$U_{eff} = \sqrt{C_1 U^2 + C_2 H \Delta T + C_3} \tag{8}$$

$$Q = \frac{1}{2} A U_{eff} \tag{9}$$

where U_{eff} is the effective velocity across the opening, where $C_1 = 0.001$ is the wind effect coefficient, $C_2 = 0.0035$ is a buoyancy effect coefficient and $C_3 = 0.01$ is a turbulence coefficient. ΔT is the temperature difference between inside and outside (°C).

Larsen and Heiselberg [34] developed a similar model including effect of wind, buoyancy and wind direction and modified it using the data from WTs:

$$Q = A \sqrt{C_a f(\beta)^2 |C_p| U^2 + C_b H \Delta T + C_c \frac{\Delta C_{p,opening} \Delta T}{U^2}} \tag{10}$$

where C_a, C_b and C_c are coefficients related to the wind direction β, $\Delta C_{p,opening}$ is the largest span (max-min) of the wind pressure coefficient at the opening.

The empirical model developed by Larsen and Heiselberg was then widely adopted by other researchers to study the SSV induced by a combination of wind and buoyancy forces [18, 47, 52, 82].

4.3 Airflow Network Models

Aforementioned empirical models are inapplicable to multi-room and multistory buildings since they are not able to account for ventilation rate differences between different rooms [84]. In this case, the airflow network model was developed to predict the ventilation rate of multiple rooms in a same floor. Various airflow network (AFN) prediction models have been developed to predict building thermal comfort or air exchange in multiple zones , such as AIRNET [89], BREEZE [90], COMIS [91], ESP [92], NORMA [93], PASSPORT-AIR [94] etc. However, few has been applied to the study of SSV. Dascalaki [14] conducted a series of experiments to predict SSV ventilation rates and compared them with the above 6 network models. He then proposed a new model predicting SSV ventilation rate by modifying the ventilation rate calculated via AFN models. In the future, AFN should be integrated with more advanced technologies such as Building Energy Simulation (BES) [95] or Machine Learning (ML) [96] to fulfill the systematic prediction of buildings considering the indoor design, the ventilation strategies, the occupant behaviors and the energy consumption control, etc.

4.4 CFD Simulations

Advanced computing speed and capacity of computers have made the CFD simulations more accessible and convenient. CFD simulations is a method of solving Navier-Stokes (N-S) equations to predict the flow field values [98]. Most popular discretization methods of N-S equations were finite volume method (FVM), finite element method (FEM) and finite difference method (FDM). In the SSV literature, Large Eddy Simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) models were two dominant CFD methods used by researchers. LES can predict the turbulent flow fields more accurate than RANS but it has much more computation expense [99].

The earliest LES studies on SSV found by the authors in the literature were by Jiang et al. [79, 80]. They compared the LES results with field measurements [79] or WTs [80]. LES is reported to be able to predict the airflow distribution and ventilation rate of SSV quite well. Other researches [21, 22, 25, 33, 38, 42-44, 66, 82] also used LES to predict SSV in terms of mean flow or turbulent fluctuation characteristics.

RANS seems to be more popular than LES in the SSV studies. It may be due to the much lower computation expense and requirement despite of the relative inaccuracy compared with LES. Various turbulence models have been tried in RANS simulations in order to predict closer results with the LES and experimental results, such as the Standard [29, 30, 33, 51, 67, 81], BSL [54, 57, 62, 63], RNG [41, 42, 45, 60, 73, 74, 81, 84,] k-ε models and SST k–ω model [22, 46, 50]. RNG k-ε model is a better choice for the simulation of the SSV ventilation rate and air distribution inside the buildings though all k-ε models fail to correctly determine the velocity components near the horizontal surfaces [81]. SST k–ω model performs excellently in the indoor air flow prediction [50, 100, 101] and the shear layer separation outside around the building [59] compared to other RANS models.

Despite the rare utilization till now, hybrid CFD models such as Detached Eddy Simulation (DES) [66] and discretization methods such as Lattice Boltzmann Method (LBM) [102] should also be widely tried in the SSV modeling.

Despite the convenience and increasing prediction accuracy, experimental validation is still required for CFD simulations. Table 6 lists a summary of predicting discrepancy on SSV of CFD models compared with experiments. The prediction errors differ a lot for different cases even though the same CFD model was adopted. The discrepancy can be affected by the grid resolution, *Re* and many other factors. Overall, LES usually shows better consistence with the results of experiments compared with RANS models.

The proportion of different methodologies applied in the reviewed SSV papers is presented in Fig. 8. Throughout the investigation history of SSV, experiments and CFD simulations has always been the two most popular methodologies used by scholars to study SSV. During the recent 10 years (2011-2020), the usage proportion of experiments, empirical models and AFN have all declined except CFD simulations, compared with SSV studies by 2010. The increasing usage of CFD is attributed to the development of computing capacity and accuracy.

To conclude, experiments, including full-scale and reduced-scale experiments were widely applied to SSV study and often used to validate the results of empirical models or numerical simulations. However, reduce-scale experiments fail to predict the influence of radiation or convection heat transfer between the walls and the indoor air flows. Empirical equations are the most simple and efficient in the case that only some quantitative indices are required, such as airflow rate across the opening(s). Airflow network models can be applied to multi-room or multistory buildings where empirical equations are inapplicable. To solve the flow fields of SSV, CFD simulations could be the best choice. Though flow fields are also available through some experimental visualization technologies such as Particle Image Velocimetry (PIV), CFD simulations still take its advantage of cost-efficiency. During recent years, the Proper Orthogonal Decomposition (POD) has also been introduced into investigating SSV by a few researchers. Wang et al. [54] compared the SSV ventilation rates respectively predicted by CFD and POD methods. The POD results were shown in good agreement with CFD simulations. Most recently, Zhang et al. [110] successfully predicted the turbulent structures around a rectangular building compared with POD by using spectral proper orthogonal decomposition (SPOD), which performed POD in the frequency domain. The the Karman-type and arch-type vortex shedding as well as other kinds of vortices can be clearly decomposed respectively. This enables us to focus on and analyze any specified vortex in the turbulent structures. It can be expected that both POD and SPOD should be widely adopted in CFD simulation to better understand the turbulent flow structures and fluid mechanics of SSV.

5. Evaluation Indices of SSV

In the literature, SSV has been evaluated both qualitatively and quantitatively.

The flow field visualization inside and outside an SSV building is a widely-adopted qualitative method to evaluate SSV. Specifically, flow field can usually be illustrated by streamlines, the distribution of wind velocity, pressure, temperature and even pollutant concentration. The flow field visualization can be realized by CFD simulations [40] or Particle Imaging Velocimetry (PIV) technology [22]. Measuring instruments such as anemometers, thermometers, pressure gauges are also able to visualize the flow field to some extent by obtaining the distribution of wind velocity, pressure, and temperature.

The quantitative evaluating methods on SSV refer to various indices relating to ventilation efficiency of SSV. Ventilation rate is a common index to quantify the ventilation capacity of an SSV configuration. Ventilation rate could be expressed in various forms to evaluate the SSV ventilation effectiveness from different aspects.

(1) Airflow rate

Airflow rate Q is the most direct and apparent form of ventilation rate, which means the volumetric flow rate across the opening(s):

$$Q = \int_A u dA \tag{11}$$

where u is the wind velocity and A is the opening area.

(2) Air change rate

Air Change per Hour (ACH) is normalized ventilation rate which can be derived from non-dimensional volumetric flow rate [103]:

$$n = \frac{Q}{V} \tag{12}$$

where n refers to ACH and V is the indoor effective volume of the ventilated building.

(3) Age of air

The mean age of air $\langle \bar{\tau} \rangle$ in a building zone is defined as the average time that air reaches a certain point since it entered into the building. It can be quantified by integrating with time the tracer concentration at certain point at the exhaust [104]:

$$\langle \bar{\tau} \rangle = \frac{\int_0^\infty t C_e(t) dt}{\int_0^\infty C_e(t) dt} \tag{13}$$

where t is the time from the t = 0 which is the initial time that the tracer concentration was recorded. $C_e(t)$ is the tracer gas concentration at the exhaust at time t. Age of air could be implemented into the CFD code using a steady-state method based on the resolution of a transport equation for an additional user-defined scalar [114].

(4) Purging flow rate

Airflow rate or ACH only expresses the volume flow rate supplied by the ventilation system. In natural ventilation, it means the volume flow rate across the façade openings. In some NV cases, such as SSV, the airflow may enter the room and then flows out soon in a short circuit, without enough mixing with indoor air [115]. In these cases, the effective ventilation rate cannot be expressed by the net volume flow rate, i.e. airflow rate or ACH. Age of air can only indicate the time that the air reaches a certain point since it entered the room and still does not provide any information on how effective the ventilation system is in removing the pollutants.

The concept of purging flow rate (*PFR*) was originally proposed by Sandberg et al. [105]. The local *PFR* can be defined as the net flow rate at which air is supplied from the inlet opening to a certain point. In other words, it means the rate at which a pollutant is flushed out from a point, or the rate at which ventilation flow is supplied to a point. Therefore, *PFR* can express the pollutant removal capability of a ventilation system. In a single zone, for example, an SSV room, mean PFR can be expressed as follows:

$$\langle PFR\rangle = \frac{m}{\langle c\rangle} \tag{14}$$

where $<PFR>$ refers to the mean PFR, m is the constant injected rate of contaminant, $<c>$ is the measured spatial-averaged contaminant concentration.

The airflow rate was found to be the earliest index to evaluate and quantify the ventilation performance [27]. It could be easily understood and directly calculated via Eq. (11) in the early-stage empirical equations or CFD simulations. There is no need to implement an additional user-defined scalar or tracer gas source for airflow rate or ACH which is often required to calculate age of air or *PFR* in CFD simulations or experiments. The airflow rate was specially welcomed in the empirical equations in the pulsation theory as it can be directly related to the pressure difference across the window openings [27], which is an essential parameter in determine natural ventilation rates. Besides, ACH is actually another form of airflow rate normalized by the indoor effective volume and can be determined together with airflow rate as long as the indoor volume is provided. Therefore, as shown in Fig. 9, most papers used airflow rate (Q) and ACH to quantify the SSV ventilation rate, and only few papers adopted age of air or PFR. Q has always been an important index before and after 2010, and the adoption of ACH is essentially promoted in the last ten years (2011-2020). As pollutant removal capability is fundamental for ventilation, PFR should have been more widely used so as to express the pollutant removal capability of SSV [104].

The worldwide pandemic disease COVID-19 has called urgent attention on the indoor air quality (IAQ) in order to decrease the risk of indoor cross infection. The importance of NV has also been highlighted to improve the ventilation rate and IAQ of indoor areas. As a common NV strategy in urban areas, the influencing characteristics of SSV on IAQ have also been regarded as a vital evaluating index by researchers. Zhong et al. [106] studied the indoor concentration dispersion in the case of SS2 using CFD simulations and found that the concentration distribution is more uniform and the concentration is lower at the building corner for larger opening separations. In multistory buildings, interunit dispersion could be a main cause of pollutant or virus transmission. Re-entry ratio, which represents the proportion of expelled air re-entering other rooms, has been adopted by many researchers to quantify the interunit transmission. In the case of SSV, the interunit dispersion pattern could be highly determined by the wind direction and building façade designs. The strongest interunit dispersion occurs for windward ventilation under oblique wind angle. In addition, balconies can intensity the interunit dispersion and increase the re-entry ratios [41]. When the wind pressure and buoyancy do not suppress each other, increase of wind speed can help to decrease the re-entry ratio and infection risk of SSV in multistory buildings [57]. The re-entry ratio was also found to be sensitive to ventilation rates and window types but not affected by the ambient temperature and pollutant release rate [62]. IAQ of SSV can also be affected by traffic architectures such as viaduct and road barriers. Hang et al. found that viaduct can reduce mean indoor gaseous pollutant concentrations and indoor particle number. However, road barrier could increase the indoor gaseous concentration but decrease the particle number. Gaseous concentration and fine particle number were decreased by the uniform heating of street or viaduct ground while the large particle distribution is much more complicated due to larger gravity [45]. Therefore, the IAQ of SSV could be influenced by many environmental or architectural factors. Proper building façade design coupled with environmental factors is required to improve the IAQ and reduce the infection risk of pandemic diseases.

6. Special Ventilation Mechanism of SSV——Pumping Ventilation (PV)

6.1 Definition of PV

Recently, a novel SSV driving mechanism has been identified by Daish et al. [20] by smoke visualization in the WTs. In this ventilation mechanism, airflow across the openings oscillates at a mean rate close to the vortex shedding frequency. As shown in Fig. 10, this phenomenon is obvious for SS2 configuration with rear ventilation, in which case the airflow enters from one opening and leaves from the other. The entrance and exhaust will alternate after a half period. The periodic behavior of airflow appears just like a pump, thus is named “pumping ventilation” (PV). PV for SSn has not been studied in literature thus will not be discussed in this literature review.

6.2 Advantages of PV

The SS2 ventilation rate in PV was found to be larger than that of SS1 even when the total opening area is identical [15]. As described in the definition, PV is induced by the shedding turbulent shear layer from the lateral walls of a building with a certain frequency. The PV flow across the two openings have identifiable periodic behavior with highly turbulent fluctuation which will largely contribute to the turbulent (unsteady) component of the ventilation rate and consequently promote the total ventilation rate of SSV [106]. PV even shows its superiority over SS2 at different wind directions that disable PV. It has been reported that compared with SS2 front ventilation with wind angle between 45°-90°, PV of rear ventilation can at most increase the ventilation rate by about 50% [20]. This superior ventilation rate of PV enables more adjustability of the NV design, where design of CV is not permitted and opening locations are restricted on a specified wall opposite to the wind direction.

6.3 Existing Studies on PV

Daish et al. [20] carried out a series of WTs to quantify the nominal ventilation rate of SS2 in different wind directions and the effect of different aperture separations on the ventilation rate. PV was then identified when openings were placed on the rear wall.

Zhong et al. [59] was the first to investigate PV using CFD simulations. In the first study, a two-dimensional building model and computational domain were constructed. The PV induced by periodic vortex shedding was well reproduced by Unsteady RANS (URANS) coupled with SST k–ω turbulence model (Fig. 11). Influences of different factors including upstream wind speeds, opening separations and building side ratios on the non-dimensional ventilation rates and PV frequencies were studied.

Since the 2D model assumes opening as the same height with the building, which is not practical, Zhong et al. [106] further performed a series of semi-3D CFD simulation and found that PV can also occur in front ventilation. Larger opening separation was also reported to be able to promote the PV ventilation rate. Albuquerque et al. [22] then conducted WTs focusing on PV and compared the experimental results with both LES and URANS. LES was reported to have a better performance than URANS especially in predicting ventilation rate due to the inherent inability of calculating turbulent fluctuations for URANS. Their results also proved that PV ventilation rates can be improved by increasing the opening separation. Similar WTs were also performed by Zhong et al. [111] to discuss the effect of different opening separations and ventilating floors. The results of WTs proved that ventilation rate is greater than that of single opening with the identical total opening area. The promotion of ventilation rate was up to about 123% on the first floor, about 65% on the second floor and about 44% on the third floor. Most recently, Carrilho da Graça et al. [112] confirmed that PV exists at both front and back of SSV and corner ventilation (CR) using WTs. They identified that PV can potentially occurs in an isolated rectangular building with SSV and CR rooms in 62% of incoming wind directions. They also developed a pressure based simplified model to predict the effective ventilation rate of CR, which is composed of pumping and CV driven by unsteady and steady pressure respectively.

The effects of upstream buildings on PV were further discussed using CFD simulation (URANS) by Zhong et al. in their following studies [75, 107]. The distance between upstream and downstream target building and the side ratio of upstream building were found to have significant but different impact on the PV frequency and ventilation rate respectively. For two buildings at tandem arrangement, PV frequency of the downstream target building is hardly affected by the building gap distance with medium building gap ratio (building distance/building width) between 0.5 and 5 but is much lower for very small gap ratios or higher for larger gaps. The non-dimensional ventilation rate of PV shows non-monotonous variation with the gap ratio and have the peak value when the gap ratio is 2.0. In addition, the ventilation rate will be higher than that of the isolated case when the gap ratio is larger than 2.0. It is owing to the fact that the pulsation flow provided by the vortex shedding from upstream building could attenuate the obstruction effect. PV frequency and the ventilation rate of the downstream target building can be reduced by the increase of the upstream building length. CFD results also indicate that PV is intensively weakened by two upstream buildings. The inner shear layers between two upstream buildings can dominate the vortex shedding and PV of the downstream target building. In the two upstream building cases, there is a specific lateral spacing between two upstream buildings which could lead to the peak PV ventilation rate of the downstream building. However, it should be noted that high building density and complex building arrangement would suppress the PV phenomenon by disturbing the regular periodic vortex shedding from ventilated buildings.

7. Discussions

According to the literature, SSV has been well investigated by researchers with various methodologies. The influence of different impact elements on the flow characteristics, thermal performance and ventilation capability has been well presented. The most fundamental problem of SSV studies is the prediction and modeling of turbulent fluctuations.

A large composition of turbulent fluctuations at the opening(s) make SSV difficult to be predicted and modelled. To precisely and efficiently predict SSV, CFD models, experimental measurements and other methodologies should focus on improving the ability of modeling and measuring the turbulent fluctuations and obtaining total ventilation rates containing mean and turbulent components. Generally, there are two ways to improve the capability of predicting the total ventilation rate of SSV with large composition of turbulent fluctuations. The first way is to directly enhanced turbulent models in CFD simulations. For RANS, since the turbulence is ruled out by the Reynolds-average method, leaving only the mean flow to be simulated, the turbulent effect is then fully modelled by the eddy viscosity or Reynold stress models. For LES, large scale turbulent eddies are directly solved and the effect of small-scale eddies are modelled through sub-grid stress models. Therefore, promoting the resolving ability of the eddy viscosity and Reynold stress in RANS or the sub-grid stress in LES is the key task to the improvement of modelling turbulent fluctuations. The second way is to consider the turbulent ventilation rate in addition to the mean one via an arithmetic method, i.e. taking the root mean square (RMS) value of the time history of simulated or measured ventilation rate as the turbulent ventilation rate and the total ventilation rate could be derived based on the mean and turbulent components by a specific equation (Eq. 5.3 in [116]) proposed by Straw:

$$Q_b = \bar{Q}(1 + \frac{2\sqrt{2}}{\pi}(\frac{\sigma_Q}{\bar{Q}})\sqrt{1 - \frac{1}{2}(\frac{\bar{Q}}{\sigma_Q})^2}) \quad (15)$$

where Q_b is the total ventilation rate, $\bar{Q}$ is the mean ventilation rate and σ_Q is the turbulent ventilation rate.

However, the equation does not always work for the ventilation rate obtained in RANS since the equation will be meaningless if $1 - \frac{1}{2}(\frac{\bar{Q}}{\sigma_Q})^2 < 0$, i.e. $\frac{\bar{Q}}{\sigma_Q} > \sqrt{2}$. Therefore, a more universal equation should be proposed to corelate the total ventilation rate with the mean and turbulent ventilation rate.

On other hand, due to the compact room arrangement of urban commercial or residential buildings, SSV, which requires opening(s) only on the same façade, is more applicable than CV. There is no doubt that SSV usually has relatively smaller ventilation rates than CV, CRV or SV. SSV alone may not be able to provide enough ventilation rates for some deep-plan and large-space buildings because the wind-driven flows through the openings in SSV do not have enough momentum provided by pressure difference to travel deep indoor. The ventilation rate of SSV, i.e. SS2 or SSn, can be promoted by stack effect when ventilation openings are mounted at different heights. In addition, to meet the basic requirements of indoor air quality and thermal comfort, SSV should be supplemented by mechanical ventilation strategy.

There are still many other potential ways to promote the ventilation rate of SSV in urban buildings. As specially introduced in the review, PV could be a promising solution to the relatively lower ventilation rate of SSV in the scope of NV strategy. However, the study on PV is still at an early stage. Existing evaluating indices on PV are limited to the ventilation rate, oscillation frequency and wind velocity at the openings. The instantaneous and temporal-averaged airflow characteristics inside the building need to be further interpreted together with the indoor pollutant dispersion. Applicable theoretical models are also required to be developed in order to quantify the frequency and ventilation rate of PV in a more efficient way and to enhance our understanding of PV flow characteristics. The former studies all considered PV in SS2 configurations but PV in SSn may be more complex in airflow characteristics and more effective in ventilation. Indoor partitions could exert significant effect to the airflow characteristics and ventilation rate on NV [19], thus may also have impact on the periodic oscillation characteristics and ventilating capacity on PV. Moreover, PV was studied only under the effect of several surrounding buildings and the influence of building arrays should be studied in urban climates by creating sufficient surrounding structures around the target building.

However, the literature review was done mostly in 2020 and might not include the most recently published papers. This review only focused on SSV and the interaction between SSV and CV in a building was not discovered though it is also important for NV. In addition, the current review was limited to theoretical review and analysis of previous SSV studies, and did not consider the applications of SSV strategy in real conditions using building simulation tools such as EnergyPlus, Modelica etc. Therefore, this review only proposed some existing essential problems on the SSV studies and some suggestions for reference only, which could not be regarded as instructions for future work on SSV studies.

8. Conclusions and recommendations

This work aims to make a review on the single-sided natural ventilation researches available in the former published literature. The classification, features, influence factors, studying methodologies and evaluation indices of SSV in literature have been reviewed and discussed. Investigations on a recently identified novel wind-driven ventilation mechanism of SSV—"pumping ventilation (PV)" have also been reviewed. Major conclusions of the review are as follows:

(1) An increasing number of researchers have paid attention to SSV than before. Publications on SSV between 2011 and 2020 were around twice as many as those between 1976 and 2010.

(2) CV, SV and SSV represent three main wind driven natural ventilation strategies. CV and SV require no less than two openings on different facades and they could usually provide higher ventilation rates than that of SSV. However, SSV is more applicable in urban residential and clustered commercial buildings. SSV is more difficult to be predicted than CV and SV, due to much larger turbulent fluctuations during air exchange across single-sided openings.

(3) Experiments, empirical models, airflow network models, and CFD simulations have been four dominant methodologies applied so far to predict SSV. In recent years, CFD simulations have become the most popular methodology due to convenience, cost-effectiveness and abundant data, comparing with model experiments and empirical equations. The results of CFD simulations still require validation with results of WTs and other experimental measurements.

(4) Airflow rate and ACH were the mostly used indices to evaluate the ventilation rate of SSV. Purging flow rate (PFR) could express the pollutant removal capability, whereas airflow rate, ACH or age of air could not do that. PFR should be more widely adopted together with other evaluation indices to quantify the ventilation efficiency in future SSV investigations.

(5) PV could improve the ventilation potential of SSV. Investigation on PV is still at an early stage and it was still restricted to SS2 configurations. More researches on PV, e.g. PV with SSn and PV at urban climates, are required to fully understand the ventilating behaviors of PV in a single building and in a real urban area.

(6) The main findings and conclusions in this review will also provide some useful information with respect to improving the modelling and measurement capability of turbulent fluctuations as well as obtaining total ventilation rates containing

mean and turbulent components in natural ventilation with a large composition of turbulent fluctuations.

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