Sustainable ventilation strategies in buildings: CFD research

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Highlights

- Sustainable ventilation strategies are analysed for school buildings
- Air change rate can be enhanced 40% via stack ventilation.
- Stack ventilation also provides promising decrease in indoor air temperature.
- CO_2 concentration in sustainably ventilated dorms is 800 ppm at 6:30am.
- CO_2 concentration in ordinary dorms is 1800 ppm, which is undesired.

ABSTRACT

Developing technology and architectural design techniques have affected the field of architecture to a great extent. As a result, human comfort has become increasingly important in recent years. A natural ventilation cooling strategy which serves as the alternative to the air-conditioning system has been effectively employed in high-rise office buildings in western countries. This paper discusses the possibility of using natural ventilation strategy in school buildings. It evaluates some of the key issues associated with natural ventilation design and school buildings, including its the types, its working principles and limitations of passive ventilation, its effects and forms of natural ventilation when used in libraries, offices, auditoriums and dormitory buildings. This work also evaluates and how does the effects of architectural design on the passive ventilation such as orientation, depth of room, the atrium and solar chimney. Based on case studies on Queens building at De Montfort University, Liberty tower of Meiji University and simulation regarding ecological dormitory building in China. These three buildings have been selected to operate as simultaneously in different climatic and thermal comfort conditions. It is concluded that single-side ventilation and cross-ventilation can have good effect on cooling and improving air quality in school buildings with different functions as long as the height and

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depth of rooms are properly designed. Solar wall and solar chimney can also be employed to enhance natural ventilation performance based on the principle of stack effect.

Keywords: Natural ventilation, school buildings, wind-driven ventilation, stack effect.

1. Introduction

The achievements of environmental comfort are highly associated with the provision of fresh air and the impact of harmful gases, heat and particles that scatter in every corner of the room [1]. Indoor contaminants can be classified as follows: moisture, heat, chemical pollutions and other gaseous substances. High relative humidity results from indoor human activities such as cooking and drying [2,3]. Rooms get too warm due to the particular activities of occupants, the use of household appliances and solar radiation. Besides, tobacco smoke has been considered as the most detrimental indoor chemical contamination. Diverse volatile poisonous gases emitted from furniture, interior decoration, construction materials and home appliances are also potential sources of pollution [4]. Apart from this, the existence of carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO) and ozone (O_3) destruct the indoor atmosphere as well. CO_2 is exhaled by users and accumulated in spaces with inadequate ventilation, which leads to headache and reduction in work efficiency [5]. CO is basically generated by smoking or incomplete combustion. The use of photocopying machines or laser printers inevitably leads to the higher level of O_3 [6].

The annual utilization of fossil fuels occupies approximately 80% of global energy consumption [7] and the building sector uses up to 40% of fossil fuel [8-12]. The environmental problems such as global warming and urban heat island effect remind the significance of energy conservation and environment protection [13,14]. Heating, ventilation and air-conditioning (HVAC) systems constitute a significant part of energy consumed in buildings [15]. Ventilation demand in dwellings has a remarkably rising trend as a consequence of enhanced comfort conditions of residents [16]. Although mechanically ventilated systems are widely used in buildings for achieving thermal comfort through a conventional way, the overuse of these systems results in excessive energy consumption and air-conditioning syndrome [17]. As for architects, some promising passive cooling strategies are developed and utilised in contemporary constructions especially over the last two decades [18-22].

Nocturnal radiation cooling that uses the sky as a heat sink has convincing performance in controlling the indoor environment in dry regions with obvious diurnal temperature range [23]. High emissive paints help to reduce the indoor temperature below surrounding environment. When the surface temperature of envelope is lower than the environment, the convective heat transfer effects are weakened. The experimental research conducted by Lee et al. [24] reflects that building in Hong Kong (humid and hot region) save 12% energy in cooling demand compared with 77% energy saving in Lanzhou and 62% in Urumqi (semi-arid region). It is also pointed out that the floor of the building is required to be restricted since the cooling demand dramatically rises with the increasing of occupants. Besides, the comparatively large roof is needed for radiator installation and the working period of the whole system is constrained within 11 hours per day. Geothermal cooling regards the earth as a heat sink. Bharadwaj and Bansal [25] report that the earth temperature fluctuation reduces with depth and eventually disappears at the depth of 4 metres, the earth temperature below 4 metres is stable for the annual variations. This technology can be employed to achieve annual thermal comfort by using earth shelter or earth tunnel cooling. The simulation on earth shelter cooling carried out by Anselm [26] reveals that the indoor air can be warmed up by warmer soil in winter and chilled by cooler soil in summer.

Besides, earth-tube heat exchangers also play a key role in avoiding overheating in summer and overcooling in winter, according to the experimental study by Sharan and Jadhav [27]. However, potential limitations can also be easily identified when geothermal cooling strategies are used in school buildings. In earth sheltering, a part or the whole building is buried underground, which causes problems like moisture penetration, mould formation, poor ventilation and high external load. As for earth tunnel cooling, in regions where cooling load is high, the earth temperature near pipes increases, and affects the performance of the whole system. Other relevant parameters influencing the system performance can be reported as depth, length and size of pipe, air inlet temperature, velocity and thermal conductivity of soil. Apart from cooling by using a natural heat sink, thermal insulation achieves comfort by reducing heat transfer. Despite the fact that thermally insulated materials have good performance in flame retardation and efficiently decreasing the structural temperature fluctuation, noise and operation cost, the volume of insulation material is large, and the emission from materials in fire accident is detrimental [28].

Based on the literature review, a number of problems are identified as possibly being associated with those passive cooling strategies if they are used in school buildings. Firstly, the performance of these systems fluctuates dynamically in different times and seasons. Secondly, despite the fact that they are environmentally friendly and have cooling effects, moisture and gaseous contaminants removal abilities of these systems are not good enough. Thirdly, the strategies maintained above would be highly dependent on the environmental conditions, site characteristics and building types. Under these circumstances, natural ventilation design would be a better choice for school buildings than systems above, which successfully mitigates noise and provides a healthier and comfortable environment for staffs and students, therefore enhancing their productivity. Research conducted by Loftness et al. [29] on naturally ventilated buildings reports an annual productivity improvement of 3-18% in office buildings. Besides, the employment of natural ventilation reduces energy consumption, maintenance and working costs of mechanical equipment and spaces for equipment installation. Apart from this, particular airflow can be provided by natural ventilation design to keep the pollution level below maximum permitted concentration level as shown in Figure 1 [30]. This paper aims to evaluate of using natural ventilation in school buildings with regard to its working principles and limitations of passive ventilation, its effects and forms of natural ventilation. For this purpose, computational fluid dynamics (CFD) method is preferred as analysis strategy to investigate examine whether the ventilation vents help to induce effective cross ventilation. The architectural methodology section includes the effectiveness and forms of natural ventilation strategies used in Queens building at De Montfort University, Liberty Tower of Meiji University, and discuss how the architectural components such as solar chimney and ventilation ducts affect the effectiveness of passive ventilation based on simulation about sustainable dormitory building in Jinan, China. The conclusion section analyses the types, working principles and limitations of natural ventilation strategies being possibly used in school buildings.

As can be seen in Figure 2 [31], the amount of energy used in space cooling constitutes an important part of the total energy consumed in both residential and commercial buildings. As an innovative aspect of our study, we can say that the amount of energy used for space cooling can be decreased by using natural ventilation instead of mechanical ventilation in buildings.

2. Research methodology

Comfort describes the degree to which occupants can more concentrate and avoid being disturbed or influenced by noise, odour, overheating and overcooling indoor atmosphere. There are several necessary characteristics and requirements for sustainable school buildings in terms of optimum comfort level. The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) standard 55-2004 points out that comfort is the condition of spaces in school buildings which can be accepted by 80% of users. People with different ages have different tolerances, under this circumstance, the condition of spaces needs to be generally understood by students, maintenance and operation staff [1]. Potential factors affecting the comfort in school buildings are considered as relative humidity, temperature, airflow velocity, noise, odour and CO_2. Considering the fact that majority passive systems merely emphasize on cooling effect, but neglect the consequences generated by indoor stale air to a great extent, natural ventilation strategies might serve as a more reliable and promising solution to achieve thermal comfort in school buildings.

3. Case studies

3.1. Liberty Tower of Meiji University

3.1.1. Climatic conditions

Liberty Tower of Meiji University is located in Tokyo, Japan, with the climates being characterised by hot, humid summers and mild winters with the rare snowy weather. The daytime temperature typically reaches 30 °C during the summer seasons which reduce to 23 °C at night. Winters are a lack of snow and generally warm, fluctuating around 10 °C at daytime with a night-time low of 3 °C. January is depicted as the coolest month while June and September are characterised as rainy and typhoon seasons respectively with excessive humidity [32]. Detailed climatic features of Tokyo are illustrated in Figure 3 [33].

3.1.2. General background and design details

The tower is generally rectangular in plan, with four identical semi-circular structures at each corner of the building which contain stairwells and service rooms. The wind floor (18th floor) with openings on four sides effectively remove hot, waste air coming from escalator voids that located in the middle of each floor and serve as vertical 'wind core' through the stack effect. Liberty tower and the working principle of wind voids are illustrated in Figure 4.

3.1.3. Natural ventilation strategies considered in Liberty Tower

Wind pressure and stack effect are all employed in natural ventilation strategy to drive air in and out of the Liberty Tower. The typical plan showing stack ventilation and the wind floor plan with cross ventilation are shown in Figure 5. The automatically controllable vent is installed on the base of each single glazing unit that used in all the lecture rooms that located on the southeast facade and classrooms on both sides. In this situation, this ventilation design does not have the necessity of opening windows so as to minimize the noise disturbance from surrounding environments and simultaneously guarantee the entry of fresh air even when the blinds are closed and multimedia projectors are used.

The fresh air that enters through openings of single-glazing, passes through lecture and classroom spaces and eventually be exhausted from dust returns on the ceiling to wind voids where the central escalator is. Space for escalator functions as a vertical path for waste, hot air in lecture rooms according to the principle of buoyancy effect. The air ascends and eventually extracted from wind floor (18th floor) owing to the fact that the hot currents flow upwards. The wind floor supplies the uplift for air that exhausted from wind voids and horizontally induces the entry of fresh air through the vents of windows on perimeters. The wind floor opens to external environments in four directions, which provides four wind paths and guarantees the stable airflow of wind floor in different seasons with the changeable prevailing wind. In the wind floor, three V-shaped glass screens that considered as wind fences surround the wind cores and effectively prevent the waste air coming from wind void from being interrupted by new air. A graduate school that is located between floors 19-23 are connected by an atrium near elevators. The air coming from each floor is induced and exhausted from vents in the upper section. Ventilation vents and the typical classroom with exhausting vents mounted on ceiling are depicted in Figure 6. The effects and working principles are similar to those of wind voids mentioned.

3.1.4. Secondary data description

The CFD simulation is conducted to examine the effectiveness of natural ventilation affected by diverse architectural components. The simulation about airflow in wind floor reveals that fresh air entering through openings flows at a steady rate everywhere without significant reduction except for the location of obstacles as ‘wind fence’. The simulation also reflects that air change rate in lecture and classroom spaces increases by approximately 40%, which demonstrates that wind floor and wind voids play essential roles in inducing air from windows on the perimeters. Apart from simulation, an experimental analysis is also employed in Liberty Tower to check the actual ventilation conditions when the building is occupied. Indoor and outdoor temperature, humidity, airflow rate and energy consumption of equipment are measured by 2000 sensors automatically for every 10 minutes.

The results reveal that the wind floor promotes the natural ventilation in occupied spaces, and is generally in line with the results of CFD simulation. For instance, as it is shown in an experiment carried out by Chang et al. [34], the air change rate in a north-facing room in 6th floor is enhanced from 0.5-0.7 per hour when the wind floor is closed to 4.6-5.5 per hour when it is occupied. However, rare exceptions do exist in the tower, the rate of north-facing rooms in 11th floor decreases from 3.2 to 2.1-2.4 per hour, which do not impact the overall performance of the whole building. Apart from the promotion of ventilation, these strategies effectively reduce cooling energy consumption by 40% in April, 62% in November and 55% in July. The sustainable building annually saves 55% cooling and heating energy compared with typical Japanese buildings that mechanically ventilated by air-conditioning systems. The view of the exhaust openings at the top of the escalator void on the wind floor is given in Figure 7. One of the three wind fences in the foreground protects the openings from cross winds in the wind floor [35].

3.2. Queens building at De Montfort University

3.2.1. Climatic conditions

In Leicester, the summers are short, partly cloudy and comfortable, and the winters are long, windy, very cold and mostly cloudy. Over the course of the year, the temperature typically varies from 1.7 to 21.1 °C and is rarely below -3.3 °C or above 26.7 °C. The cool season usually lasts four months, from November to March, with an average daily high temperature below 9.4 °C. The coldest day of the year is seen in February, with an average low of 1.7 °C and high of 6.7 °C [36].

3.2.2. General background and design details

The east part of Queens Building is an electrical laboratory, which is composed of main entrance atrium surrounded by two four-storey buildings that house the computer laboratories of electrical engineering department with high heat gain emission. The floor plan is narrow as approximately 6 metres, which suggests that the building can achieve cross-ventilation if openings of both windward and leeward facades are large enough. The west part of Queens Building is a mechanical laboratory. The major part of the building is a double-height mechanical hall with controlling rooms on both sides. Some smaller-sized rooms situated on the ground and first floor adjacent to the mechanical hall is employed for particular mechanically engineering use. Two air-handling units are installed to promote ventilation because of the special properties of the rooms. The central part is the most significant space of the building reflecting the effectiveness of natural ventilation strategies. In the north part, two lecture rooms are situated below double-height 150 seated auditoriums on the first floor, the second-floor functions as drawing room mainly for utilizing top and northern light. Classrooms are located on the ground floor of the south part below the double-height comprehensive laboratory in the first and second floor, staff-rooms are settled on the third floor. The two parts are separated by full height and top lighting atrium with an air corridor connecting the north-facing drawing room and the south-facing staff-rooms. The external view of the Queens Building and the section perspective of the central building are shown in Figure 8.

3.2.3. Natural ventilation strategies considered in Queens Building

Owing to their narrow plan, the electrical laboratories can achieve the effective cross ventilation by manually opening windows on windward and leeward side. The classrooms on the ground floor and the comprehensive laboratory on the first floor of the central building which opens to the external environment on one facade are all cross-ventilated. The fresh air enters through external windows and exhausts through stacks or skylights. As for the natural ventilation design of auditorium, the central problem lies in the fact that occupants need to be prepared for the most natural environment with the apparent increase of temperature in summer and noise interference generated by traffic. In this situation, it is difficult to meet the thermal and acoustic environment standards in those rooms supported by air-conditioning.

The section shows how natural ventilation operates in Queens Building. Fresh air enters through openings on the street facade, passing through motorized volume control dampers and an acoustically lined plenum, eventually being distributed by voids suspending under the seats. Coming out from finned heating tubes under seats, the air passes through a grille made of aluminium mesh. Importantly, there are no air filters along the air path not to cause disturbance and interruption for fresh air. After being heated by occupants, lighting and equipment in the auditorium, the hot, waste air is ultimately exhausted from automatic windows at the top of stacks with a slight overhanging at the top that prevents rainwater from entering.

3.2.4. Secondary data description

Indoor thermal testing involves salt water modelling and computer modelling. In saltwater modelling, when the organic glass model of the auditorium is constructed and submerged into water, dyed salt solution injected into the model and the resultant water flow patterns are recorded and analysed. The density of salt solution represents the heat gain of interior spaces. However, the major shortcoming lies in the fact that organic glass modelling fails to consider the thermal inertia of building materials. Besides, De Montfort University also employs computer simulation for performance assessment. In the simulation, 10 litres fresh air per person per second is prepared within the scope of odour control for a particular external day with a temperature of 25 °C maximum, 13 °C minimum and 19 °C average. The result of the simulation is comparatively conservative as it merely takes temperature difference into consideration without wind pressure, which reflects that the indoor temperature will not exceed the outdoor environment by 4-5 °C.

Building management system (BMS) records the temperature data by sensors. The results reflect that the indoor temperature enhances slowly with increasing of external temperature and is approximately 8 °C less during the external peak, which is significantly better than the results of simulation and calculation. Besides, when the dampers are open, the internal environment is warmed by less than 1°C in three hours and remains comparatively cool during the external peak [37].

3.3. Sustainable dormitory building

3.3.1. Climatic conditions

The sustainable dormitory building is located in Jinan, Shandong province, China. It is a place where has a temperate and monsoonal climate with four clearly distinct seasons. The temperature in Jinan reaches minus 5-10 °C in winter and 35-39 °C in summer.

3.3.2. General background and design details

The plan of ecological dormitory building with east-west orientation is similar with that of common dormitory buildings in university, which makes it easier to analyse and compare the technical parameters and ventilation performance between different buildings so as to show the strength of natural ventilation. All toilets of north-facing and south-facing dorms in common dormitory buildings attach to external walls and exchange the air by opening windows in closed balconies, however, the layout obviously decreases the size of external windows and affects the effectiveness of daylighting and natural ventilation. The sustainable dormitory building with 3D view is illustrated in Figure 9.

In the ecological building, firstly, the bathrooms of south-facing rooms are moved to the north and adjacent to the central corridor in order to promote the ventilation and daylighting. In this situation, bedrooms and study areas receive more natural light and wind when the sizes of external windows become larger. Secondly, 0.9×0.9 m ventilation vents are installed above the doors of all dorm units, which provide the cross ventilation and natural cooling effects in spring, summer and autumn. Thirdly, the solar chimney, which is made of dark-coloured metal construction material and connects with a central corridor, is employed to promote ventilation based on buoyancy effect. The air in the chimney is heated and eventually extracted through vents at the top when the metal material is exposed to the sun. When the external windows of south-facing and north-facing dorms are open, air passes through vents and central corridor, enters and exhausts through the solar chimney. In the daytime, the fixed windows on the western wall of solar chimney help to guarantee the daylighting of the corridor. In the evening, fresh air coming from the external environment enters and cools the main structure when the windows are open. The layouts of ordinary and sustainable dormitory are shown in Figure 10 whereas the section views are given in Figure 11. The solar chimney considered with the working principle is illustrated in Figure 12.

3.3.3. CFD simulation results

CFD simulation is used to respectively check the effectiveness of solar chimney in the promotion of stack ventilation, and examine whether the ventilation vents help to induce effective cross ventilation. Permanent opening vents of the windows in external walls with the heights of 0.5 metre are situated 0.5 metres above the floors from the ground floor to the fifth floor, while the same-sized openings in internal walls are situated 0.5 metres below the ceilings. Besides, the ceilings and glazings of each floor are 0.3 m and 0.1 m thick, respectively. The solar chimney extends the roof for 5.5 metres with a slightly overhanging that used to prevent the rainwater entering. The external temperature in CFD simulation is considered to be 23 ^{o}C during the daytime. Equivalent internal heat gains for convective heat transfer on the floors of the dorms are 40 W//m^2 and solar heat gain on the inside surface of the solar chimney is 44 W/m^2, respectively. Considering the restriction of computer software (CFD simulation) and computer laboratory, a three-storey model with stacks is developed in CFD to represent the dormitory building although the ecological dormitory is a six-storey building.

The contours of static temperature and the velocity vectors in stack ventilation from the CFD analysis are illustrated in Figure 13. The static temperature of interior spaces for dorms decreases from 36 ^{o}C in floors to 22 ^{o}C in ceilings, which is comparatively cooler than space in the solar chimney since the direct sunlight heats its dark-coloured metal external wall. The temperature of the air near openings in both external and internal walls is determined to be 25 ^{o}C, which is slightly warmer than average temperature of air (23 ^{o}C). Besides, when the surrounding environment is involved, the air temperature in solar chimney increases significantly from bottom to the top. The velocity distributions show that cool air that enters the openings at a lower position of external walls is heated, rises and eventually goes back or enter the solar chimney with the velocity of 0.489 m/s through the vents at a higher position. The heated air in solar chimney rises and is exhausted through the openings at the top with the velocity 0.415 m/s through the stack or buoyancy effect. It is reported in literature that the solar chimney operates as passive cooling by promoting natural ventilation when the outdoor temperature is comparatively lower. In tropical regions where the outdoor temperature is competitively higher, the solar chimney functions as thermal insulation by decreasing heat absorption. However, when the wind-driven ventilation is taken into consideration, the contradiction happens that the sinking wind with high velocity (0.707 m/s) entering through the vents at the top of the solar chimney might disturb the extraction of climbing hot air. Apart from this, conduction and radiation heat transfer are neglected in the simulation. In that case, it is difficult to directly evaluate whether or not the effectiveness of buoyancy-driven ventilation overweighs that of wind-driven ventilation in the solar chimney.

3.3.4. The effectiveness of wind-driven ventilation

According to the climate data, the velocity of the wind that 10 metres above the ground is 2.492 m/s. and the exterior environment temperature is 23 °C. The result of simulation shows that the 0.9×0.9 m ventilation vents installed on the internal walls are effective to induce cross ventilation. The wind velocity of windows from ground floor to the second floor is 1.090 m/s, 1.011 m/s and 0.951 m/s respectively, which can be altered changing the sizes of external windows or ventilation vents. By employing this simple strategy, the dorms and central corridor are better ventilated as long as the windows on external walls of windward side and leeward side are open, even though without the help of stack effect generated by the solar chimney. The contours of static temperature and the velocity vectors in cross ventilation from the CFD analysis are illustrated in Figure 14. The contours of static temperature reflect that the cross ventilation also helps to effectively reduce indoor temperature, especially the areas that adjacent to internal walls.

The concentrations of carbon dioxide in the normal dorm and ecological dorm are also investigated for every three hours during the test period as shown in Figure 15. The recording of raw data reflects that the concentration in ecological dorms is approximately one-third of that in normal dorms despite that the changing patterns are essentially similar. Besides, the maximum concentration in ecological dorms reaches 800 ppm at 6:30am, which is obviously lower than normal dorms (just over 1800 ppm). Under this circumstance, the conclusion can be drawn that natural ventilation strategies used in ecological dormitory building involving the new layout of rooms, ventilation vents, solar chimney have a good effect in cooling, improving indoor air quality and eliminating harmful indoor gases.

4. Conclusions

Considering the fact that most of the passive cooling systems in current construction merely concentrate on cooling effects, more strategies that reduce the indoor temperature and simultaneously enhance the indoor air quality need to be identified and employed in buildings, especially in school buildings where the air quality is a basic prerequisite.

In this study, the influence of solar chimney in the promotion of stack ventilation and whether the ventilation vents can enhance effective cross ventilation are examined via CFD simulation. The simulation results showed that the static temperature of interior spaces for dorms decreases from 36 °C in floors to 22 ^{o}C in ceilings. The temperature of the air near openings in both external and internal walls is determined to be 25 ^{o}C, which is slightly warmer than average temperature of air (23 ^{o}C).

Although it is an indisputable fact that the use of natural ventilation strategies helps to improve indoor environment, there are also limitations in the architectural simulation. The combining effectiveness of stack-ventilation and wind-driven ventilation cannot be simulated in CFD, conduction and radiation heat transfer are not involved in the simulation. Under this circumstance, the differences do exist between the actual performance of sustainable strategy and that of computer models. Overall, it appears that the application of natural ventilation strategies in school buildings can play an effective role in indoor environment cooling and air purification, but this is by no means the perfect approach without any shortcomings. Firstly, social constraints, traffic noise and security problems may restrict the use of natural ventilation. Secondly, the adjacent building or other forms of obstacles constructed surrounding selecting locations have an effect on the design of passive ventilation. Thirdly, site characteristics and climate conditions might set a restriction on the prospect of those buildings simply depending on natural ventilation cooling strategy. For example, this passive ventilation cooling strategy does not appropriate for school buildings in extremely cold or hot climates and regions with serious atmospheric or sound pollution. To tackle with the problems, hybrid ventilation would be a feasible sustainable strategy, which employs a combination of natural ventilation that achieved by controllable vents or atriums and mechanically ventilated systems which provide partial cooling and air distribution.

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List of Figures

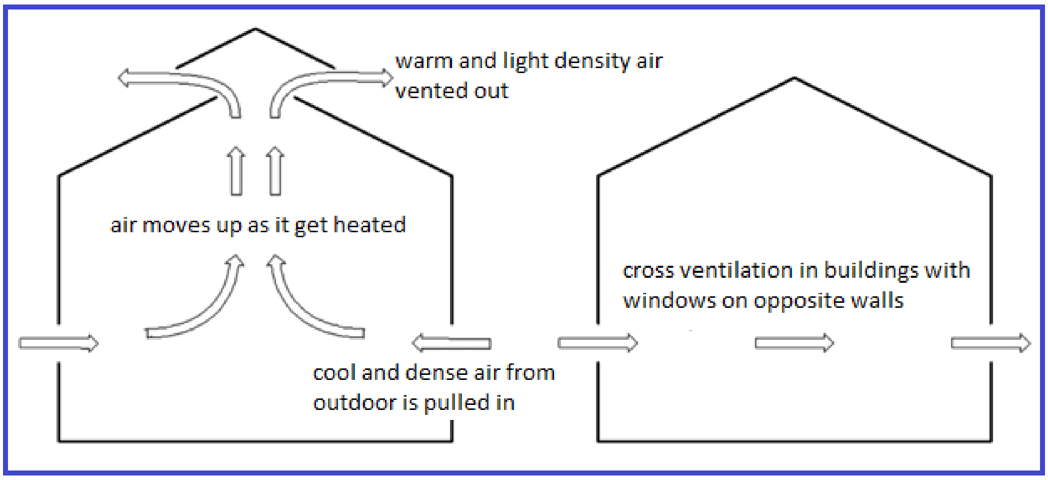

Figure 1. Natural ventilation design [30].

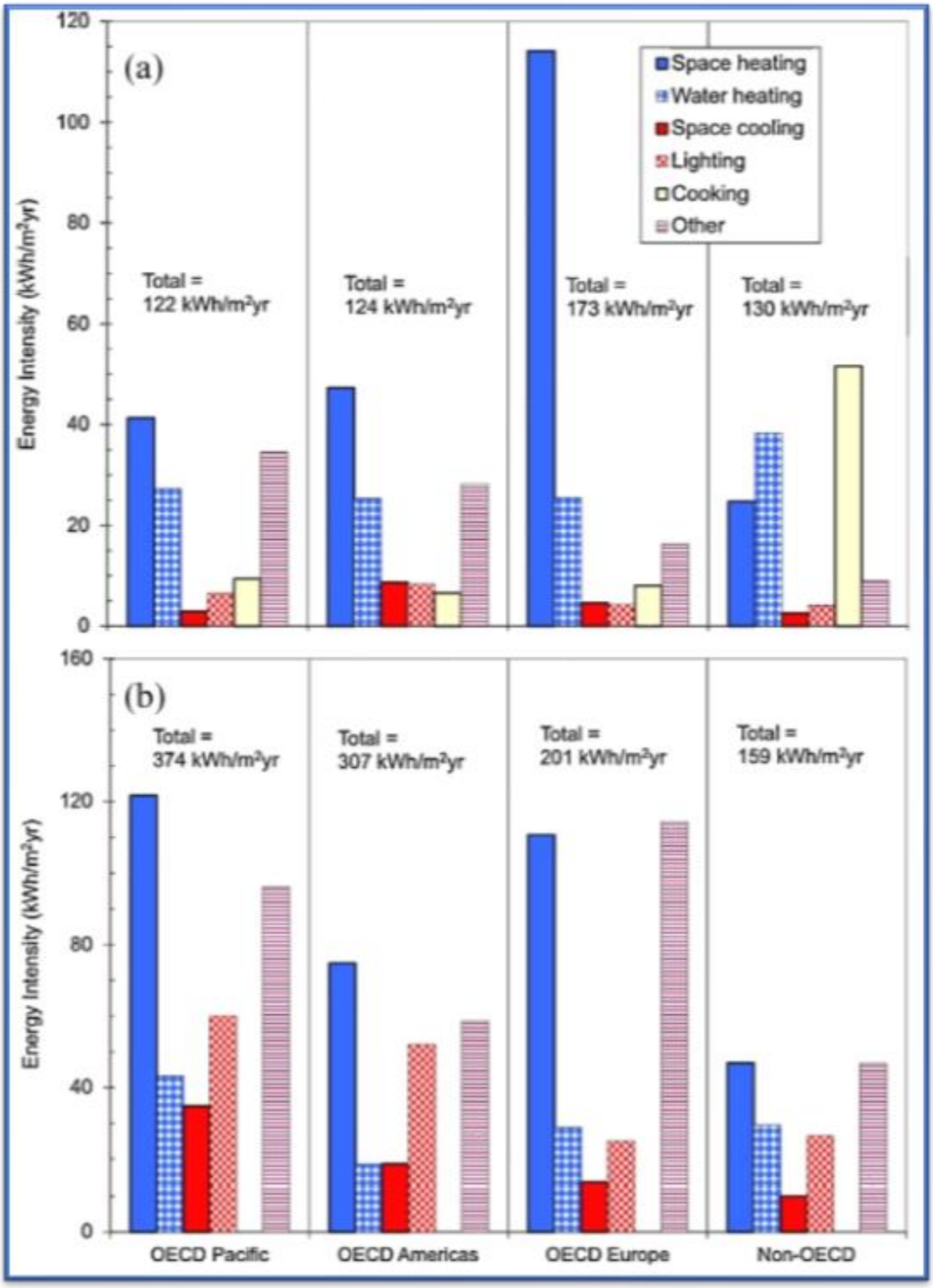

Figure 2. Average energy intensities for space heating, water heating, space cooling, lighting, cooking and other for the four regions in the ETP2012-2 dataset, computed from the ETP2012-2 energy amounts and floor areas. (a) Residential, and (b)commercial buildings. 'Other' for commercial buildings includes cooking. [31].

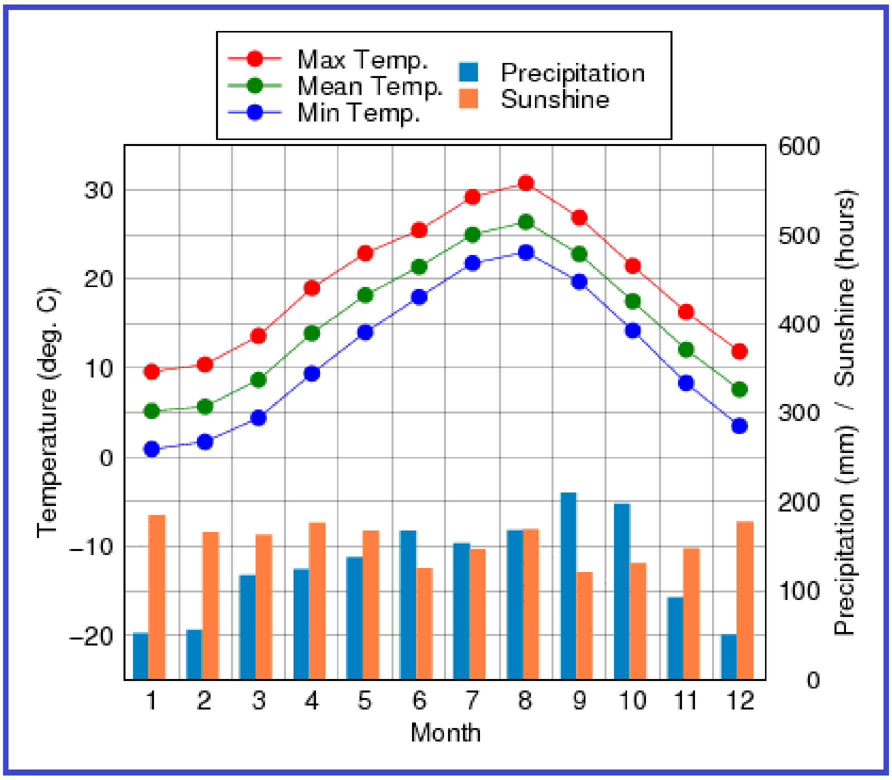

Figure 3. Wind and climate map of Tokyo, Japan [32].

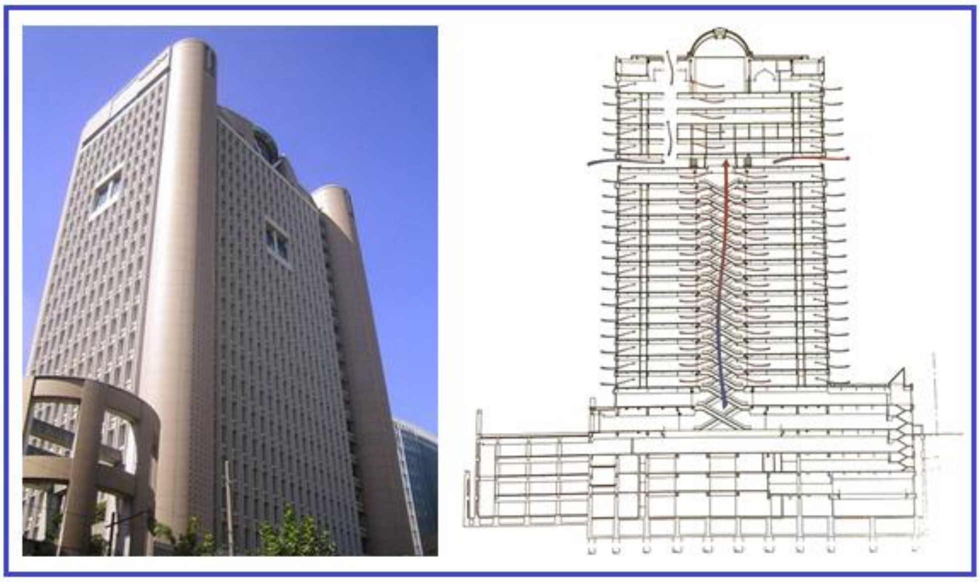

Figure 4. Liberty tower (on the left) and the working principles of wind voids (on the right).

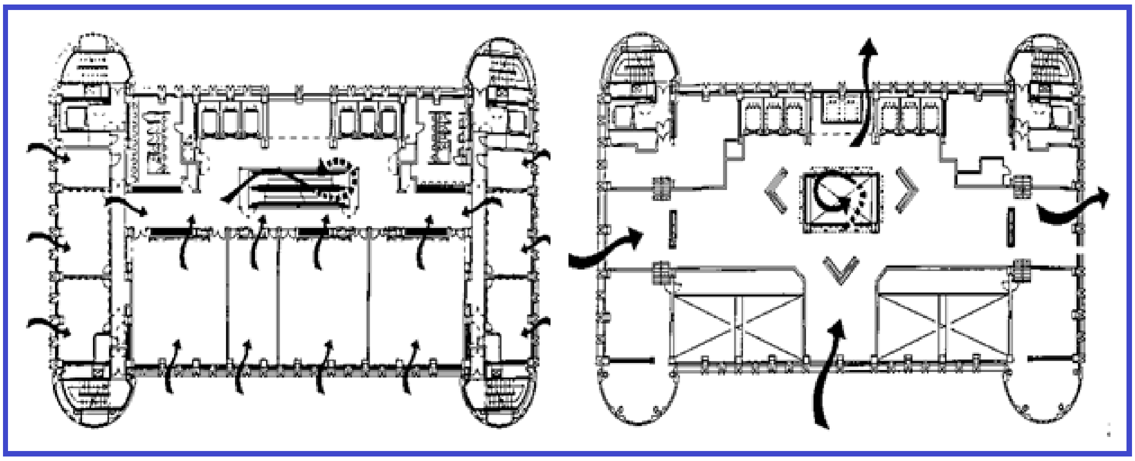

Figure 5. The typical plan showing stack ventilation (on the left) and the wind floor plan with cross ventilation (on the right).

Figure 6. Ventilation vents (on the left) and the typical classroom with exhausting vents mounted on ceiling (on the right).

Figure 7. Exhaust openings at the top of the escalator void on the wind floor [35].

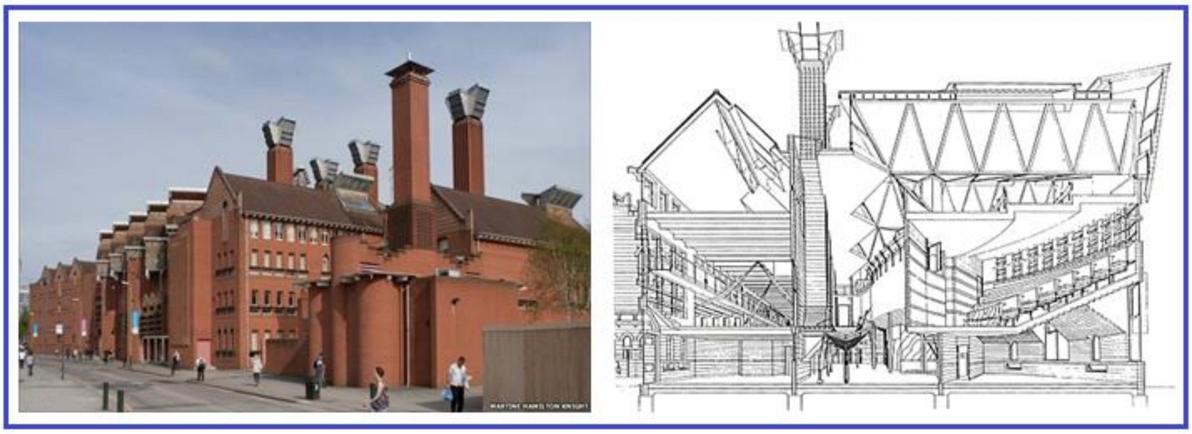

Figure 8. Photograph of Queens Building (on the left) and the section perspective of the central building (on the right)

Figure 9. Sustainable dormitory building and 3D sketch.

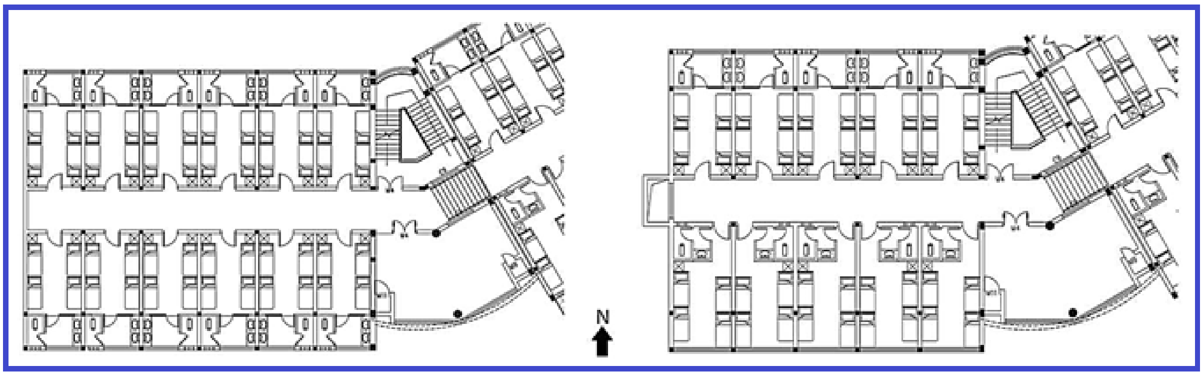

Figure 10. The layouts of ordinary (on the left) and sustainable dormitory (on the right).

Figure 11. Section views of ordinary (on the left) and sustainable dormitory (on the right).

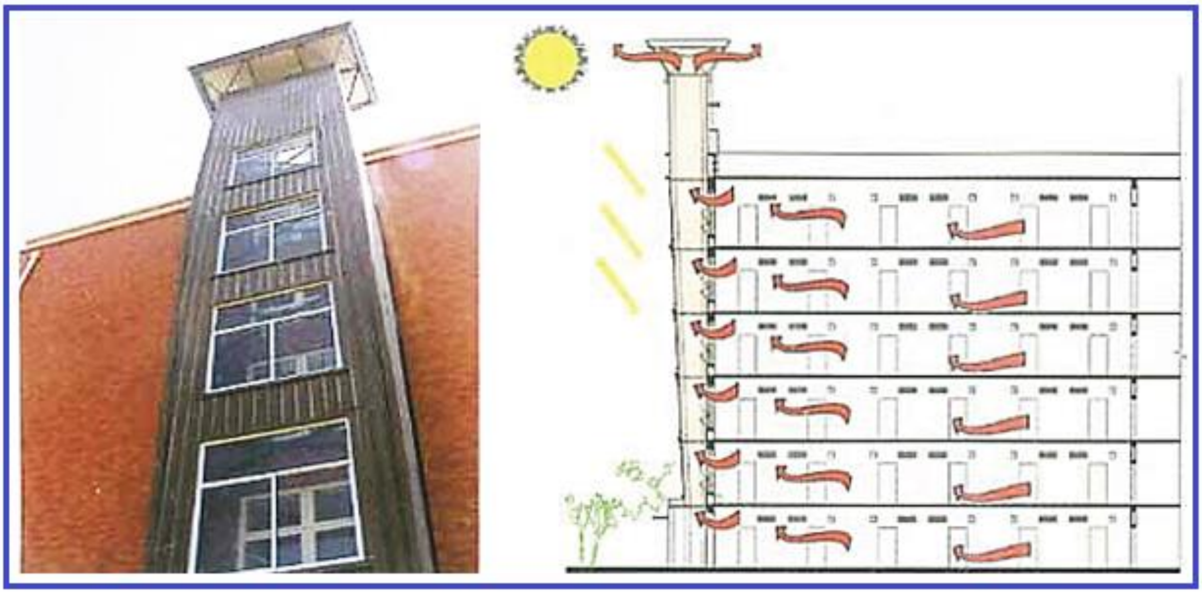

Figure 12. The solar chimney considered in the building (on the left) and the working principle (on the right).

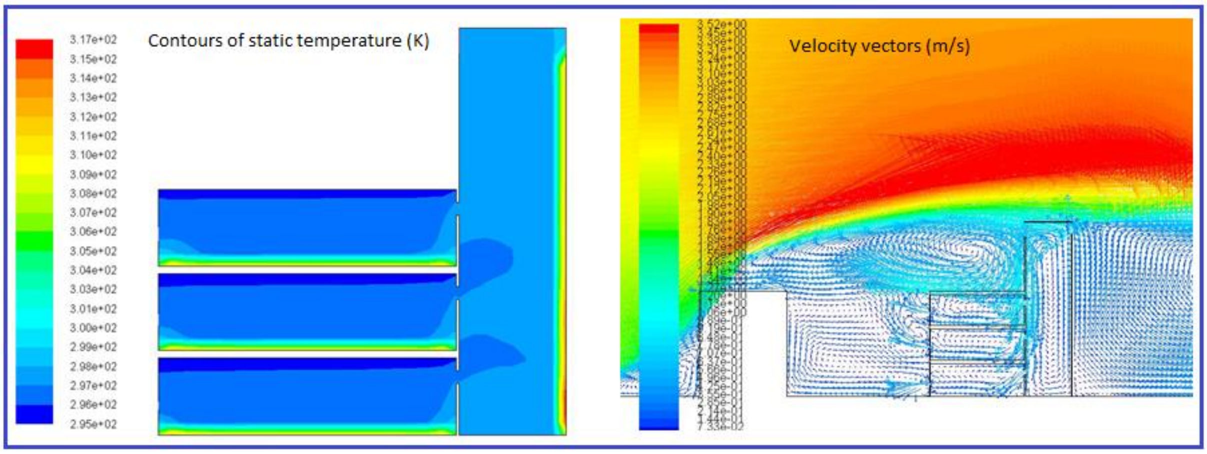

Figure 13. The contours of static temperature (on the left) and the velocity vectors (on the right) in stack ventilation from the CFD analysis.

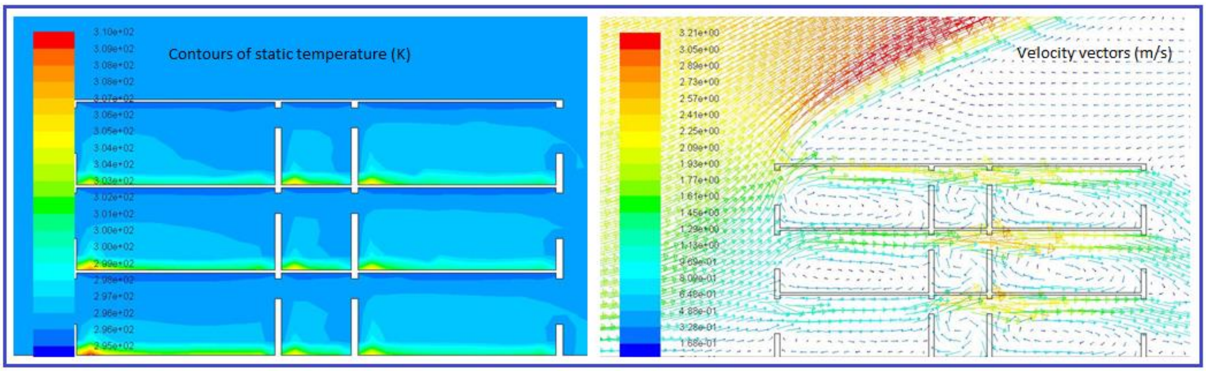

Figure 14. The contours of static temperature (on the left) and the velocity vectors (on the right) in cross ventilation from the CFD analysis.

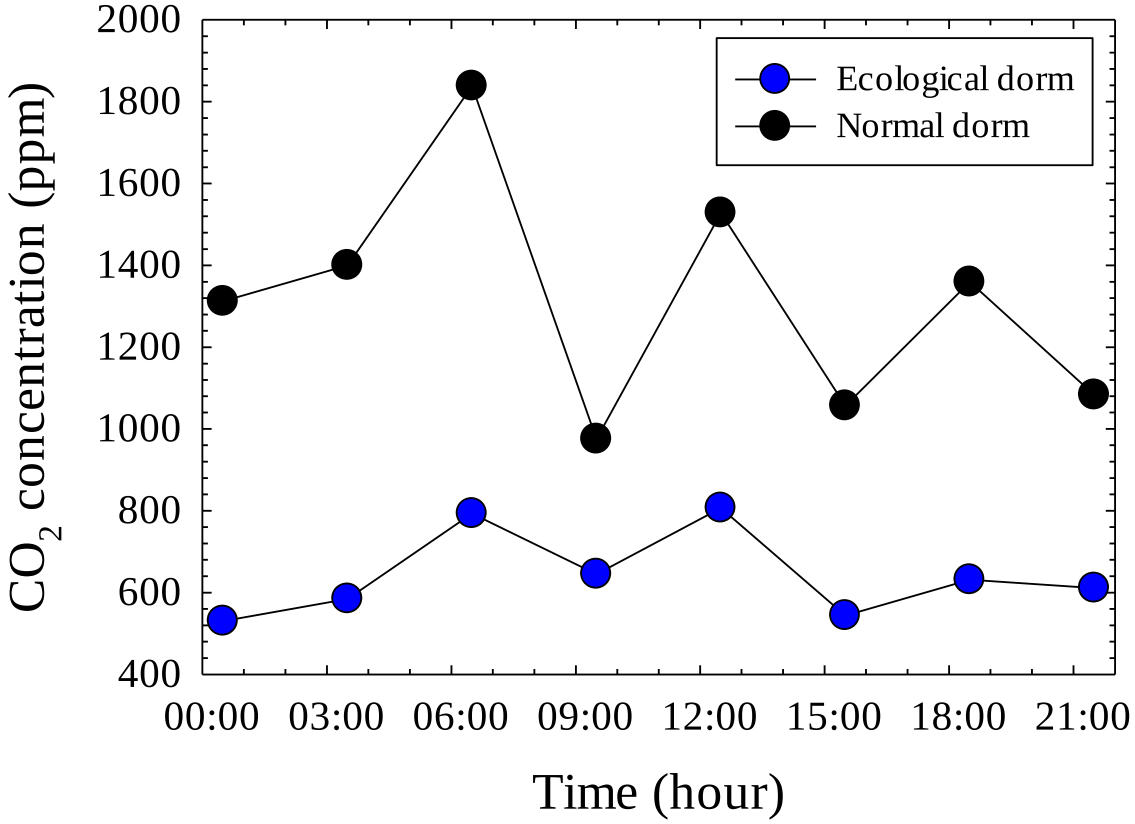

Figure 15. CO_2 concentrations in dorms during a typical one-day test period.