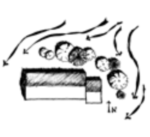


CHAPTER SIX

Chen, Q. 2007. "Chapter 6: Wind in building environment design," Sustainable Urban Housing in China, Edited by L.R. Glicksman and J. Lin, Springer.

WIND IN BUILDING ENVIRONMENT DESIGN

Qingyan Chen

INTRODUCTION

Wind can be a building's "friend" because it can naturally ventilate the building, providing a comfortable and healthy indoor environment, as well as saving energy. Conventional design approaches often ignore opportunities for innovations with wind that could condition buildings at a lower cost, while providing higher air quality and an acceptable thermal-comfort level by means of passive cooling or natural ventilation. Natural ventilation can be used for cooling in the spring and autumn for a moderate climate (e.g., Nashville, TN), the spring for a hot and dry climate (e.g., Phoenix, AZ), the summer for a cold climate (e.g., Portland, ME), and the spring and summer for a mild climate (e.g., Seattle, WA). Natural ventilation can also be used to cool environments in a hot and humid climate during part of the year (e.g., New Orleans, LA) (Lechner 2000).

On the other hand, wind can be a building's "enemy" when it causes discomfort to pedestrians, usually as a result of high wind speed around the building. Table 1 summarizes the effects of wind on people. The wind speed is normally referred to as the speed of wind at ten meters above an open terrain. The wind speed at pedestrian level is roughly 70 percent of the tabulated values. Visser (1980) proposed comfort criteria with different activities versus the frequency of wind speed higher than five meters per second, as shown in Table 2.

For example, in an area where the number of days with an average wind speed higher than 5 m/s is 150 days per year (or the frequency of wind with a speed higher than 5 m/s is 150 days/365 days x 100 percent = 41 percent), people who walk fast would feel unpleasant. Clearly, wind speeds greater than five meters per second are considered uncomfortable for most activities. Therefore, it is essential to reduce the wind speed around buildings.

In addition, in a mild, moderate, and cold climate, it is very important to minimize infiltration of cold air into the building during the winter to reduce wind speed around buildings. The reduction of wind speed can be achieved by: avoiding windy locations such as hilltops; using wind barriers like evergreen vegetation; clustering buildings for mutual wind protection; and designing buildings with streamlined shapes and rounded corners to both deflect the wind and minimize the surface-to-volume ratio (Lechner 2000).

For small-scale buildings, there are established guidelines for passive solar heating. However, natural ventilation and outdoor thermal comfort are very difficult to design, even in simple cases. The purpose of the present chapter is to demonstrate, with the help of the computational fluid dynamics (CFD) technique, how architects can work with engineers to design naturally ventilated buildings and comfortable outdoor environments around buildings.

Beaufort Number	Description	Wind Speed	Wind Effect
2	Light breeze	1.6 – 3.3	Wind felt on face
3	Gentle breeze	3.4 – 5.4	Hair disturbed; clothing flaps; newspaper difficult to read
4	Moderate breeze	5.5 – 7.9	Raises dust and loose paper; hair disarranged
5	Fresh breeze	8.0 – 10.7	Wind force felt by body; possible stumbling when entering a windy zone
6	Strong breeze	10.8 – 13.8	Umbrellas used with difficulty; hair blown straight; difficult in walking steadily; wind noise on ears unpleasant
7	Near gale	13.9 – 17.1	Inconvenience felt when walking
8	Gale	17.2 – 20.7	Generally impedes progress; great difficulty with balance in gusts
9	Strong gale	20.8 – 24.4	People blown over

Table 1 Effects of wind on people. Beaufort number classifies wind as 0 (calm) to 12 (hurricane) (Source: Bottema 1993)

Activities	*Acceptable*	*Unpleasant*	*Intolerable*
Walking fast: carpark, sidewalk, road, cycle-track	<35%	35% - 75%	> 75%
Strolling: park, shop center, footpath, building entrance, bus station	<5 %	5% - 35%	>35%
Sitting/standing short: shop center, square, playground	<0.1%	0.1% - 5%	> 5%
Sitting/standing long: terrace, swimming pool, open-air theater	0%	0% - 0.1%	> 0.1%

Table 2 Comfort criteria for different frequency (day/year) when wind speed is higher than 5 m/s (Source: Visser 1980)

WIND DATA

To design naturally ventilated buildings and/or comfortable outdoor environments, the first step is to obtain reliable wind information, such as wind speed and direction. For example, the National Renewable Energy Laboratory derived a set of typical meteorological weather data for 229 stations throughout the United

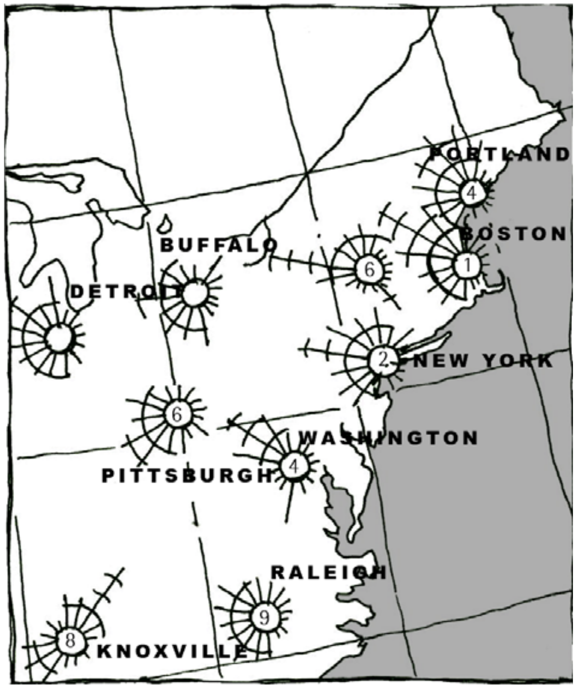


Figure 1 Surface wind roses in January for northeastern U.S. (Source: adapted from NOAA 1983)

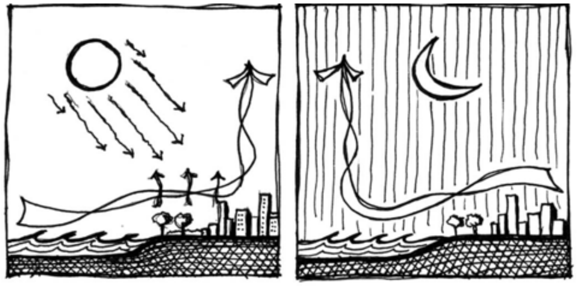


Figure 2 Diurnal and nocturnal air movements near a large body of water (Source: adapted from Moore 1993)

States and its territories (Marion and Urban 1995). The database provides hourly wind speed and directions that can be used directly in natural ventilation and outdoor comfort design. Rather than accounting for every hour in a full reference year, a designer should analyze the data and divide it into eight directions (N, NE, E, SE, S, SW, W, and NW) for several wind speeds (e.g., Beaufort number <2, 3-4, 5-6, >7, where Beaufort number classifies wind as 0 for calm to 12 for hurricane). The weather data can also be used to determine the percentage of wind for each direction and speed combination (32 in total). The total number can be reduced, eliminating those with very low probabilities.

For countries where typical meteorological weather data are not available, wind roses can be used. Figure 1 shows a part of the wind rose map for northeastern United States in January. The wind roses give the wind direction and percentage. The number inside the wind rose stands for the percentage of calm period. NOAA (1983) uses another figure to provide the monthly average wind speed over a year.

Note that the wind data from weather databases, wind roses, or a weather station is for an open terrain. Numerous factors could have a significant impact on the local climactic conditions. For example, a large water body, such as a lake, can create a local wind from the water body to the land during the day and a local wind from the land to water during the night (Figure 2). This is because water has a higher effective thermal mass than that of land. Under the sun, the surface of land is heated much faster than water. The warmer air above the land goes up due to the buoyancy effect, creating an air pressure differential from the water to land. During the night, land cools faster than water due to thermal radiation. It is again the thermal buoyancy in the air that forms a land-to-water wind. Other factors include valleys, mountain ranges, and even large building blocks.

DESIGN TOOLS

Traditionally, many architects predict the airflow in and around buildings by using "smart arrows," as shown in Figure 3. Drawing the airflow correctly requires a rich knowledge of fluid mechanics. Unfortunately in many cases, the "predicted" airflow pattern can be completely different from that in reality. Furthermore, the smart arrows cannot give the wind speed, or at least the reliable air speed, which is an important parameter for evaluating the benefits of natural ventilation and outdoor comfort. Chandra, Fairey and Houston (1983) developed a simple model for calculating the air exchange rate for natural cross ventilation. However, it is limited in that it can only be applied to buildings with simple geometry and surroundings.

Many empirical and analytical tools have also been developed for manual prediction of natural ventilation in buildings and outdoor thermal comfort, as documented by Allard (1998), Awbi (1996), CIBSE (1997), and Linden (1999). These manual methods are generally very simple and can be expressed by algebraic equations and spreadsheets. Despite being useful, these empirical and analytical tools have great uncertainties when used for complex buildings.

As a result, most traditional studies use wind tunnels to simulate and measure the airflow around buildings for outdoor thermal comfort and a full-scale mock-up room to determine natural ventilation. Figure 4 shows a site model placed in a wind tunnel. By rotating the site model disc and by changing the fan speed, different wind directions and speeds can be simulated.

When the buoyancy effect is not strong, such as during natural cross ventilation, the wind tunnel, together with modeling theory, can also be used to study natural ventilation. For buoyancy-dominant natural ventilation, such as single-sided natural ventilation, ideally a full-scale mockup is needed in order to satisfy both the Reynolds number that represents inertial force from the wind and the Grashov number that represents the buoyancy force. The experiment usually measures wind speed in the wind tunnel, and wind speed and temperature in the mockup room. Rarely is the wind direction also measured. Although the experimental approaches provide reliable information concerning airflow in and around buildings, the available data is generally limited due to the expensive experimental rigs and processes. Moreover, the approach is not practical for a designer who wishes to optimize his or her designs because the experimental method is very time-consuming. Alternately, another fluid such as heavy refrigerant vapor (Olson, Glicksman and Ferm 1990) or water (Linden 1999) can be used for modeling. These fluids allow the model size to be substantially reduced. Whole buildings can be simulated with the water models. Also, by relaxing some of the modeling criteria, such as matching the Reynolds number, small-scale air models can also be employed.

Numerical simulation has become a new trend for determining natural ventilation and outdoor thermal comfort. Two numerical methods are available for predicting natural ventilation. The first one is the zonal method, which calculates inter-zonal airflow using the Bernoulli equation along with experimental correlations of flow resistance through doorways, windows, and other orifices.

The prediction of the inter-zonal airflow relies on the external pressure distribution caused either by wind or the buoyancy effect. However, the determination of the external pressure is very complex, since the pressure distribution depends on incoming wind speed and direction, building size and shape, and the size and location of the building's interior opening (Vickery and Karakatsanis 1987). Therefore, the accuracy of the zonal method depends on the accuracy of the pressure distribution. Furthermore, the zonal model is incapable of determining thermal comfort around a building, because it does not provide wind velocity information. However, such a method can supply good preliminary estimates of air flow and temperature levels within a building if reasonable estimates of external wind pressure distributions can be made.

The other numerical method, CFD, calculates the airflow distribution for both indoor and outdoor thermal comfort. The CFD technique numerically solves a set of partial differential equations for the conservation of mass, momentum (Navier-Stokes equations), energy, species concentrations, and turbulence quantities. The solution provides the field distribution of pressure, air velocity, temperature, concentrations of water vapor (relative humidity), and contaminants, and turbulence. Refer to Chen and Glicksman (2000) for a more detailed description of the CFD technique. Despite having some uncertainties and requiring an engineer with sufficient knowledge of fluid mechanics and a high-capacity computer, the CFD method has been successfully used to predict airflow in and around buildings (Chen 1997, Murakami 1998). With the rapid increase in computer capacity and the development of new CFD program interfaces, the CFD technique is becoming very popular.

The following sections will discuss the applications of CFD to outdoor thermal comfort and natural ventilation design. CFD generally includes large eddy simulation and Reynolds averaged Navier-Stokes equation modeling. Large eddy simulation, as reviewed by Murakami (1998), can give more detailed results, such as an instantaneous airflow field, but it requires more computing time than that of the Reynolds averaged Navier-Stokes equation modeling. Large eddy simulation has started appearing in building environment research,

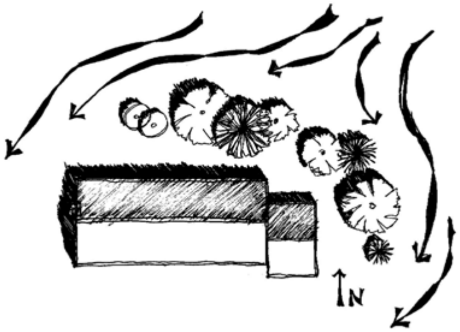


Figure 3 Smart arrows used by architects to predict airflow in and around buildings (Source: adapted from Moore 1993)

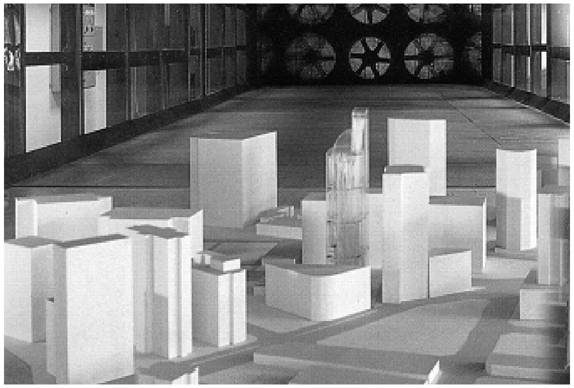
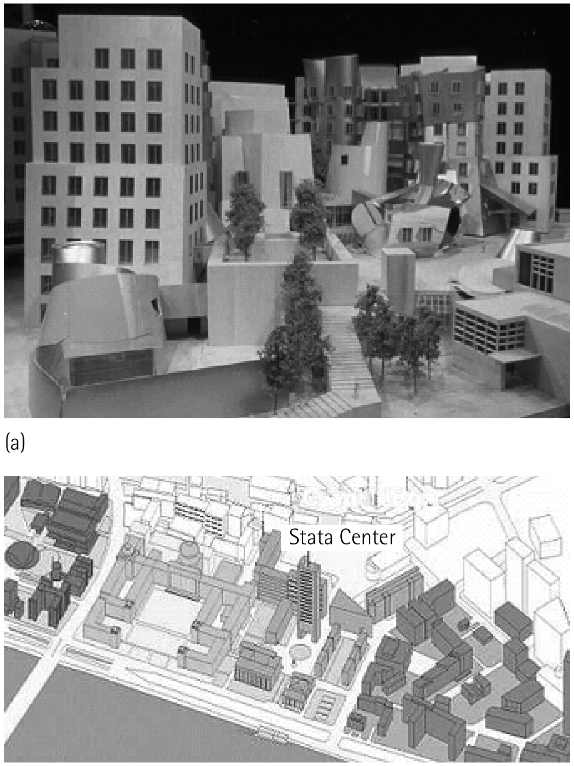


Figure 4 A building site model within a wind tunnel



(a)

(b)

Figure 5 Stata Center: (a) model shown without glass roof and (b) surroundings

but has yet to be applied as a design tool. Therefore, this chapter focuses on Reynolds averaged Navier-Stokes equation modeling. Many commercial CFD programs based on the Reynolds averaged Navier-Stokes equation modeling are available on market and are rather similar to each other. This investigation uses the PHOENICS program (CHAM 2000).

OUTDOOR THERMAL COMFORT STUDIES

Outdoor thermal comfort design will be illustrated by two application examples. The first example concerns the design of the Stata Center at the Massachusetts Institute of Technology, and the second is a high-rise residential building complex in Beijing.

Stata Center

Figure 5a shows a model of the Stata Center and its surroundings designed by Frank O. Gehry and Associates. Since this campus building has windy surroundings, the architect was concerned about the outdoor thermal comfort in the plaza (the front part of Figure 5a). At one time, the architect wanted to add a glass roof that would provide a wind shield over the plaza. Since the glazed roof would cost several million dollars, the architect initiated a study of the wind distribution around the Stata Center, which was researched by the author.

This investigation used a commercial CFD program (CHAM 2000) for the study. The CFD program allows one to read data from an AutoCAD file. This feature is very important because of the complicated geometry of the buildings. Similar to a wind tunnel, CFD requires detailed information on the surroundings of the Stata Center in order to calculate the airflow. The surrounding buildings can either block or enhance the wind speed around the center. The computational domain for the building and surroundings is shown in Figure 5b. The domain length is about five times that of Stata Center in the four horizontal directions (or 100 times the Stata Center area size). The wind distributions around Stata Center were calculated for the north, east, south, and west wind directions with a typical wind speed for each direction. Figure 6 shows the wind distribution around Stata Center with an east wind. This study used about one million grid points; the study required three days of computing time on a Pentium II 450 PC with 512 MB of memory. That PC was considered to be high-end in 1999. Obviously, the grid number was too coarse so the wind information was not sufficiently detailed.

Therefore, the investigation used a zoom-in approach to study the details of the wind distribution. The zoom-in approach used the wind information computed (Figure 6) as boundary conditions in calculating the wind speed distribution just around Stata Center, as shown in Figure 7. With the zoom-in approach, the CFD results provided very detailed wind speed information. For example, the wind speed was found to be almost identical around Stata Center with or without the glass roof. Hence, the glass roof was not necessary.

A High-Rise Residential Building Complex in Beijing

In the past, a good living environment in China implied ample space between buildings filled with trees and grass. High-rise buildings have been regarded as a symbol of modernity and luxury. A typical building consisting of such residential units is shown in Figure 8. Jiang et al (1999) made a detailed analysis on the design and found that such a design is not sustainable in terms of energy efficiency and Chinese culture. The study showed that the best design would be made up of low-rise buildings with varying-sized courtyards. This would avoid a harsh winter wind, let the winter sun in, and promote the use of natural ventilation.

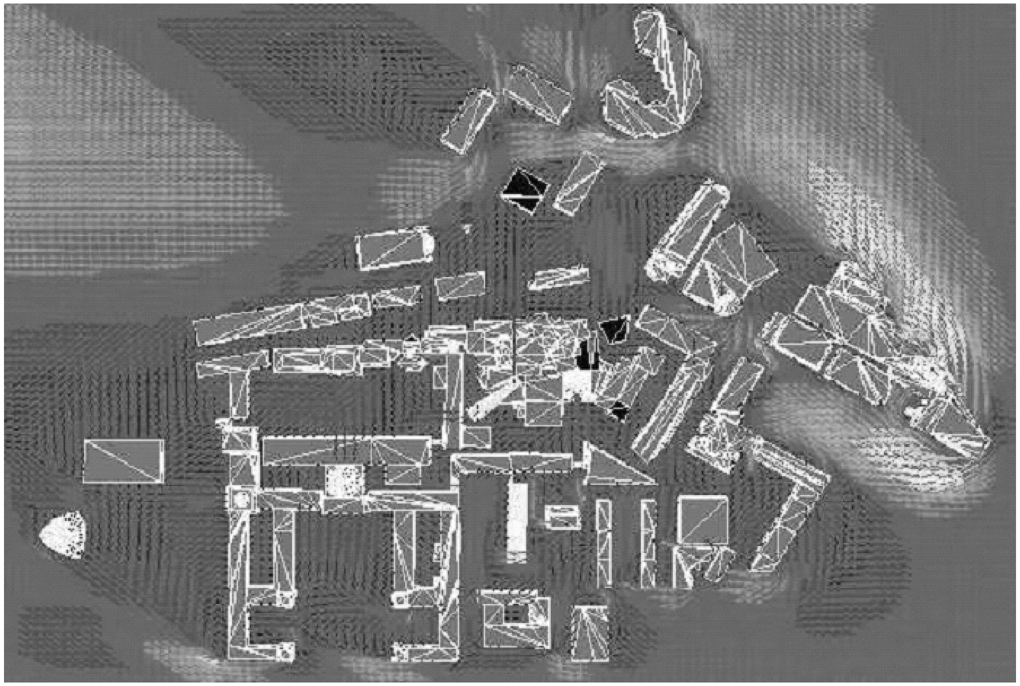
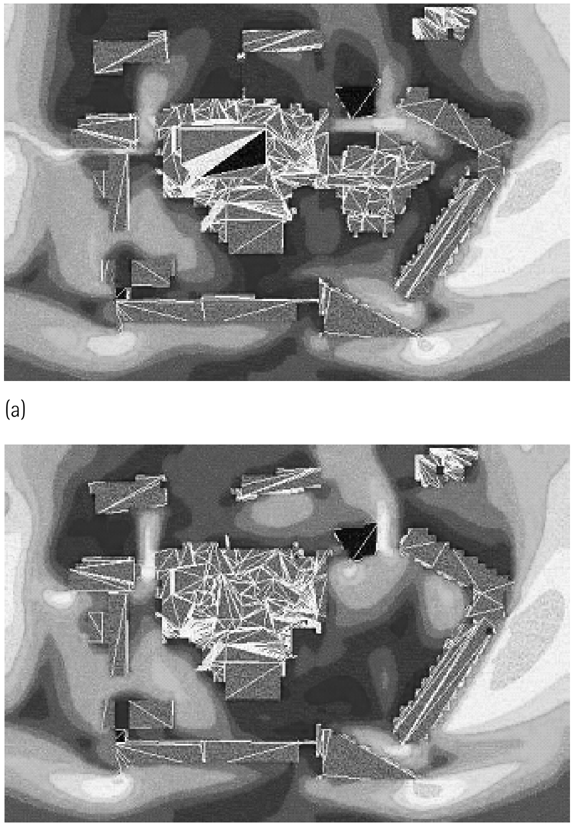


Figure 6 Wind distribution around Stata Center at the ground level (dark - low velocity and light - high velocity)



(a)

(b)

Figure 7 Wind distribution around Stata Center (zoom-in): (a) with a glass roof and (b) without a glass roof (dark - low velocity and light - high velocity)

Figure 8 Beijing Star Garden - a high-rise residential development

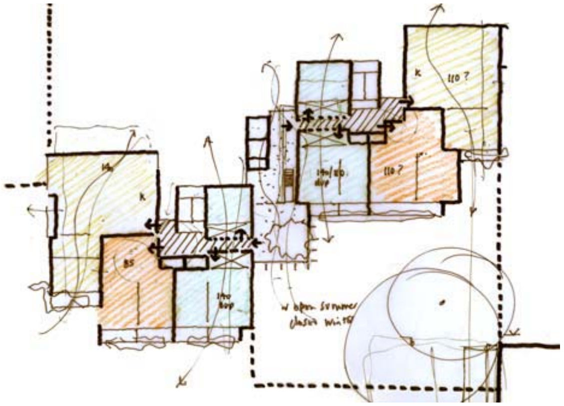
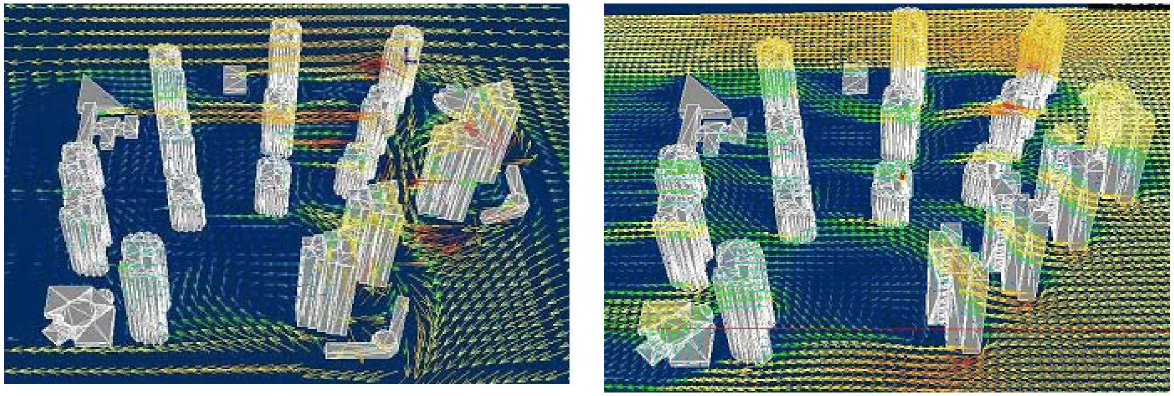


Figure 10 The unit layout in the four new towers allows more effective natural ventilation in the summer (north is up)



(a)

(b)

Figure 9 Wind distribution on the building site: (a) original design, and (b) design with four proposed towers to the north (to the right) (red indicates high velocity, yellow - moderate velocity, and blue - low velocity)

As is the case with many downtown areas with skyscrapers, high-rise buildings sometimes create a wind tunnel effect that is very uncomfortable to pedestrians. The proposed design for Beijing Star Garden forms a wind tunnel effect on the site with prevailing winter winds from the north. Figure 9a shows the wind distribution on the site with a north wind from the right. There are a few places that have very high wind speeds (see red arrows in Figure 9a). The developers did not adopt our suggestion of lowering the building height and creating courts to eliminate "wind tunnel" problems and enhance contact between neighbors. Instead, they sought to change the shape of the four towers in the north to eliminate high wind spots. The new design used a different building shape to deflect the wind to the westward direction. Figure 9b shows the airflow distribution with a north wind under the new design of the four towers that reduces areas of high winds.

Of course, wind is not the only factor in producing an energy-efficient building design. Changing the tower shape may have an impact on the desire to have south-facing windows. This can be achieved through architectural design, as shown in Figure 10. The thin structure also allows the use of natural ventilation in the summer. See *Chapter 11, Case Study Two – Beijing Star Garden* for more information.

NATURAL VENTILATION STUDIES

The last ten years have seen a significant shift in the development and integration of environmental, ecological, and energy issues into the architectural design of buildings. Energy-efficient buildings address not only the issues of consumption and performance, but also the development and integration of a series of design and system technologies. Buildings should provide the basic amenities of shelter and yet practice responsible use of resources. Whatever the climate zone, energy-conscious design utilizes strategies that optimize the passive environmental systems in reference to active "sealed system" strategies. This leads to the use of natural ventilation and the maximization of daylighting wherever reasonable. Even under unfavorable outdoor climate conditions, passive-based technology can be combined with active systems during shoulder seasons and sometimes for night cooling in conjunction with adequate thermal mass.

Leading architects of this generation in the United Kingdom, Germany, France, Switzerland, and Scandinavia have turned their attention to a more sustainable form of practice in both building system technologies and building typologies. This approach can be witnessed in the work of architects such as Foster and Partners, Renzo Piano, Alan Short, Thomas Herzog, Michael Hopkins, Edward Cullinan, and Kiessler and Partners. In their designs, the issue of resources and the environment is at the heart of making intelligent and well-crafted architecture. Their buildings provide an interaction between the enclosure systems and the environmental and mechanical strategies for the internal space. The buildings are reputed to save a considerable amount of energy while improving indoor air quality and comfort.

Table 3 shows the potential of using natural ventilation in the United States for residential buildings. With proper design of building orientation, location, shape, and openings, daytime natural ventilation and/or night cooling can provide a thermally comfortable indoor environment for a long period in most all U.S. climates. Even if it is not possible to avoid the use of air-conditioning in the summer, air-conditioning units can be much smaller with natural ventilation, reducing first and operating costs.

Climate Region and Reference City	**Periods Suitable for Natural Ventilation (NV) and when Air-Conditioning (AC) or Heating (H) is Needed for Residential Buildings**											
Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1. Hartford, CT	H	H	H	H	NV	NV	NV	NV	NV	H	H	H
2. Madison, WI	H	H	H	H	NV	NV	NV	NV	NV	H	H	H
3. Indianapolis, IN	H	H	H	NV	NV	NV	AC	AC	NV	NV	H	H
4. Salt Lake City, UT	H	H	H	H	NV	NV	AC	AC	NV	NV	H	H
5. Ely, NV	H	H	H	H	NV	NV	NV	NV	NV	NV	H	H
6. Medford, OR	H	H	H	NV	NV	NV	NV	NV	NV	NV	H	H
7. Fresno, CA	H	H	NV	NV	NV	NV	NV	NV	NV	NV	H	H
8. Charleston, SC	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
9. Little Rock, AR	H	H	H	NV	NV	AC	AC	AC	NV	NV	NV	H
10. Knoxville, TN	H	H	H	NV	NV	AC	AC	AC	NV	NV	NV	H
11. Phoenix, AZ	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
12. Midland, TX	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
13. Fort Worth, TX	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
14. New Orleans, LA	H	H	NV	NV	NV	AC	AC	AC	AC	NV	NV	H
15. Houston, TX	H	NV	NV	NV	AC	AC	AC	AC	AC	NV	NV	H
16. Miami, FL	NV	NV	NV	NV	AC	AC	AC	AC	AC	AC	NV	NV
17. Los Angeles, CA	H	H	NV	NV	NV	NV	AC	NV	NV	NV	NV	H

Table 3 The potential for natural ventilation in the U.S. (Source: Lechner 2000)

Age	< 19		20-40		40-60		> 60	
Sex	M	F	M	F	M	F	M	F
Like AC (%)	43	52	48	35	38	37	22	30
Neutral (%)	43	32	43	53	37	37	37	33
Dislike AC (%)	14	16	9	12	25	26	41	37

Table 4 A survey conducted in Beijing with respect to the use of air-conditioning in homes (Source: Jiang 1999)

Furthermore, it is very interesting to see the survey conducted in Beijing by Jiang (1999) regarding the acceptability of air-conditioning systems. Table 4 shows the survey results separated into categories according to age and sex. People who like air-conditioning think that it provides a cool temperature (40 percent), represents a modern technology (34 percent), and offers an ability to control the climate (23 percent). On the other hand, those who dislike air-conditioning believe that air-conditioning separates them from nature (47 percent), leads to draft and a high-noise environment (26 percent), and causes high electricity and first costs (23 percent). In general, younger people tend to like air-conditioning more than elderly people do. The results show a great potential for using natural ventilation in Beijing.

It should also be noted that natural ventilation has its shortcomings; these include issues of humidity control, noise control (10 dB deduction for an open window versus 30 dB deduction for a sealed window), heat recovery, security concerns, and rain. In addition, in areas with high outdoor pollution, natural ventilation has difficulty in controlling air quality. One solution could be the use of night cooling that closes the window during daytime, as illustrated by Carrilho da Graça et al (2002) and as described in chapter 5.

According to CIBSE (1997), natural ventilation can be classified as:

- cross ventilation;
- single-sided ventilation;
- stack ventilation; and
- mechanically assisted ventilation.

Cross ventilation occurs where an indoor space has ventilation openings on both sides. Air flows from one side of the building to the other due to a pressure difference built up by wind. Single-sided ventilation implies that an indoor space has all of the openings on one side. Stack ventilation makes use of density differences due to buoyancy in promoting an outflow from a part of a building (e.g., roof) and drawing in fresh and cool air from another part of the building (e.g., windows and doors). Mechanically assisted ventilation uses mechanical ventilation to increase the airflow in any of the above-mentioned systems. A building may have more than one of the ventilation systems described above.

This section will describe the applications of CFD to design cross ventilation and single-sided ventilation in buildings. The method can be used for other ventilation systems as well.

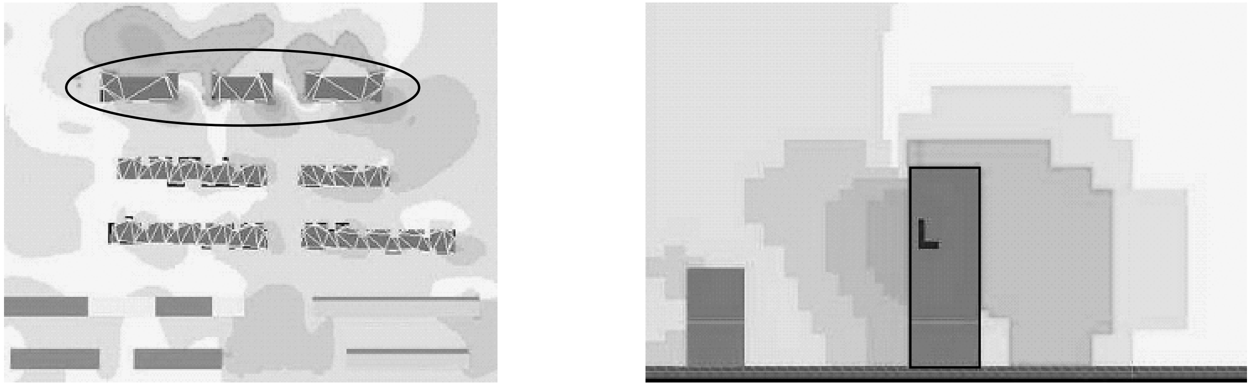
Cross Ventilation in a Building

The design team was requested to design three mid-rise buildings for a residential building development in Shanghai (Figure 11).

Since wind around the buildings is the driving force in cross ventilation, this investigation involves the simulation of indoor and outdoor airflow by CFD. In order to study the impact of surrounding buildings, the computational domain for outdoor airflow should be sufficiently large (e.g., an area of tens of thousands to a million square meters). Due to the limitation in current computer capacity and speed, the grid size used cannot be very small (it can be a few meters). On the other hand, the grid size for indoor airflow simulation should be small enough (in terms of a few centimeters) for one to see the details. Therefore, the indoor and outdoor airflow should be separately simulated. For natural ventilation design, the outdoor airflow simulation can provide flow information as boundary conditions for the indoor airflow simulation. Zhai et al (2000) have discussed a few methods to provide the flow information.

For simplicity, this investigation used a CFD program to calculate the pressure difference around the buildings and uses it as the boundary conditions for indoor airflow simulation. Ideally, the calculation should be performed for different wind directions under various wind speeds in a period suitable for natural ventilation, such as summer. Figure 12 illustrates the pressure distribution under the prevailing wind direction (southeast) and speed (3 m/s). In order to correctly take the impact of the surrounding buildings into account, the computational domain is much larger than the one shown in the figure. Clearly, the pressure difference is the highest between the northern and southern façades. It is also interesting to note that the highest pressure difference is neither at the top floor nor at the bottom floor, but somewhere near the top, as shown in Figure 12b.

Figure 11 Architectural elevation and plans of final design for Shanghai Taidong Residential Quarter



(a)

(b)

Figure 12 Pressure distribution around the buildings proposed (shown circled) for Shanghai Taidong Residential Quarter, due to prevailing winds, from the southeast at 3 m/s (dark gray - high pressure, light gray - low pressure): (a) is the plan (north is up) and (b) is the section looking west (see color version of Figure 12b in chapter 12, Figure 34)

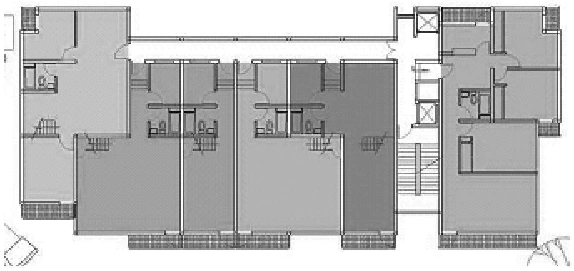


Figure 13 Building floor plan - unit G (the unit farthest to the right) was analyzed for interior CFD studies

By working together with the architects, the design team evaluated the ventilation performance for the buildings. Unit G in the middle building was used (Figure 13) as an example to illustrate the evaluation of cross-ventilation design.

With the unit layout in Figure 13, a CFD model can be established, as shown in Figure 14a. With the pressure distribution from Figure 12, the CFD program can calculate the distributions of airflow, air temperature, relative humidity, predicted percentage dissatisfied (PPD), and the mean age of air, as shown in Figure 14. CFD uses the humidity ratio and air temperature to determine the relative humidity. The PPD is determined by using the air velocity, temperature, humidity ratio, and environmental temperature. The results shown in Figure 14 are with an outside air temperature of 24°C and a relative humidity of 70 percent.

The computed results by CFD indicate that the maximum air velocity in the unit is less than one meter per second – a comfortable value for cross ventilation. The air exchange rate varies from 16 ACH on the first floor to a maximum of 40 air changes per hour (ACH) two-thirds up the height of the building. With the air exchange rate of 16 ACH, the indoor air temperature increases less than 1°K, although there are heat sources in the unit. The relative humidity is around 65 to 70 percent, a value close to that of the outdoors. Since the air exchange rate is high, the mean age of air is less than 120 seconds. Therefore, the air quality would be very good when outdoor air quality is high.

Since the air exchange rate is a very important parameter in cross ventilation design, this investigation indicates the design to be very successful. However, the wind is not always at the prevailing speed and direction, and the outdoor air temperature varies over time. A more complete evaluation of the design should be combined with an energy analysis of the building, as described in chapter 5. Carrilho da Graça et al (2002) have shown how to combine the information from flow and energy analysis for such a building. The paper also emphasizes the importance in using different control strategies. For example, in Shanghai it is more appropriate to use night cooling and minimum daytime ventilation to achieve an indoor air temperature lower than that of the outdoors. This is superior to ventilating buildings twenty-four hours a day. See *Chapter 12, Case Study Three– Shanghai Taidong Residential Quarter* for more information.

Single-Sided Ventilation in a Building

The building studied is a student dormitory in Cambridge, Massachusetts. Single-sided ventilation was evaluated for a typical room that is 4.7 meters long, 2.9 meters wide, and 2.8 meters high. The general room model used throughout the study is shown in Figure 15. The furniture within this room consisted of a bed, desk, closet, and bookcase. The heat sources were a computer (300 W), a TV set (300 W), and one occupant (100 W). For each of the heat sources, convective and radiative heat transfer was approximately equal. The surrounding walls, ceiling, and floor absorbed the radiative component and released it back to the room air by convection. Solar gains were not included for purposes of the time-averaged ventilation study. The window designed for the room consisted of an upper and lower window (0.4 m^2 each), as shown in Figure 15. The outdoor air temperature was maintained constant at 25.5°C, the average noon temperature for Boston in July. The intention was to analyze the results for this fixed outdoor temperature, and then apply them to a range of outdoor temperature conditions to develop trends.

This study stacked three identical dormitory rooms vertically above one another to evaluate the effect along a building's height. This three-story setup was placed within a larger outside domain (Figure 15b). The extension

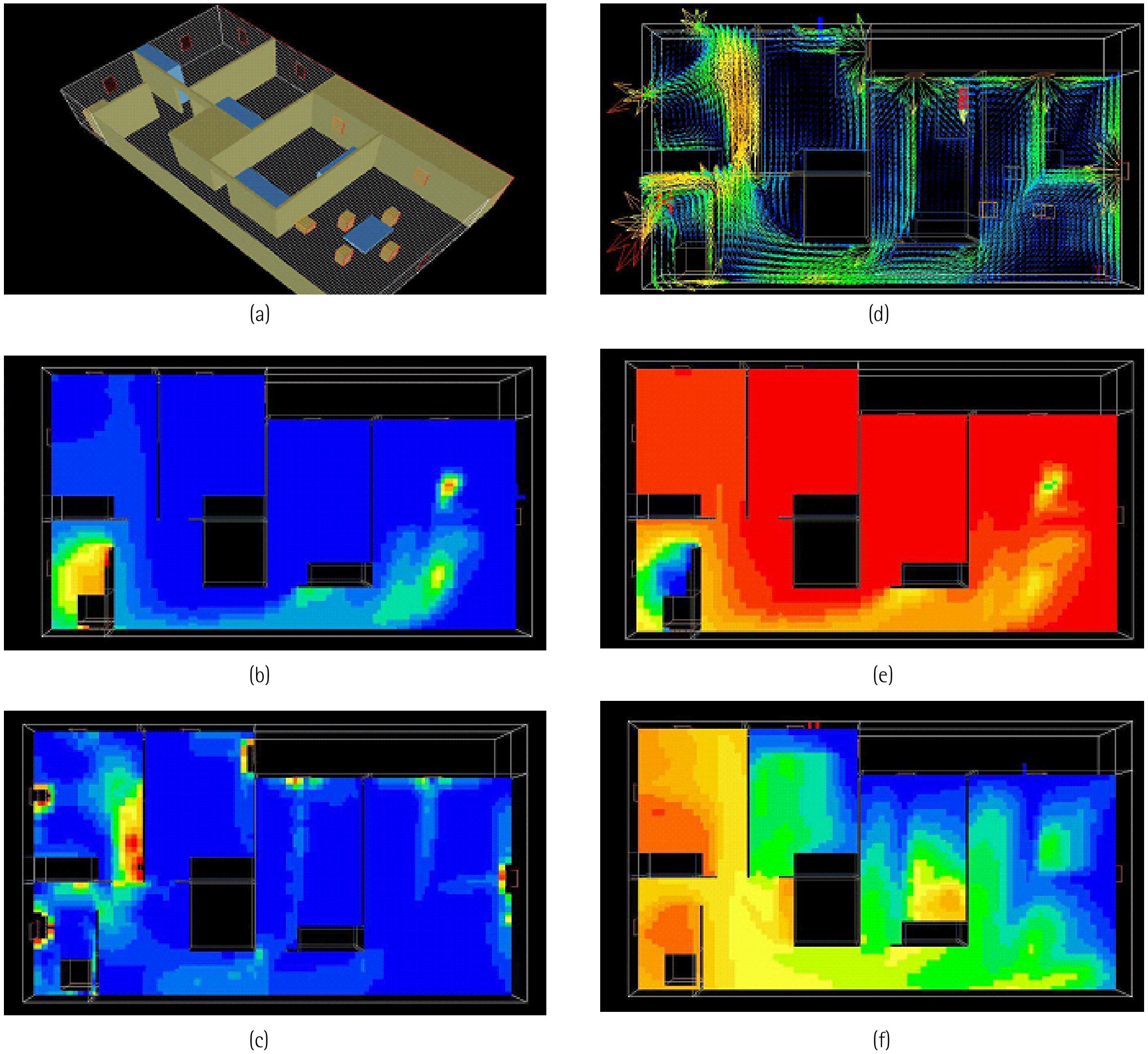
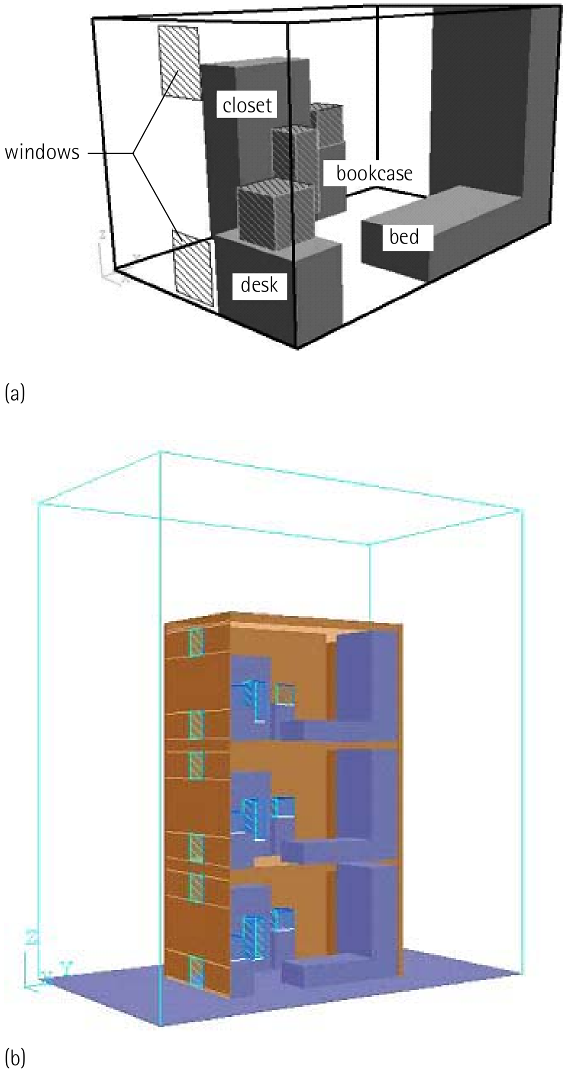

(a) (d) (b) (e) (c) (f)

Figure 14 Cross ventilation performance analysis of Beijing unit interior (red – high, yellow – moderate high, green – moderate low, blue – low): (a) unit model, (b) air temperature, (c) predicted percentage of dissatisfied people (PPD) due to thermal comfort, (d) air velocity, (e) relative humidity, and (f) mean age of air



(a) (b)

Figure 15 The CFD model used to study single-sided ventilation in an MIT dormitory room: (a) the room model and (b) the building and environment model

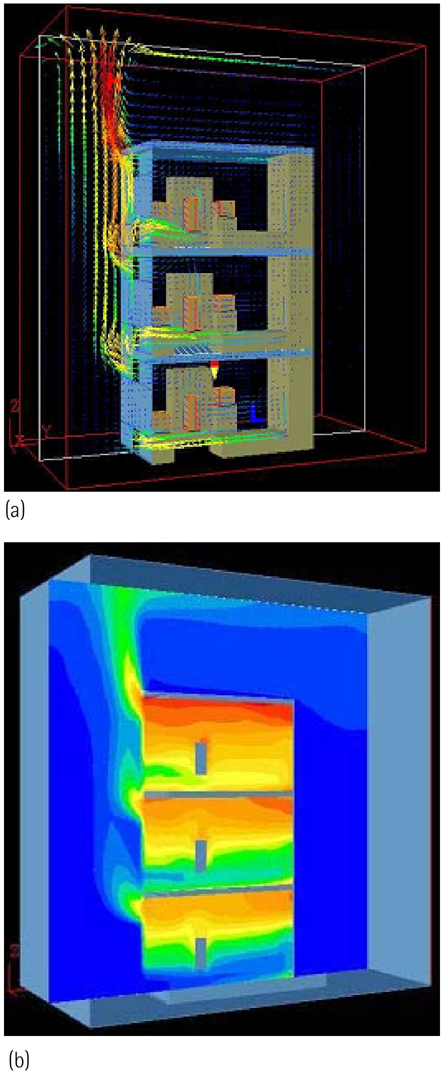


Figure 16 CFD results in the center of the rooms with stack effect (red – high, yellow – moderate high, green – moderate low, blue – low): (a) air velocity distribution and (b) air temperature distribution

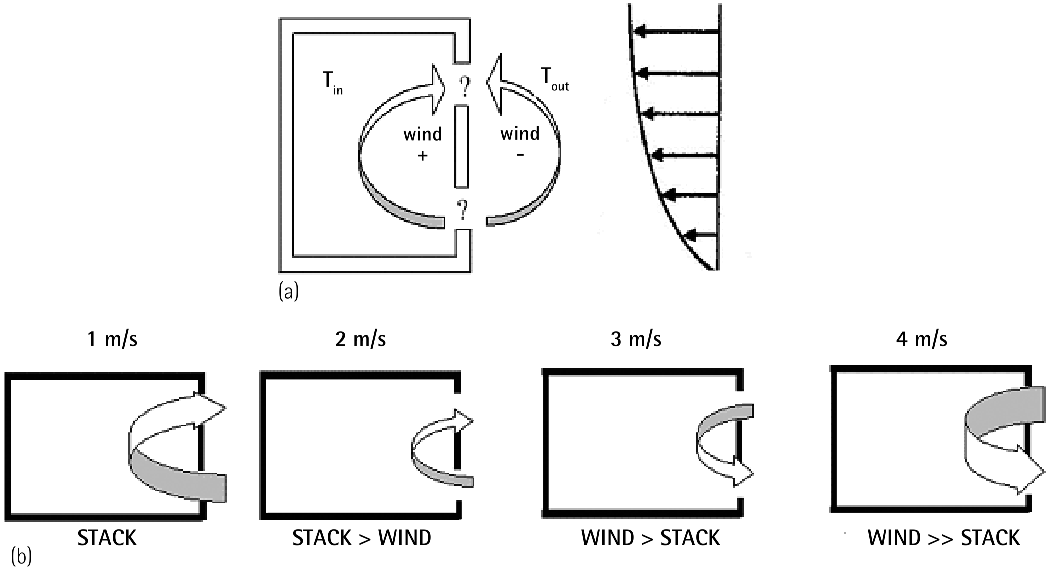


Figure 17 Uncertain effects of combined wind and stack forces: (a) reinforcing vs. counteracting effect and (b) depiction of counteracting wind and stack effects over a progression of wind speeds

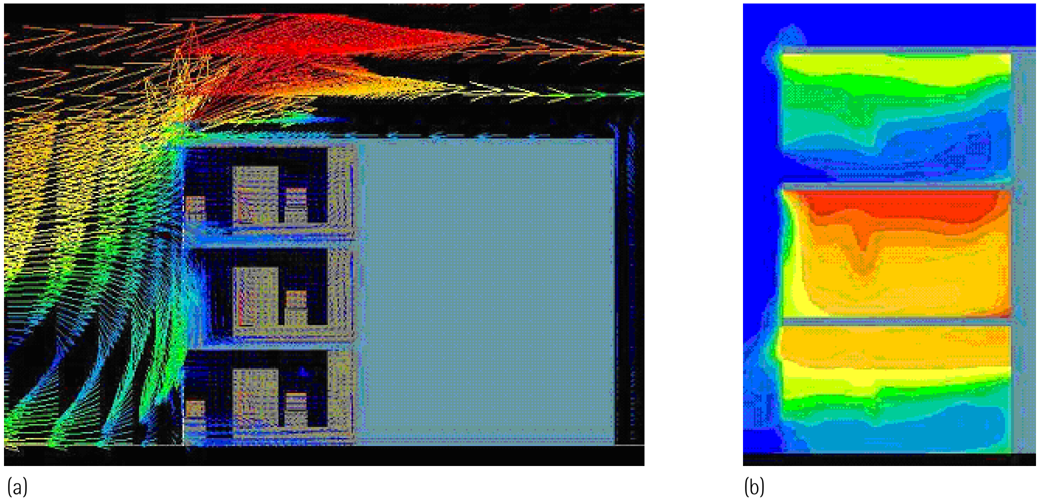


Figure 18 CFD results in the center of the rooms with the combined wind and stack effects (red – high, yellow – moderate high, green – moderate low, blue – low): (a) air velocity distribution and (b) air temperature distribution

of the flow domain to the outdoors allows us to consider the vertical (hydrostatic) pressure distribution.

Under a buoyancy-driven scenario (windless condition), the temperatures in each space increased with height due to the outside thermal plume from one room entering the room above (as shown in Figure 16) despite the fact that the spaces were physically and thermally isolated from one another. This can clearly be seen from the shifts in the graph of indoor temperature versus height, as shown in Figure 16b (Allocca, Chen and Glicksman 2003). This type of effect seems plausible due to the small distance between the upper openings of one space and the lower openings of the space above. Analytical solutions or experimental measurements do not easily discover such a phenomenon found in the CFD simulation.

Although the study of pure buoyancy effects on single-sided ventilation is interesting, it is more useful to examine the effects of combined wind and buoyancy on the ventilation. The experiments (Phaff et al 1980) showed that, for a particular tested room, wind and stack flow reinforced each other. Our study found that wind and stack forces did not always reinforce each other. In fact, they opposed each other in some instances. This ambiguity is illustrated in Figure 17a. An example of the counteracting wind and stack effect during an increasing progression of wind speeds is also shown in Figure 17b.

A counteracting wind and stack flow took place in the middle unit. Figure 18a shows the airflow at the mid-section in the room. The wind force at the upper opening was stronger than the buoyancy force, thereby forcing a clockwise flow into the unit through the upper opening and out through the lower opening. Since the two forces opposed each other, the ventilation was reduced. As a result, the temperature in the middle unit was the highest, as shown in Figure 18b. However, in the upper unit, the wind aided the buoyancy effects by driving air in through the lower opening and out through the upper opening. The room air temperature was the lowest in the building. In the lower unit, the buoyancy effects were stronger than the opposing wind effects. The air still flowed in from the lower opening and out through the upper opening. The corresponding temperature in the unit was moderate since the wind velocity was lower near the base of the building.

There are no guiding rules to determine where counteracting wind and stack effect will occur. Ordinary design guides may not provide useful information, unless detailed air velocity distributions near the openings are known. It seems that CFD analysis can provide detailed information to a designer, ensuring a successful design of natural ventilation systems.

SUMMARY

The results in this chapter show that wind can have many positive attributes in an architectural environment such as providing a comfortable and healthy indoor environment that can also save energy by means of passive cooling or natural ventilation. However, this chapter illustrates that wind can also cause discomfort to pedestrians if its speed around a building is too high, and it can also increase energy loss in the winter.

This chapter has discussed different methods available for wind design. Among the methods studied, CFD seems to be attractive for building environment design, since it is the most affordable, accurate, and informative when it is properly applied. This chapter has also illustrated a number of architectural indoor and outdoor environment designs that have utilized CFD. These include: