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Using computational tools to factor wind into architectural environment design

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Abstract

Wind can have many positive attributes in an architectural environment such as providing a comfortable and healthy indoor environment and that can also save energy, by means of passive cooling or natural ventilation. However, 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.

Firstly, this paper will discuss the design strategies for wind in environmental and building design. It will then compare the available techniques used to study the wind effect in building design, such as a model mockup, wind tunnel, nodal/zonal models, and computational fluid dynamics (CFD).

Among the techniques studied, CFD seems to be one of the most attractive for building environment design, since it is the most affordable, accurate, and informative method. This chapter will also illustrate a number of architectural indoor and outdoor environment designs that have utilized CFD. These include:

☞ Airflow around a building complex
☞ Using building shape to prevent draft due to cold wind in a high rise building site
☞ Cross natural ventilation in a building
☞ Single-sided natural ventilation design

1. Introduction

Wind can be a friend of a building because it can naturally ventilate the building, providing a comfortable and healthy indoor environment, as well as saving energy. 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 some of the year (e.g. New Orleans, LA) [1]. 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.

On the other hand, wind can be an enemy to a building when it causes discomfort to pedestrians – usually as a result of high wind speed around the building. Table 1 summarizes the

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effects of wind on people [2]. Beaufort number classifies wind as 0 (calm) to 12 (hurricane). The wind speed is normally referred to as the speed of wind at 10 m above an open terrain. The wind speed at pedestrian level is roughly 70% of the tabulated values. Visser [3] proposed comfort criteria with different activities versus the frequency of wind speed higher than 5 m/s, as shown in Table 2. For example, in an area where the number of day with an averaged 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% = 41%), people who walk fast would feel unpleasant. Clearly, wind speeds greater than 5 m/s are considered not comfortable 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 keep cold temperatures out during the winter by reducing wind speed around buildings. The reduction of wind speed can be achieved by: avoiding windy locations such as hill tops; 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 [1].

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 study 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.

2. 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. The National Renewable Energy Laboratory [4] derived a set of typical meteorological weather data for 229 stations throughout the United States and its territories. 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 is not available, wind roses can be used. Figure 1 shows a part of the wind rose map for the United States in July [5]. The wind roses give the wind direction and percentage. The number inside the wind rose stands for the percentage of calm period. NOAA [5] 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 (See 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 up 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.

3. 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 et al. [6] have developed a simple model for calculating the air exchange rate for cross natural 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 [7], CIBSE [8] and Linden [9]. 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 building complex.

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 mockup 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 can also be used to study natural ventilation together with modeling theory. For buoyancy-dominant natural ventilation, such as single-sided natural ventilation, a full-scale mockup is needed in order to satisfy both Reynolds number that represents inertial force from the wind and 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 [10] or water [9] can be used for modeling. These fluids allow the model size to be substantially reduced. Whole buildings can be simulated with the water models.

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. 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 [11]. 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.

The other numerical method, computational fluid dynamics (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 [12] 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 [13, 14]. 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 [14], 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, but has yet to be applied as a design tool. Therefore, this paper 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 a commercial CFD program, PHOENICS [15] that uses the standard k-ε model [16], staggered grid distribution [17], and simple algorithm [17].

4. 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 residential building complex in Beijing.

4.1 Stata Center

Figure 5 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 5). At one time, the architect wanted to add a glass roof that would provide a wind shield over the plaza. Since the piece of glass would cost a few million dollars, the architect initiated a study of the wind distribution around the Stata Center.

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 of 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 on Figure 5. 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 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. Nevertheless, the results are converged with a mass residual no higher than 1%.

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. The picture on the left in Figure 5 shows the final design without the glass roof.

4.2. 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 apartments is shown in Figure 8. Jiang et al. [18] 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 different sized courtyards. This would avoid a harsh winter wind, let the winter sun in, and promote the use of natural ventilation.

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 forms a wind tunnel effect on the site with prevailing winter winds from the north. Figure 9(a) shows the wind distribution on the site with a north wind from the right. There are a few places which have very high wind speeds (arrows red color). The developer did not adapt 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 9(b) shows the airflow distribution with a north wind under the new design of the four towers.

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. The thin structure also allows the use of natural ventilation in the summer.

5. Natural ventilation studies

The last ten years have seen 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 favor of active “sealed system” strategies. This leads to the use of natural ventilation and the maximization of day lighting wherever reasonable. Even under unfavorable outdoor climate conditions, passive-based technology can be combined with active systems during shoulder seasons and sometimes at night for nighttime 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 both in the form of building system technologies and building typologies. This approach can be witnessed in the work of architects such as Norman Foster, 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 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 be saving 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 of the 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.

Furthermore, it is very interesting to see the survey conducted in Beijing by Jiang [19] for 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%), represents a modern technology (34%), and offers an ability to control the climate (23%). On the other hand, those who dislike air conditioning believe that air-conditioning separates them from nature (47%), leads to draft and a high noise environment (26%), and causes high electricity and first costs (23%). In general, younger people tend to like air conditioning more than elderly people do. The results show a great potential in 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. [20].

According to CIBSE [8], natural ventilation can be classified as:

- Cross ventilation
- Single-sided ventilation
- Stack ventilation
- 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 only has one opening(s) 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.

5.1 Cross ventilation in a building

A design team from Massachusetts Institute of Technology was requested to design three mid-rise buildings for a residential building development in Shanghai. Figure 10 shows the architecture rendering of the buildings.

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) in order 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. [21] 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 11 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 11(b).

By working together with the architects, the design team has evaluated the ventilation performance for the buildings. Here, the right-hand unit in the middle building is used (see Figure 12) as an example to illustrate the evaluation of cross ventilation design.

With the unit layout in Figure 12, a CFD model can be established, as shown in Figure 13(a). With the pressure distribution from Figure 11, 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 13. 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 13 are with an outside air temperature of 24^{o}C and a relative humidity of 70%.

The computed results by CFD indicate that the maximum air velocity in the unit, which is less than 1 m/s - a comfortable value for cross ventilation. The air exchange rate varies from 16 ACH on the first floor to a maximum of 40 ACH 2/3 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%, 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. Carrilho-da-Graca et al. [20] has 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 maintaining the building openings 24 hours a day.

5.2 Single-sided ventilation in a building

The building studied is a student dormitory in Cambridge, MA. Single-sided ventilation was evaluated for a typical room that is 4.7 m long, 2.9 m wide, and 2.8 m high. The general room model used throughout the study is shown in Figure 14. 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 released it back to the room air by convection. This study did not include solar gains, 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 14. 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 (see Figure 14(b)). The extension 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 15) 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 15(b) [22]. 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. Using analytical solutions or experimental measurements does 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 [23] have found, for a particular tested room, that wind and stack flow reinforce each other. Our study shows that wind and stack forces do not always reinforce each other. In fact, they oppose each other. This ambiguity is illustrated in Figure 16(a). An example of the counteracting wind and stack effect during an increasing progression of wind speeds is also shown in Figure 16(b).

A counteracting wind and stack flow took place in the middle apartment. Figure 17(a) shows the airflow at the mid-section in the room. The wind force at the upper opening is stronger than the buoyancy force, thereby forcing a clockwise flow into the apartment through the upper opening and out through the lower opening. Since the two forces oppose each other, the ventilation is reduced. As a result, the temperature in the middle apartment is the highest, as shown in Figure 17(b). However, in the upper apartment, the wind is aiding the buoyancy effects by driving air in through the lower opening and out through the upper opening. The room air temperature is the lowest in the building. In the lower apartment, the buoyancy effects are stronger than the wind effects, although the wind tends to push airflow clockwise. The air still flows in from the lower opening and out through the upper opening. The corresponding temperature in the apartment is moderate.

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.

6. Conclusions

This chapter discusses the available methods for designing a building to take advantage of the wind, such as model mockup, wind tunnel, nodal/zonal models, and computational fluid dynamics (CFD). CFD can provide detailed and useful information and is becoming an attractive and popular design tool. The examples illustrate how to collect wind information, develop different strategies for outdoor and indoor environment design, and use a CFD program to conduct the design. The outdoor design aims at developing pedestrian thermal comfort by varying building shape. The indoor design focuses on promoting natural ventilation, a good measure for reducing energy use in buildings and providing better indoor air quality.

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Table 1. Wind effect on people

Beaufort No.	*Description*	*Wind speed (m/s)*	*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 2. Comfort criteria for different frequency (day/year) when wind speed higher than 5 m/s.

Activities	*Acceptable*	*Unpleasant*	*Intolerable*
Walking fast: car-park, 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 3. The potential in using natural ventilation in the U.S.[1]

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 4. A survey conducted in Beijing with respect to the use of air conditioning in homes [19].

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

Figure 1. Surface wind roses in January for Northeastern United States [5].

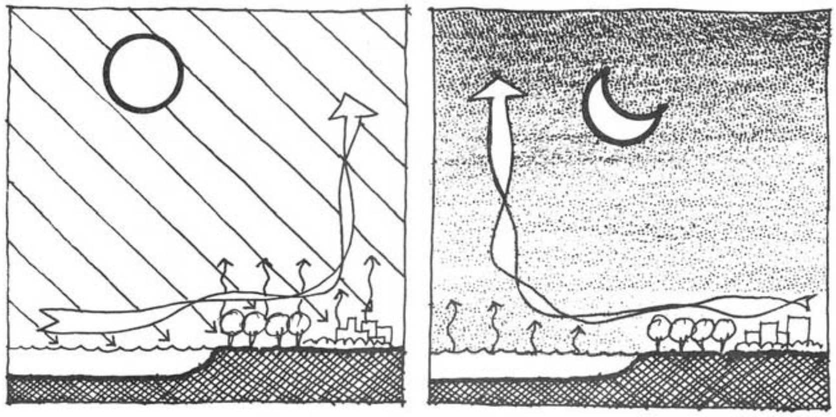

Figure 2. Diurnal and nocturnal air movements near a large body of water [24].

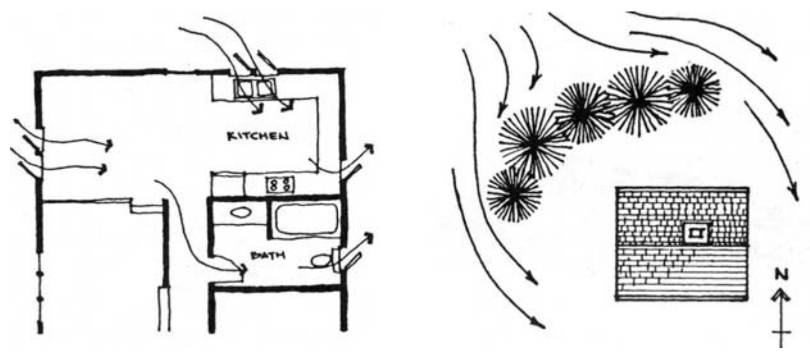

Figure 3. Smart arrows used by architects to predict airflow in and around buildings [24]

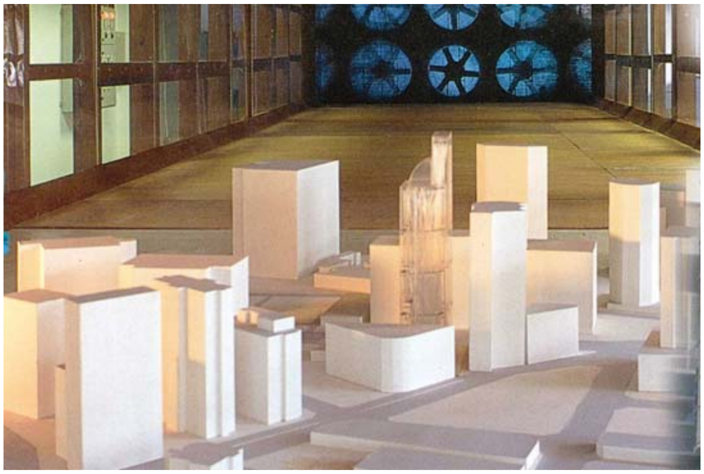

Figure 4. A building site model within a wind tunnel.

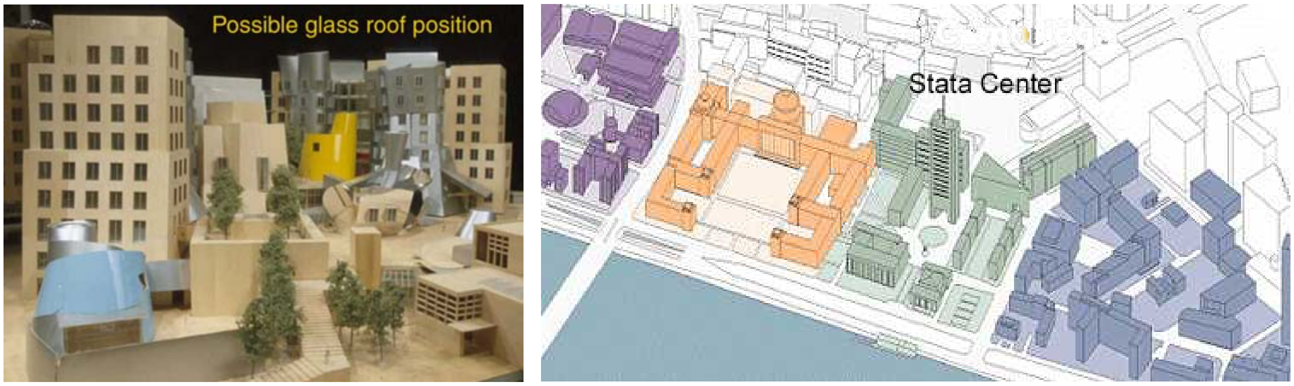

Figure 5. Stata Center (left) and its surrounding (right).

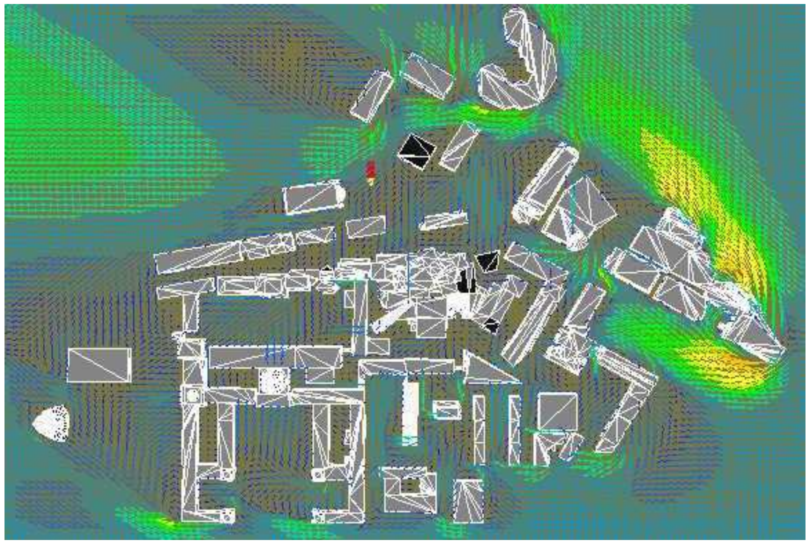

Figure 6. Wind distribution around Stata Center at the ground level (yellow – high wind speed, green – moderate wind speed, and blue – low wind speed).

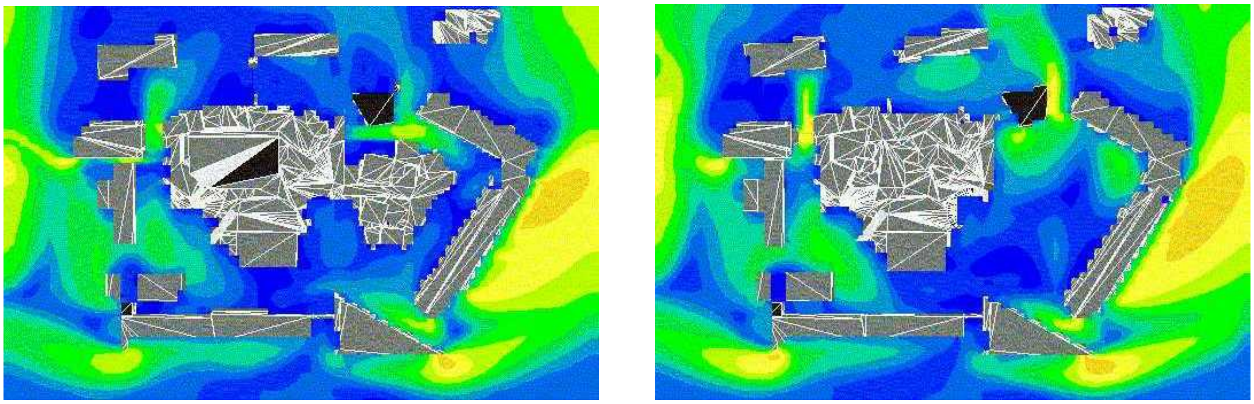

Figure 7. Wind distribution around Stata Center (zoom-in). Left, with a glass roof and right, without a glass roof (yellow – high wind speed, green – moderate wind speed, and blue – low wind speed).

Figure 8. A high rise residential building complex in Beijing

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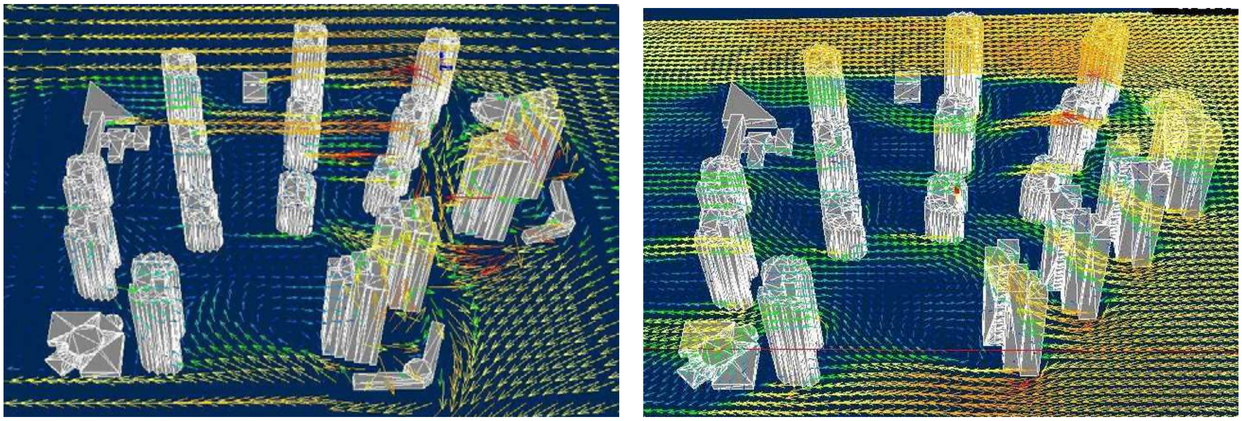
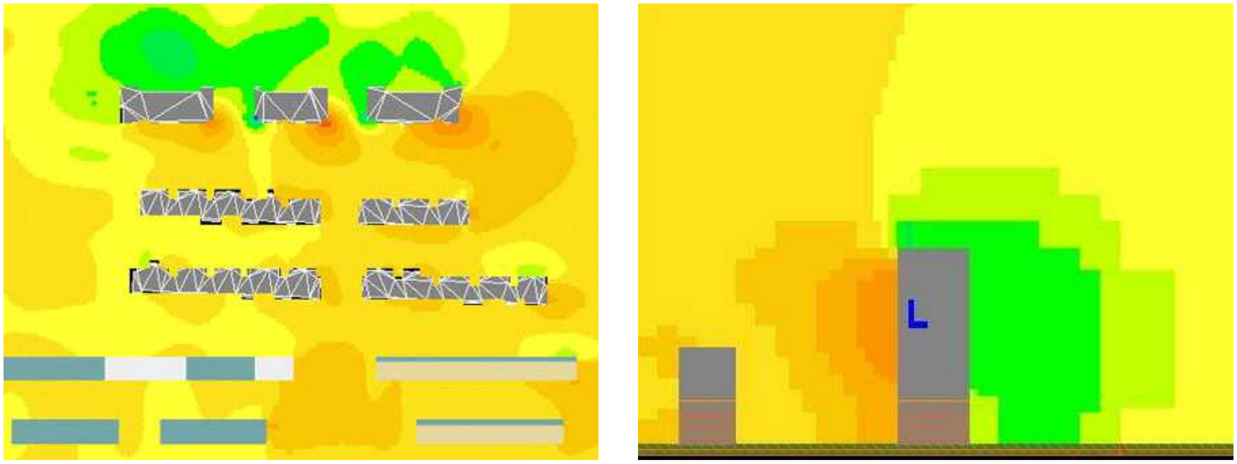


(a) (b)

Figure 9. Wind distribution on the building site, (a) original design and (b) design with four proposed towers to the north.

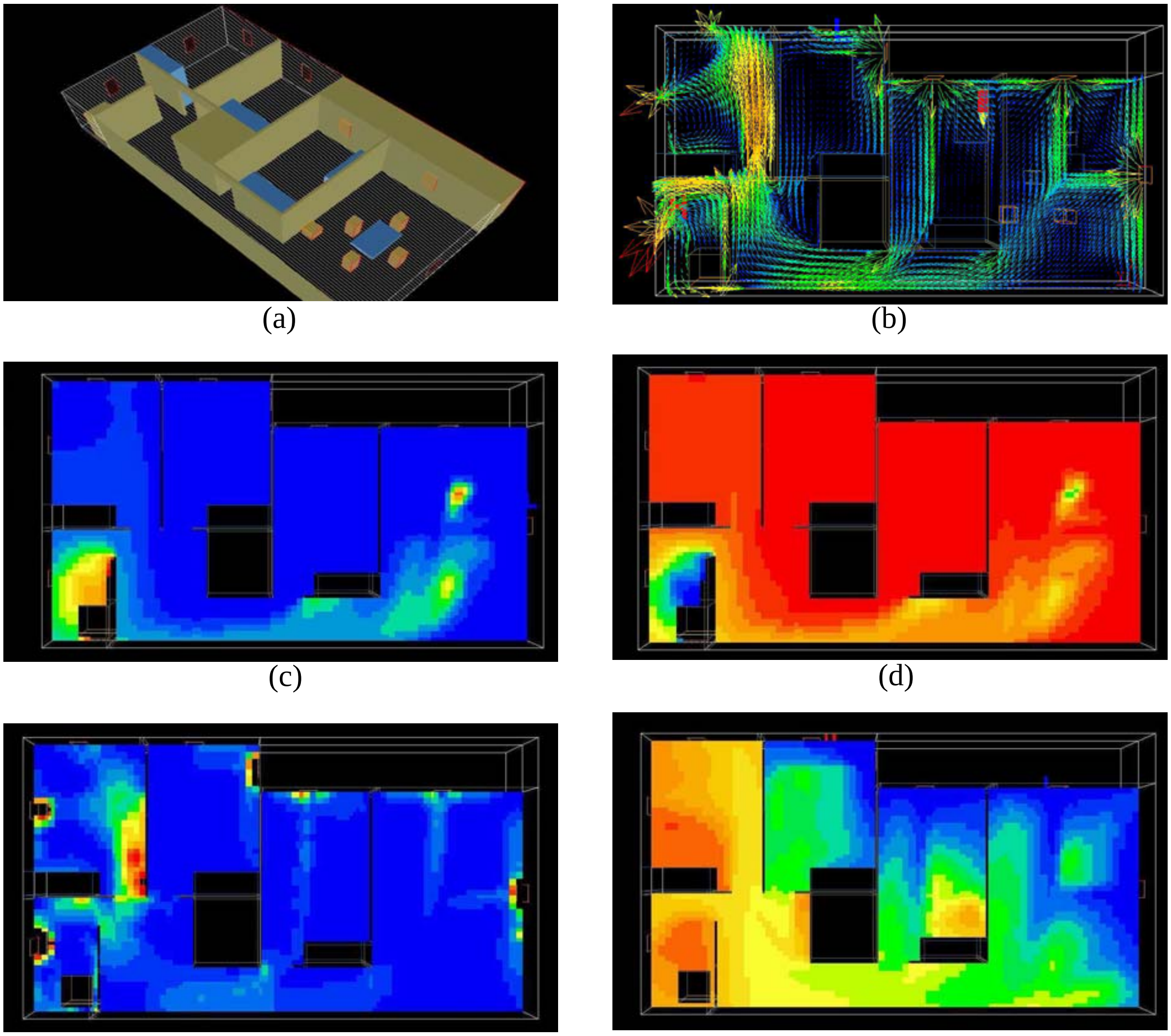
Figure 10. Architectural rendering of the three residential buildings.



(a) plane (b) section (from the east)

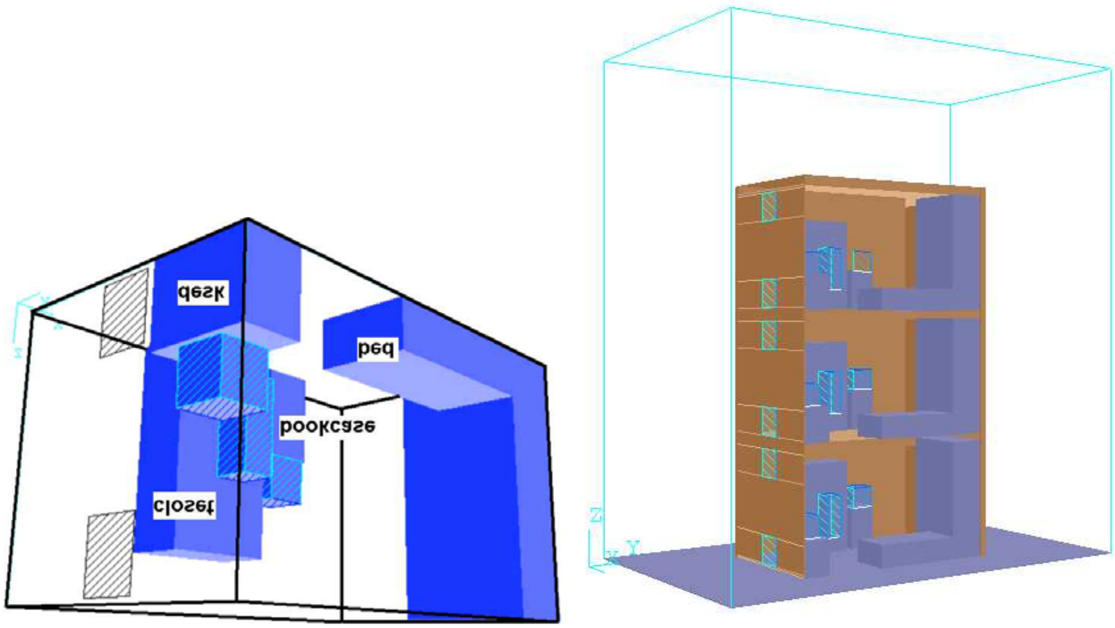
Figure 11. Pressure distribution around the buildings the prevailing winds, Southeast at 3 m/s (red – high pressure, yellow – moderate pressure, and green – low pressure).

Figure 12. Building floor plan.



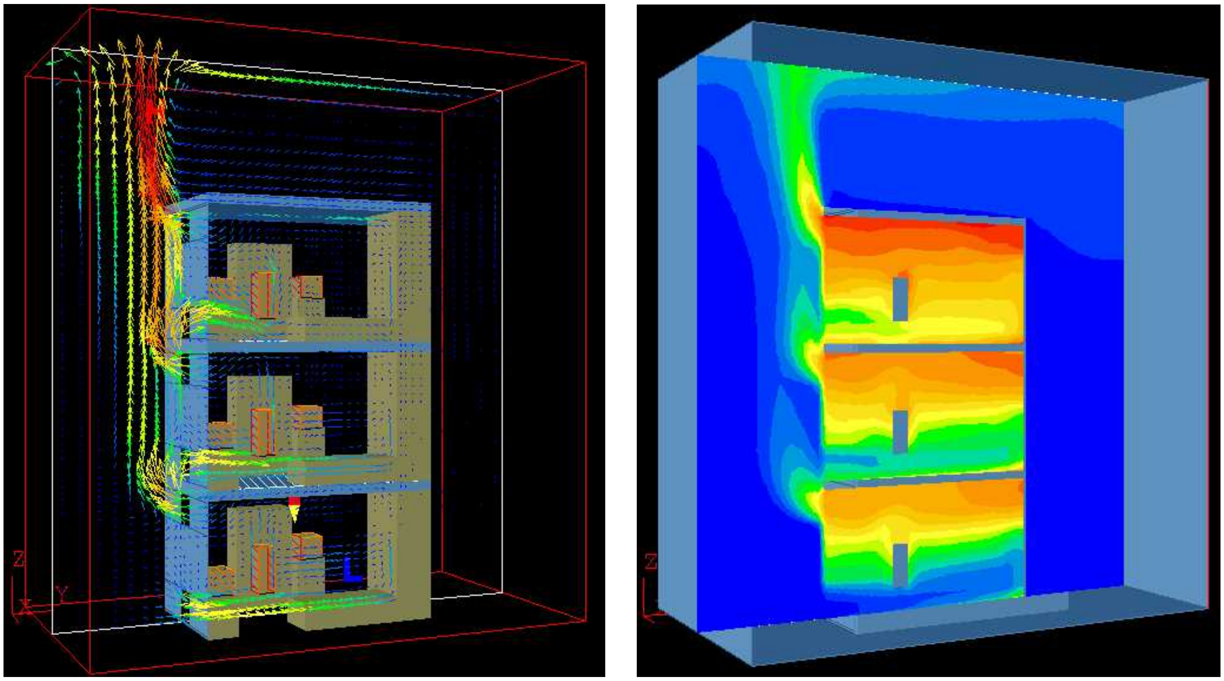
(a) (b) (c) (d) (e) (f)

Figure 13. Cross ventilation performance analysis (red – high, yellow – moderate high, green – moderate low, blue – low). (a) unit model, (b) air velocity, (c) air temperature, (d) relative humidity, (e) Predicted percentage dissatisfied people due to thermal comfort and (f) mean age of air.



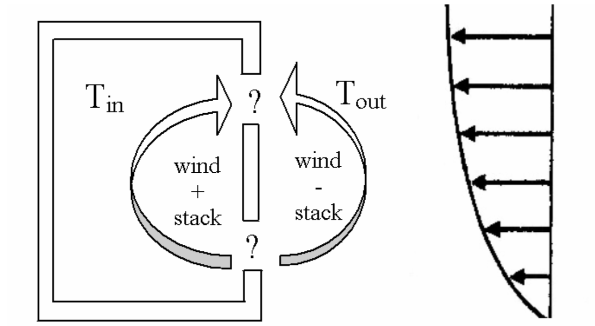
(a) (b)

Figure 14. The CFD model used to study single-sided ventilation in a dormitory room: (a) the room model and (b) the building and environment model.

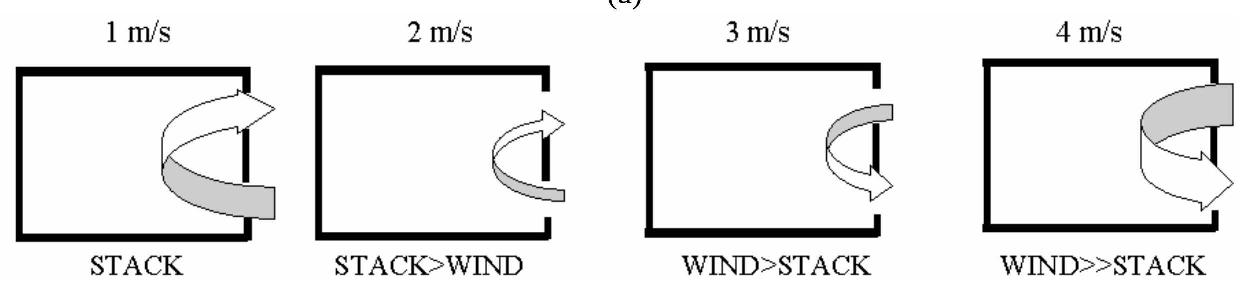


(a) (b)

Figure 15. 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 [22].

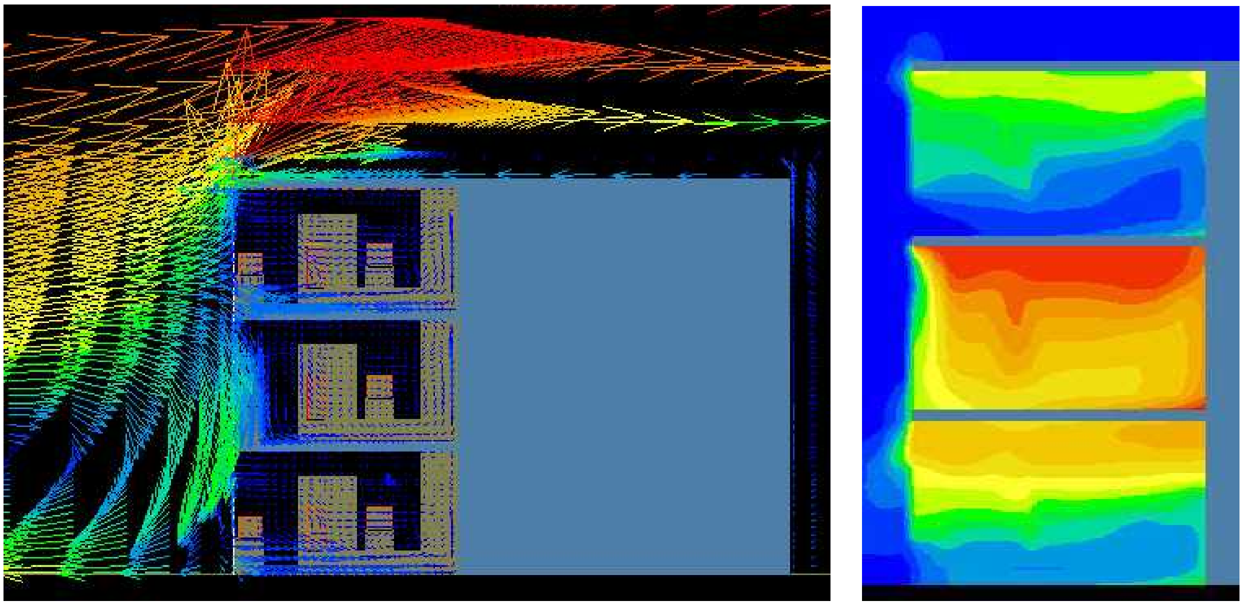


(a)



(b)

Figure 16. Uncertain effects of combined wind and stack forces: (a) reinforcing vs. counteracting effect (b) depiction of counteracting wind and stack effects over a progression of wind speeds.



(a) (b)

Figure 17. 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 [22].