A holistic approach to natural ventilation studies

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Abstract. Natural ventilation in buildings can increase thermal comfort and reduce air-conditioning use. However, it is very challenging today to accurately determine the natural ventilation rate through a building. This paper outlines a method to calculate the wind distribution around a building site from information obtained at a meteorological station miles away. This paper also discusses the influence of surrounding buildings on the wind flow around a target building at the site, and presents various geometrical models. In addition, the use of hour-by-hour wind velocity typically available from a meteorological station may give rise to some errors because of the large time step. A correlation method can be employed to convert the hour-by-hour wind velocity to minute-by-minute velocity. One can then use CFD to calculate the airflow around the building and wind-driven cross ventilation through an apartment simultaneously. However, prediction of single-sided natural ventilation is difficult because of the bi-directional flow at the room opening and the complex flow around buildings. This paper presents an empirical model that can predict the mean and fluctuating ventilation rates due to the pulsating flow and eddy penetration of wind-driven single-sided ventilation in buildings with three types of windows. One must use the correct strategy in a building in order to achieve the maximum benefits of natural ventilation.

1. Introduction
The use of natural ventilation in buildings can provide a comfortable air temperature in indoor spaces when the outdoor climate conditions are appropriate. Natural ventilation can reduce energy use in buildings because the operating time for air conditioning and mechanical ventilation is reduced. The natural ventilation rate is normally higher than the mechanical ventilation rate, and occupants would still feel comfortable when the air temperature is slightly higher than normal, because of the higher indoor air speed. Meanwhile, Lai et al. [1] conducted measurements of natural ventilation use in all the climate zones in China and found that natural ventilation can be used when the outdoor air temperature is less than 26°C. On average, building occupants in China keep their windows open one-third of the time. In Beijing, natural ventilation can transform 584 hours of air-conditioning use to none air-conditioning in summer while providing the same comfort level [2]. The energy saving potential is evident. However, it is not easy to design buildings with natural ventilation because of the unsteady nature of wind and the impact of surrounding buildings on the airflow around a target building with natural ventilation. This paper describes a holistic approach to the study of natural ventilation in and around buildings.

2. Wind around buildings
Most cities have one or two meteorological stations that provide hourly weather information, such as air temperature, relative humidity, wind speed, wind direction, etc. Even in mega cities with multiple meteorological stations, the distance between two stations is greater than ten kilometers. In built-up
areas, surrounding buildings and land topography would have a significant impact on the wind distribution of a target building with natural ventilation. Designers often use wind information from the nearest meteorological station to design natural ventilation. This approach would contribute an error of more than 100% [3]. To correctly predict the wind distribution around a building, a designer could use the computational fluid dynamics (CFD) technique and build a geometrical model of the buildings and land topography between the meteorological station and the target building. The results of this numerical simulation could agree with the wind data measured in the target building. However, unless digital city building models were available, it would take hundreds of hours to build the geometrical model. In addition, the simulation would require a power workstation and tens of hours of computing time. One could use surface roughness to represent the buildings between the neighborhood of the target building and the meteorological station and consider the building details only in the immediate neighborhood. As shown in Figure 1, the wind distribution predicted by CFD with surface roughness would be very close to that with detailed buildings between the neighborhood and the meteorological station.

![Figure 1](image1.png)

**Figure 1.** Wind velocity distribution simulated by CFD for a neighborhood (left) with detailed building models and (right) with surface roughness between the neighborhood and a meteorological station.

The neighborhood shown in Figure 1 contains many buildings. If the largest target building dimension is L (where the dimensions are length, width, and height), the surrounding buildings within a distance of 3L should be included in the CFD simulation in order to obtain a reliable wind distribution around the target buildings [4].

Note that the wind distribution around a building is useful not only for studying natural ventilation in the building, but also for investigating thermal comfort and pedestrian safety around the building. Therefore, studying the wind distribution around a building is very important. At present, the use of CFD with the above approach can provide reasonably accurate information at minimal cost.

3. Cross natural ventilation through an apartment

Wind magnitude and direction change continuously. Cross natural ventilation through an apartment is highly dynamic and unsteady. However, a meteorological station provides wind information only on an hourly basis, and this information is not the average for a given hour; rather, it is the data for the first two minutes of the hour. If this hourly wind data were used to simulate cross natural ventilation through a building, it would be very difficult to obtain good agreement with the measured ventilation rate. The measured rate as determined with a tracer gas is the average ventilation rate during the experimental period. Robaa [5] found that wind speed around a building is proportional to that from a meteorological station. If one could measure local wind speed minute by minute on a building rooftop, $U_t$, the following equation could be used to interpolate the hourly wind data from a meteorological station, $U_{met,ave}$, to minute-by-minute wind speed, $U_{met,t}$.

$$U_{met,t} = U_t / U_{ave} \times U_{met,ave}$$

(1)
We found that the minute-by-minute wind speed on a rooftop, $U_t$, calculated by CFD with the $U_{met,t}$ was in good agreement with the measured $U_t$ [4]. This implies that the transient wind distribution information around a building obtained with the above method is close to the actual data. We actually simulated cross natural ventilation through an apartment in a building by extending the CFD simulation to the apartment. As shown in Figure 2, the calculated average ventilation rate was within 20% of the measured data obtained by the tracer-gas method [6]. The CFD simulation, which used the RNG k-ε model, was not very accurate and may have generated errors. According to our previous study [7], when large eddy simulation (LES) was used in place of the RNG k-ε model, there was much better agreement between the pressure coefficient calculated by LES and that measured by Katayama [8]. Meanwhile, Figure 3 compares the calculated and measured air velocity distribution in the apartment. The velocity magnitude was almost the same, but the airflow pattern differed slightly. Considering that the LES used a limited number of grid cells for the apartment, the results were rather good.

4. Single-sided natural ventilation in an apartment

For the case of single-sided natural ventilation, Figure 4 shows that bi-directional flow occurred at the room opening. The non-uniform wind pressure distribution along the opening height governed the inflow and outflow. If the outdoor wind is assumed to be a homogenous turbulent flow, the wind pressure along the opening height can be determined by CFD in a similar manner as that for cross natural ventilation. The dynamic and unsteady nature of wind influences the fluctuating ventilation rate because of eddy penetration through the opening. It would be ideal to include the fluctuating ventilation rate in natural ventilation studies, but the calculation would require large eddy simulation, which could be time consuming. Fortunately, the fluctuating ventilation rate is a secondary effect in comparison with the mean flow caused by the pressure difference between indoor and outdoor spaces [9]. For single-sided natural ventilation, the buoyancy effect can play a very important role because of the temperature difference between indoor and outdoor spaces. By combining the wind and buoyancy effects, we developed Equation (2) for determining the ventilation rate of single-sided natural ventilation [10]:

$$Q = C_d w \int_{z_0}^{h} \left[ C_p \frac{U_{ref}^2}{z_{ref}^2} \frac{T_i}{T_a} (2z_0^2 + \frac{2(T_i - T_o)}{T_a} g(z_0 - z)) \right] \, dz$$

(2)

where $Q$ is the ventilation rate through the opening, $C_d$ the discharge coefficient, $w$ the opening width, $C_p$ the pressure coefficient, $U_{ref}$ the wind speed at reference height $z_{ref}$, $z_0$ the neutral plane height, $g$ gravity, and $T_i$, $T_o$, and $T_a$ the indoor, outdoor, and average air temperature, respectively.
Case number, increasing with $T$ for each wind direction

Figure 5 compares the measured ventilation rate with that calculated by Equation (2) for different wind directions and speeds under various indoor-outdoor temperature differences. We conducted the measurements under 50 different sets of wind and temperature conditions for an apartment in a dense urban area. The results show that the windward cases had an average error of 12.7%, while that for the leeward cases was 11.2%. Large errors occurred with a large indoor-outdoor air temperature difference. Equation (2) exhibited the worst performance for the parallel wind cases, with an average error of 15.1%.

Equation (2) is intended for single-sided ventilation with a simple opening. In reality, openings can be awning (top-hinged) windows, hopper (bottom-hinged) windows, or casement (side-hung) windows, as shown in Figure 6. Since these window types may obstruct the flow through the window opening, the ventilation rate could be substantially different from that through a simple opening. We have developed the following equation for these windows [11]:

$$Q = C_{d,ref}w_1\sqrt{C_{p}^{\frac{u_{ref}}{w_1}}} \int_{z_{ref}}^{h_{aw}} \sqrt{z^{2/7} - z_0^{2/7}} \, dz + \left(1 - 0.5|\cos \theta_n|\right) \frac{w_1}{2} C_{d,ref}w_2\sqrt{C_{p}^{\frac{u_{ref}}{w_1}}} \int_{z_{ref}}^{h_{aw}} \sqrt{z^{2/7} - z_0^{2/7}} \, dz$$

where $w$ is opening width. Please refer to [11] for a more detailed definition of the parameters.

We used a validated LES to simulate the ventilation rate through different types of windows with various wind incident angles. Figure 6 shows the dimensions used in the LES. Equation (3) was also used to calculate the ventilation rate for comparison with the LES results. Figure 7 presents typical results for the three window types at an opening angle of 45°. Significant differences between the LES and Equation (3) can still be observed for some wind incident angles. At those angles, the windows were in the flow separation region, in which there existed an adverse pressure distribution in the direction of the airflow [12]. The adverse pressure gradient would have created a pressure difference along the
horizontal direction of the opening, which was not considered in Equation (3). This phenomenon is more obvious for the casement window because it is asymmetric in the horizontal direction and is more sensitive to the horizontal pressure difference than are the hopper and awning windows. The ventilation rates predicted by Equation (3) were within 30% error, which is not bad with such a simple equation.

Figure 7. Comparison of ventilation rates through different windows as calculated by CFD simulations and by Equation (3) for an opening angle of 45°

5. Single-sided natural ventilation in an apartment
Natural ventilation capability in a building does not automatically guarantee thermal comfort and energy conservation. It is very important to teach building users how to properly operate the system [2]. Let us use an apartment in Building as an example that was our early work [2]. First, we consider the case of a shaded outdoor space with a lot of natural ventilation. According to Figure 8, if a person were to stay in this space during the warm season, he or she would have a sense of discomfort or feel too warm 20% of the time. The reference case shown in Figure 8 was a typical design with mediocre natural ventilation capability, which was not the same apartment illustrated in previous sections. Because of the internal heat gain and reduced ventilation rate, the discomfort rate for the reference case was slightly higher than for the outdoor case, as shown in the figure. Under the night-cooling strategy, windows were opened when the outdoor air temperature was lower than the indoor air temperature, and closed when the outdoor air temperature was higher. This strategy allowed the building structure to absorb heat during the daytime and release heat at night, which lowered the discomfort rate to only 9% in the warm season. The daytime ventilation case was that of an apartment with excellent cross natural ventilation design, where windows were open all the time. The daytime ventilation improved the thermal comfort slightly in comparison with the reference case. The number of “discomfort hours” under daytime ventilation was close to that for ambient air temperature. Air moved through the apartment during the day, not only removing the heat gains (a positive process) but also heating the building structure (a negative process). The NC+DV case in Figure 8 was a typical scenario in which occupants closed the window when the outdoor air became very hot.

Figure 8. Comparison of discomfort rates under different operating strategies. Figure 9. Daily maximum air temperature in the apartment with night cooling to outdoor air temperature.
Figure 9 compares the daily maximum air temperature in the apartment with night cooling to the outdoor air temperature for the apartment in Beijing during the warm season (from May 1 to September 30). In this particular year, the outdoor air temperature at times exceeded 38°C. The night-cooling strategy kept the indoor air temperature below 31°C during the day. Of course, the night-cooling strategy would be effective only for a building structure with reasonable thermal mass. Reference [2] provides detailed information about the building structure, natural ventilation design, and simulation technique used in the study.

6. Discussion
It should be noted that applications of natural ventilation may be limited. When the outdoor air temperature is too high or too low, natural ventilation cannot be used. The design of natural ventilation would require great effort from architects and urban planners. In addition, in heavily polluted countries, such as China and India, outdoor pollution would render natural ventilation useless. We would strongly recommend the use of air cleaners in combination with natural ventilation in these countries.

7. Conclusions
This paper sought to present a holistic approach to the study of natural ventilation. The investigation led to the following conclusions:

- A new approach was recommended for determining the wind distribution around a building.
- Cross natural ventilation in a building can be designed by CFD.
- Single-sided natural ventilation in a building can be designed with semi-empirical equations.
- Night cooling is the most effective strategy for buildings with natural ventilation capability.
- Natural ventilation can improve thermal comfort and reduce energy consumption in buildings, but one should be careful about outdoor air pollution.

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References
[1] Lai D, Jia S, Qi Y and Liu J 2018 Build Environ 142 234
[2] Carrilho-da-Graca G, Chen Q, Glicksman LR and Norford LK 2002 Energy Build 34 1
[3] Liu S, Pan W, Zhang H, Cheng X, Long Z, and Chen Q 2017 Build Environ 117 11
[4] Liu S, Pan W, Zhao X, Zhang H, Cheng X, Long Z, and Chen Q 2018 Build Environ 140 1
[5] Robaa SM 2003 Int J Atmósfera 16 157
[6] Liu S, Zhou X, Liu X, Zhang W, Li J, Dong J, Lai D and Chen Q 2019 Energy Build 0
[7] Jiang Y and Chen Q 2002 Build Environ 37 379
[8] Katayama T, Tsutsumi J, Ishii A, Nishida M and Hashida M 1989 J Wind Eng Ind Aerodyn 32 41
[9] Wang H and Chen Q 2012 Energy Build 54 386
[10] Pan W, Liu S, Li S, Cheng X, Zhang H, Long Z, Zhang T and Chen Q 2019 Build Environ 147 372
[11] Wang H, Karava P and Chen Q 2015 Energy Build 96 373
[12] Stratford BS 1959 J Fluid Mech 5 1