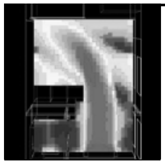

CHAPTER SEVEN

DESIGN OF NATURAL VENTILATION WITH CFD

Qingyan Chen

INTRODUCTION

As the previous chapter demonstrated, if a building is properly designed, natural ventilation can provide both a comfortable and healthy indoor environment as well as energy savings. Most architects and designers know about the principles of passive solar heating and can indicate how they desire small buildings to also take advantage of natural ventilation, as shown in Figure 1. Natural ventilation and thermal comfort, however, are difficult to understand and model, even for simple buildings. It is important that the architects and engineers collaborate early in the design process when key decisions about master planning and building geometry are made.

The present chapter illustrates, using examples from the Sustainable Urban Housing in China case studies, how architects can work with engineers to design a sustainable building. With the help of the computational fluid dynamics (CFD) technique, we suggest a design procedure as follows: First, an architect produces an initial design. Next, an engineer uses the CFD technique to calculate airflows in and around the buildings. Based on the calculated results, the architect modifies the design. Several iterations are often necessary to achieve satisfactory indoor and outdoor environment for the building. Since an architect generally does not have sufficient knowledge of fluid dynamics or numerical skills, the engineer plays an essential role in helping the

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architect obtain the detailed flow information. The engineer, in turn, relies on the architect to make the building comfortable and healthy.

This chapter illustrates this process through the design of a small, naturally ventilated building in Beijing (Beijing City Garden) and the analysis of a building site in Beijing for outdoor thermal comfort and natural ventilation (Beijing Star Garden).

Natural Ventilation Design

Figure 2 shows the location of the six-story (20 meters) demonstration building and its surroundings in Beijing City Garden, Beijing. There is a long, mid-rise building, 40 meters high, to the north and low-rise six-story buildings to the east and south. A wide street runs along the west of the demonstration building. Our design in this case focused on natural ventilation.

The design of natural ventilation in the demonstration building required data on indoor and outdoor airflow distributions. The wind rose in Beijing, as shown in Figure 3, indicated that in the summer the prevailing wind is from north and south. The corresponding mean wind speed is 1.9 m/s. Figure 4 breaks the reference weather data in Beijing into different comfort categories. Although heating is an important issue in Beijing, buildings there also require cooling from June through August. However, the figure illustrates that the period of comfort can be increased substantially, and the level of mechanical cooling reduced, if mean air speed in the building is at least 2 m/s through natural ventilation or internal overhead fans. Indeed, air-conditioning may not be necessary in Beijing if natural ventilation is combined with night cooling. Excess wind speed, however, is detrimental, causing discomfort to pedestrians. In Beijing, winter winds around some buildings can reach speeds of 14 m/s. Considering the low air temperature in the

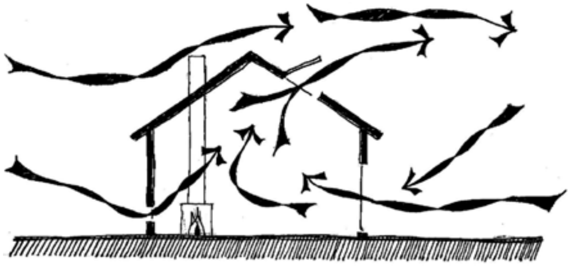


Figure 1 Smart arrows used by architects (Source: adapted from Moore 1993)

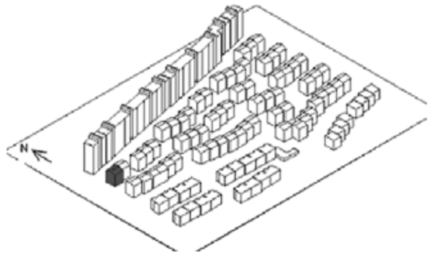


Figure 2 The demonstration building (shaded) and its site (Beijing City Garden)

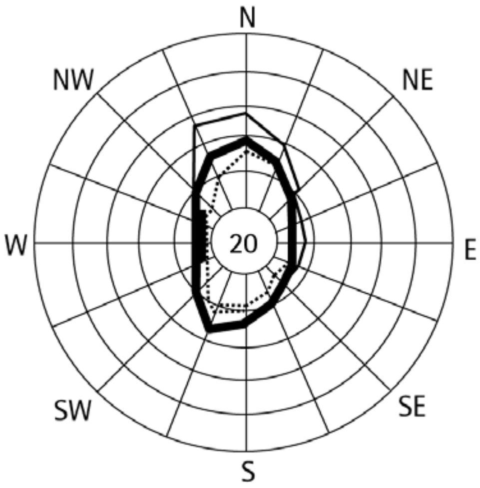


Figure 3 Wind rose for Beijing. Thick solid line: whole year; thin solid line: winter (December, January, and February); dashed line: summer (June, July, and August).

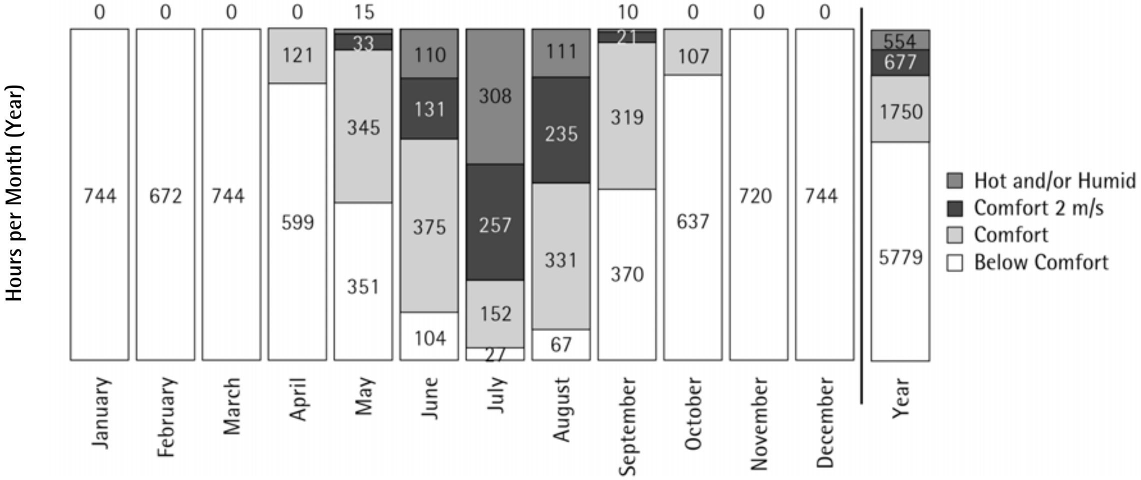


Figure 4 Comfort zones for developing countries (Source: Carrilho da Graça et al 2002)

winter, the chilling effect of this wind prevents pedestrians from walking comfortably and safely.

Using the wind information and building site, a CFD program calculated the airflow around the demonstration building, as shown in Figure 5. When wind was from the north, the air speed around the building was about 0.1 m/s ~ 0.4 m/s, which is too low to support natural ventilation of units. This reduction in air velocity occurs because the building site is in a recirculation zone, created by the tall building to the north. When the wind was from the south, the air speed around the demonstration building was higher but still low, between 0.3 and 0.8 m/s. The small distance between the demonstration building site and adjacent buildings to the south deflects wind before it reaches the building.

Despite these conditions, the design team chose to use the available, albeit low-velocity, wind to provide natural ventilation to the building. Since the design of natural ventilation does not usually increase building construction and operation costs, it is always worthwhile to try to incorporate such systems, when basic climatic conditions will permit thermally comfortable through-ventilation. Figure 6 shows two design schemes for a typical floor of the demonstration building, both designed to allow free passage of wind. This chapter demonstrates how the CFD technique is used to determine the necessary size of the court to the south. The project team expects that the court will increase natural light in the building, create a social space for the building residents, and channel wind from the south for ventilation.

Figure 7 shows the airflow distribution in and around the demonstration building when the wind comes from the south. The separation of detailed airflow information within the demonstration building from the airflow around Beijing City Garden (Figure 5b) reduced computing time significantly. Because wind speed from the south around the demonstration building is 0.3 ~ 0.8 m/s, CFD models of airflow within the building assumed wind from the south at a uniform speed of 0.5 m/s. The model shows that the building layout permits free, easy ventilation of the units. However, court size has no significant impact on the airflow pattern and flow rate. Furthermore, the results suggest that mechanical ventilation or stack ventilation might be needed in order to enhance the ventilation in the building. Chapter 5 documents the impact on thermal comfort of specified air change rates assisted by mechanical ventilation. With an open interior design for natural ventilation, fan power for adequate stack ventilation will be kept to a minimum. These results were important in refining the final ventilation design. See *Chapter 10, Case Study One – Beijing Prototype Housing* for more information.

Outdoor Comfort and Site Planning

A second example demonstrates how architects and engineers can work together to design a comfortable outdoor and indoor environment. Acceleration of airflow among high-rise buildings may create outdoor comfort problems. This study uses the Beijing Star Garden Project as an example of how to design a comfortable outdoor environment.

Because it is mainly the chilling effect of the wind in the winter that causes the outdoor discomfort problem, the design analyzed the airflow distribution on a winter day. The wind rose for Beijing (Figure 3) illustrates that in the winter the prevailing wind is from the north (5° inclined to the west). In a typical year, there are nine days during which the wind speed is higher than 7.6 m/s in Beijing (ASHRAE 1997), and high wind days generally occur in the winter. The present investigation studied a scenario with a north wind of 7.6 m/s for outdoor thermal comfort consideration.

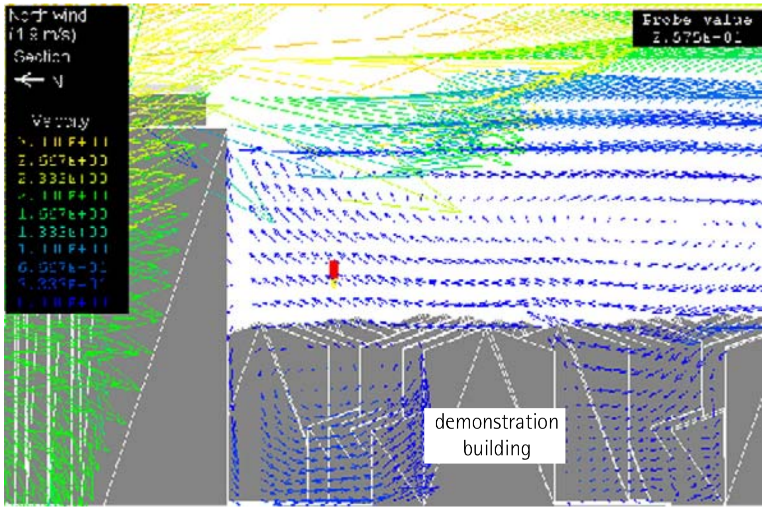


Figure 5a The airflow distribution around the demonstration building section with a north wind; existing tall buildings shown on the left-hand side of the figure

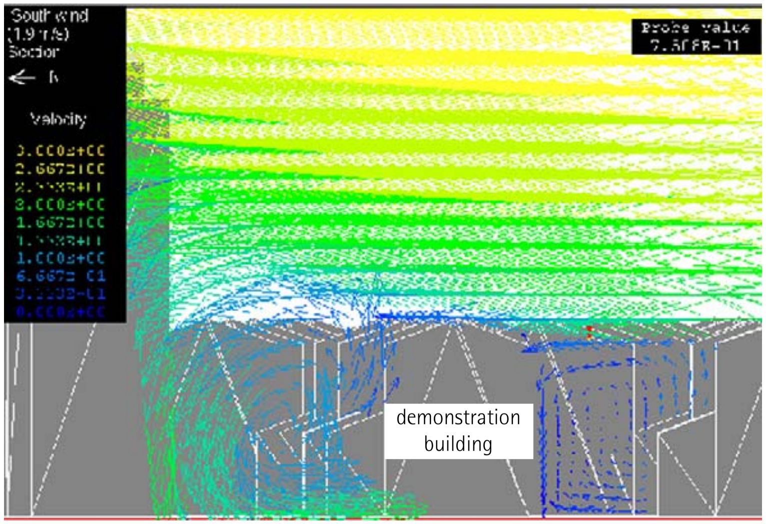


Figure 5b The airflow distribution around the demonstration building section with a south wind; existing tall buildings are shown on the left-hand side of the figure

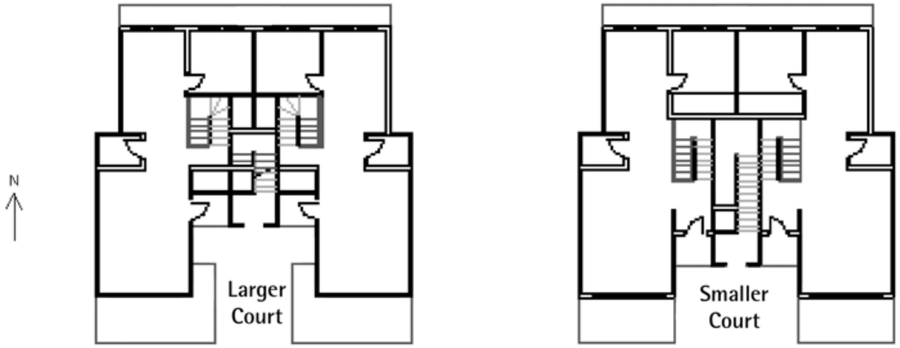
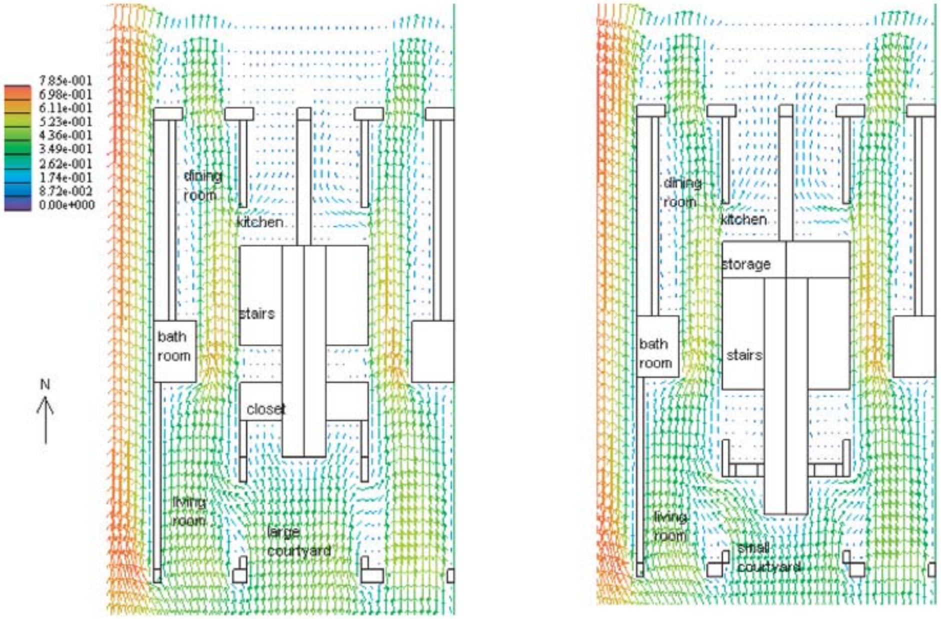


Figure 6 A typical floor plan of the demonstration building with different court sizes



(a) (b)

Figure 7 The air velocity in and around the demonstration building at a height of 1.2 meters above the floor: (a) shows air velocity in the plan with the large court, and (b) shows a similar plan with a smaller court

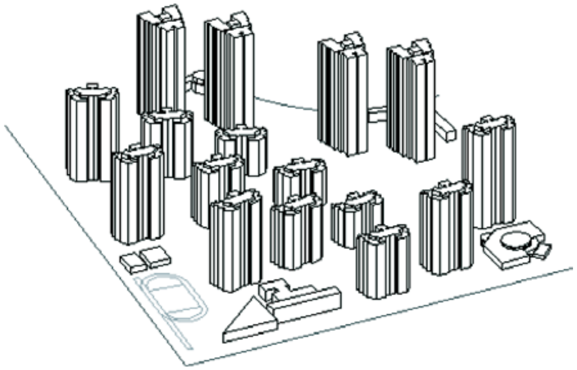


Figure 8a Original design for Beijing Star Garden by an architectural firm (scheme I)

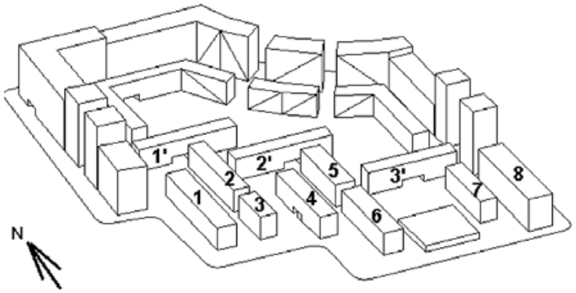


Figure 8b Preliminary redesign for Beijing Star Garden by MIT project team (scheme II)

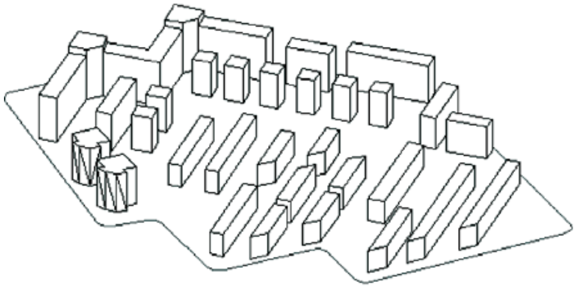


Figure 8c Second redesign for Beijing Star Garden by MIT project team (scheme III)

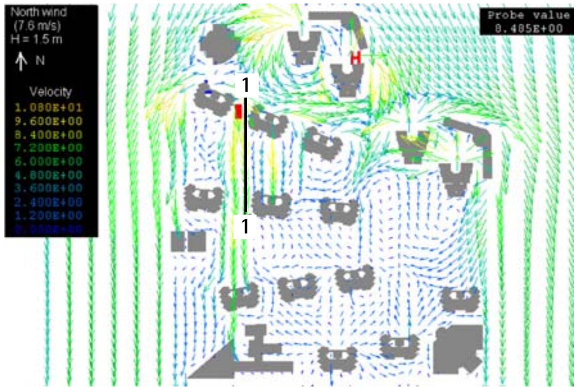


Figure 9 Wind velocity distribution at the height of 1.5 m above the ground around the buildings for scheme I with a north wind (blue - low velocity, green - moderate velocity, and yellow/red - high velocity)

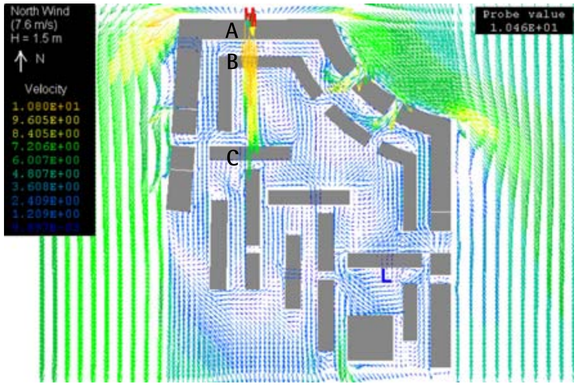


Figure 10 Wind velocity distribution at the height of 1.5 m above the ground around the buildings for scheme II with a north wind (blue - low velocity, green - moderate velocity, and yellow/red - high velocity)

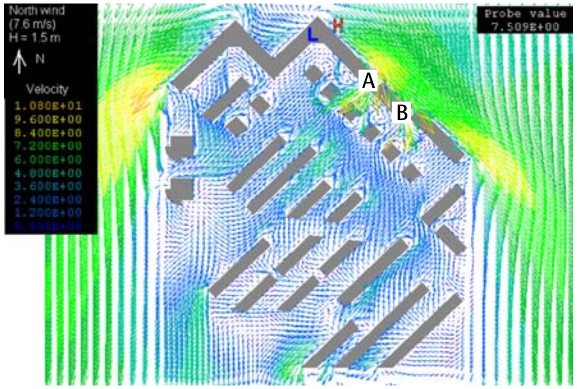


Figure 11 Wind velocity distribution at the height of 1.5 m above the ground around the buildings for scheme III with a north wind (7.6 m/s) (blue - low velocity, green - moderate velocity, and yellow/red - high velocity)

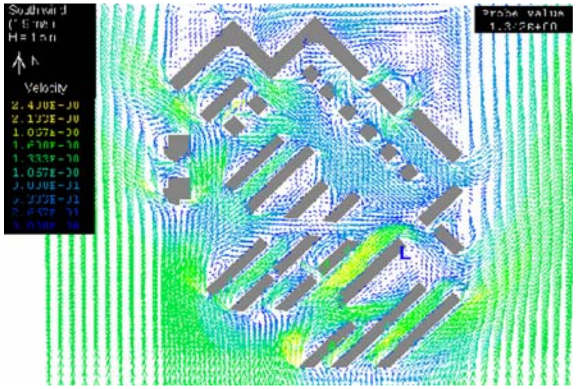


Figure 12 Wind velocity distribution at the height of 1.5 m above the ground around the buildings for scheme III with a south wind (1.9 m/s) (blue - low velocity, green - moderate velocity, and yellow/red - high velocity)

Figure 8a shows the developer's original site design (scheme I). The design for scheme I consisted of sixteen high-rise buildings ranging from 33 to 90 meters high. This chapter presents the wind speed distribution at the height of 1.5 meters above the ground to evaluate pedestrian comfort (Figure 9). The wind speed at section 1-1 is around 8~9 m/s (grade 5), too high to be accepted even for a short stay in the winter. The linear arrangement of the buildings permits wind to pass freely. The CFD calculation also shows that at a height of 30 meters, the wind speed among most of the buildings is 9~10 m/s, and at a height of 70 meters, the wind speed is above 12 m/s (grade 6). The high wind speed leads to excessive infiltration in the winter and difficulties in using the wind for natural ventilation in the summer. Therefore, the MIT team made recommendations to the developer that the building site should be redesigned, and the height of the buildings should be reduced.

Since the CFD calculations showed that the height of buildings in design I causes a serious discomfort problem, the MIT design team produced schemes II and III (Figures 8b and 8c) with the following features:

- lower overall building height (building heights range from 20 to 60 meters in scheme II, and from 20 to 50 meters in scheme III) to reduce winter infiltration and to provide opportunity for summer natural ventilation, without compromising the population density; and
- protection from the north wind in the winter by using relatively high buildings in the north.

Figure 10 shows that scheme II reduces the discomfort problem greatly, but problems remained. For example, in entrances A, B, and C, the wind speed was very high because of the linear arrangement. Staggering the entrances could easily solve this problem. A number of other issues needed to be carefully examined. For instance, natural ventilation in the summer may not be effective in scheme II. As shown in Figure 8b, more than half of the buildings have a long side facing east or west. Since the prevailing wind in the summer is from the south in this site, the buildings with the long side facing east or west may not take advantage of natural cross ventilation. In addition, the orientation was not good for passive heating design, and it was difficult to shade the building from the strong solar radiation in the summer.

Based on the results for scheme II, the MIT team designed scheme III. The low-rise buildings were now tilted 45°, with the long side facing southeast and northwest. In scheme III, both outdoor thermal comfort and natural ventilation were considered. When studying the outdoor thermal comfort, the incoming wind was set to be 7.6 m/s from the north. Figure 11 shows the wind distribution for scheme III for evaluating pedestrian comfort. The high-rise buildings on the north side can block the high wind from the north. As a result, the wind speed in the site is low. While wind speeds at points A and B were high, these are vehicular entrances that will not affect pedestrian comfort.

Since the high-rise buildings were used to block the wind in the winter, it is hard to use north wind for natural ventilation in the summer. In Beijing, protecting pedestrians from the cold winter wind was more important than utilizing natural ventilation in the summer. However, it was feasible to use south wind for natural ventilation. The mean wind speed in the summer from the south is 1.9 m/s. With such a wind speed, Figure 12 shows that the wind speed around most of the buildings at 1.5 meters above the ground is above 1.0 m/s. This wind speed is sufficiently high for natural ventilation. The tilted building arrangement helped to introduce more wind into the site. Furthermore, the staggered arrangement prevented the front buildings from blocking winds. Therefore, scheme III provided good outdoor thermal comfort and potential to use natural ventilation. Note that scheme III was not the final design. In addition to the ventilation studies shown in this chapter, the design team studied other important issues, such as sun availability, natural lighting, and energy in buildings. See *Chapter 11, Case Study Two – Beijing Star Garden* for more information.

SUMMARY

This chapter shows how engineers can use CFD to help architects design natural ventilation in buildings and zones of thermal comfort around buildings. With the help of the CFD technique, engineers can calculate the airflow distributions in and around buildings, and architects can use the resulting information to modify their designs.

The CFD technique allows engineers to quickly and inexpensively analyze airflow in and around buildings. The information can help architects to design buildings that can be more effectively ventilated in summer and that can avoid strong outdoor wind in winter to achieve better thermal comfort. This chapter describes two examples of building design with CFD, one for natural ventilation and another for outdoor thermal comfort. The step-by-step design procedure shows the usefulness of CFD and how engineers and architects can work together to achieve better building design.

In the natural ventilation design, the results showed that the wind direction and building site information were most crucial for the ventilation rate, while the court size was not as important. In the case of outdoor thermal comfort design and site planning, the results indicate that one can improve the design by building shape and orientation. However, other factors, such as solar availability, should also be considered to obtain a sustainable design.

Several iterations may be necessary to design a building with satisfactory indoor and outdoor comfort environment. This design procedure, undertaken by a team of architects and engineers at MIT, shows that the CFD technique is a very useful tool for building design. This kind of cooperation between architects and engineers is necessary to design good buildings.

Although the CFD technique has great potential for building design, it is time consuming. To mitigate this, the architects and engineers on a project should review initial designs based on their experience and knowledge. This discussion will reduce the required number of iterations significantly and can speed up the design process. The CFD technique should be used only to evaluate a few, final design alternatives because of the difficulty of performing the analysis.

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