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Developments in Strategies Used for Natural and Mechanical Ventilation in China

A.G. Li[a] P.J. Jones[b]

[a]Department of Environmental Engineering, Xi'an University of Architecture and Technology, Xi'an, PR China, and
[b]Welsh School of Architecture, Cardiff University, Cardiff, UK

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Natural ventilation · Mechanic ventilation · Built environment · Wind effect · Stack effect · Climate zone of China

Abstract
Ventilation design has a long history in China. The ancient pioneers used engineering skills to change the indoor environment. In this review, basic natural ventilation design ideas are introduced from both a historical and modern viewpoint. Attention is paid to new natural ventilation system developments, such as the design and testing of natural ventilation inlets and outlets for the stack and solar chimneys. Theoretical aspects of ventilation design are also considered. Today, the use of mechanical ventilation systems in China is growing for both domestic and non-domestic buildings. The use of mixed-mode or hybrid ventilation systems as a response to needs for indoor comfort and energy efficiency is increasing, and such systems are now widely used.

Historical Examples of Ventilation in China

Mankind has long taken advantage of natural ventilation to provide fresh air for living spaces from cave dwelling to the present day. Unfortunately little remains from the earliest times, but one important site has survived and has been revealed through excavation. The first museum of ancient artefacts to be established in China which has evidence of the deliberate use of ventilation is located at the Banpo village ruins to the east of Xi'an city (fig. 1a). It was first opened to the public on April 1, 1958. Initially, it had a ground area of 70,000 m^2 and a collection of 20,000 pieces from the Neolithic and Palaeolithic Ages. A remarkable hall of 3,000 m^2 to protect the site has been built over the primitive residential section of the village (fig. 1b). The remains of burnt pits and the coarse and crude 'chimneys' for natural ventilation are still in evidence, as well as the daily utensils and art works once employed by the people of Banpo, Xi'an city.

China is an ancient country whose civilisation has a long history and culture. Many ancient buildings still exist in the country, some of which show innovative facilities for natural ventilation [1, 2]. Figure 2, for example, shows an example of an ancient strategic castle (ancient stone battery) located at Shantou. In this building, the strategy for natural ventilation uses a combination of a sheltered parapet wall and ventilating caps. On the windward side, wind caps are in a zone of negative pressure because of the effects of the shelter wall. However, note that the top of the wind cap is lower than the upper edge of the shelter wall. The pressure at the wind caps is therefore lower than that in the interior of the building, and they exhaust indoor air across this pressure gradient. On the leeward side, the wind caps are in a positive pressure zone, providing fresh

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Prof. An-Gui Li
Department of Environmental Engineering
Xi'an University of Architecture and Technology, 13 Yanta Road
Xi'an 710055 (PR China)
E-Mail visitli@yahoo.com.cn

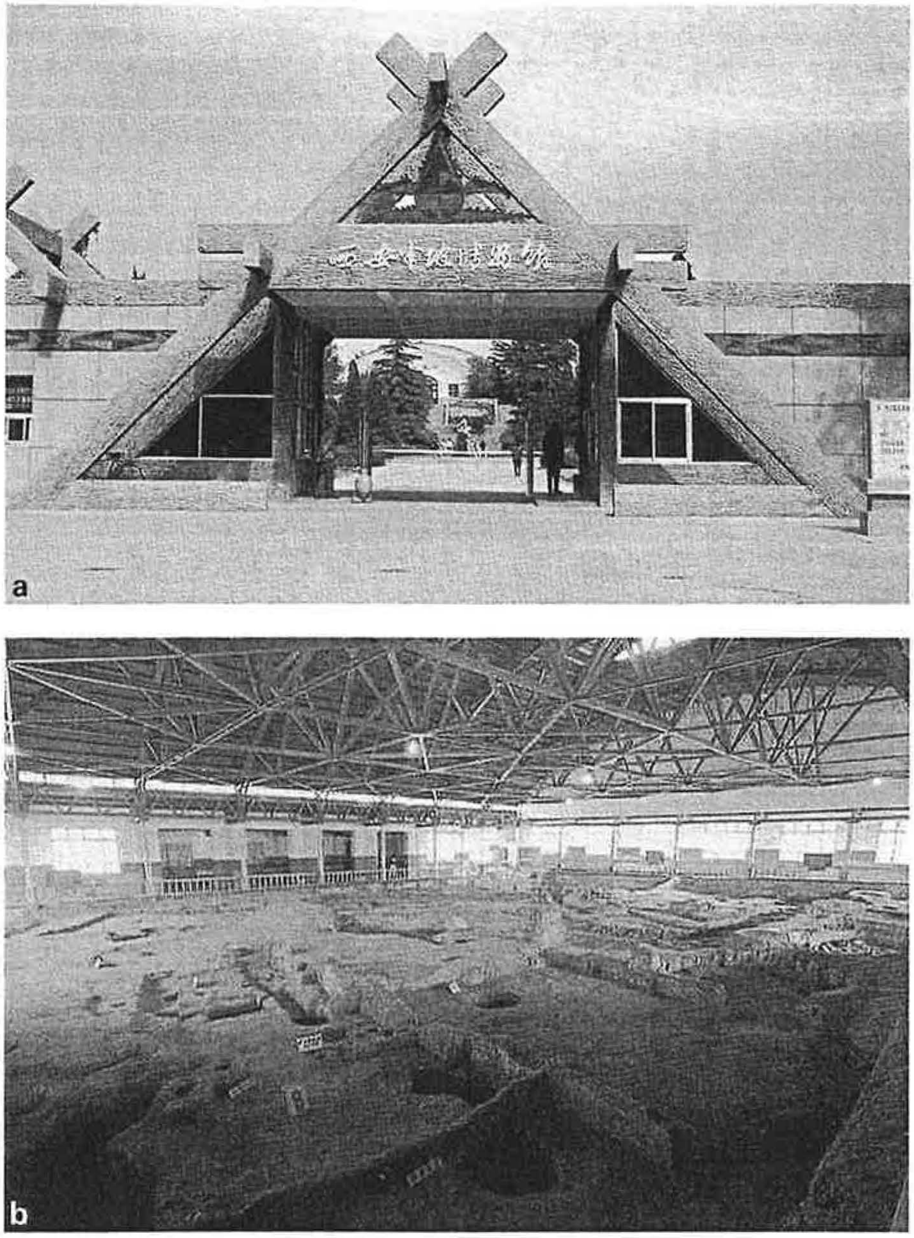


Fig. 1. The Banpo primitive residential village in Xi'an. **a** The entrance. **b** The covered hall.

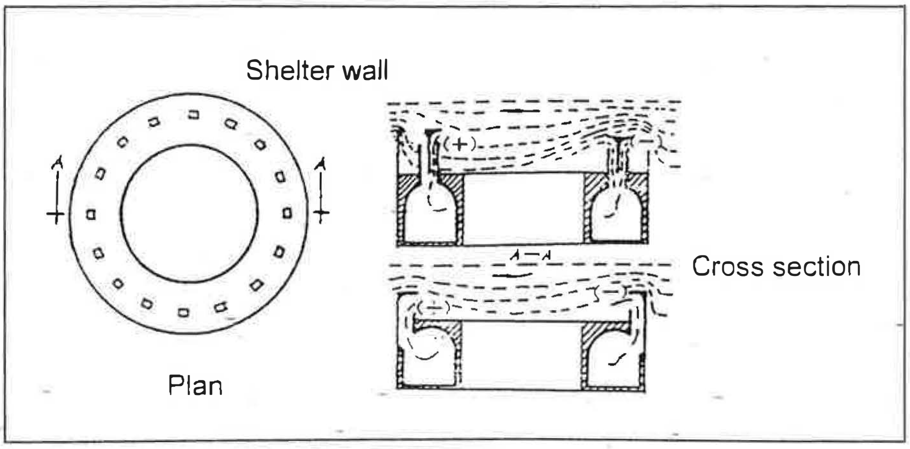


Fig. 2. Natural ventilation of the ancient battery in Shantou in China showing pairs of wind caps uniformly distributed along the perimeter. This allows the interior to be maintained in a favourable condition regardless of wind direction.

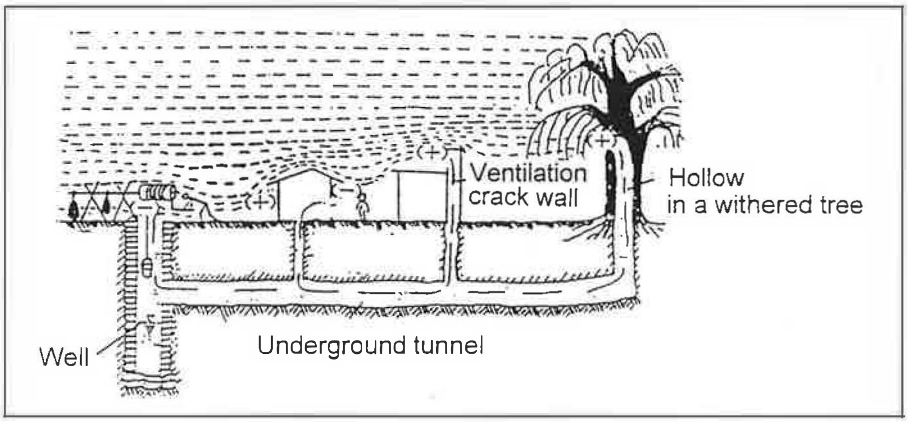


Fig. 3. Diagram showing the natural ventilation of underground tunnels in the War of Resistance against Japan (1937–1945).

air supply into the interior. In fact, there are many pairs of wind caps uniformly distributed around the ancient stone battery; maintaining a steady and favourable condition, regardless of wind direction. The ancient pioneers' main achievement was to demonstrate engineering skill and to have the ability to change their indoor environment, using empirical knowledge gained from observation.

China fell behind the rest of the world in the development of ventilation strategies during the Qing Dynasty (1644–1911), creating a situation further aggravated by World War II. However, there is an ingenious example of natural ventilation systems used during this period for ventilating underground tunnels. During the 1930s, in the 'War of Resistance against Japan', also named the 'Underground Tunnel War', which took place in the north of China in the Jizhong Plain region, an underground tunnel system was constructed. These tunnels provided shelter from attack, and of necessity they had to be ventilated. Figure 3 illustrates the natural ventilation diagram for such an underground tunnel system of a type which was widely used. Withered trees contained hidden chimneys, and there were openings for air intakes in buildings, wells and other constructions.

Modern Examples of Natural Ventilation

The historic use of natural ventilation in China was based on empirical knowledge gained from observation. It was not until the development of instruments to measure wind velocity, air temperature and atmospheric pressure, that there was the opportunity for theoretical predictions and rational designs. Today, both in the design of new buildings and the retrofitting of old buildings, the focus is not only on energy efficiency, but also on optimal use of sustainable technology. Natural ventilation is often considered a preferred solution, although with some systems it is combined with mechanical ventilation to provide a hybrid solution. Up to the present time, much research work has been carried out in China to investigate how to achieve good standards of ventilation efficiency [3–6]. However, as a language barrier exists between China and the English-speaking world, the theoretical work and new ventilation developments are not widely known outside of China. For example:

(1) Low-rise or high-rise residential buildings in cities use natural ventilation to maintain acceptable living environments indoors for most of the year in all regions of China.

(2) Office buildings use both natural ventilation and air-conditioning (mostly individual unit air-conditioning equipment) to maintain thermal comfort or working conditions.

(3) Industrial buildings generally use natural ventilation and/or hybrid ventilation systems to provide occupied zone thermal environments.

(4) There is a tendency for natural ventilation or cool blast or ceiling ventilator systems to be used during summer off-peak time, while the use of air-conditioning systems is becoming more popular during the summer peak. That said, the percentage of air-conditioned buildings is gradually rising along with the fast economic growth.

In the vast rural areas and countryside villages of China, the dwellings are mostly single-storey detached houses with various types of roof structures. In these parts, the basic principles of natural ventilation are considered when designing the building layout and while choosing room location, window types, chimney shape and heights, even paying attention to the tree planting in the yard at the front or rear of the houses.

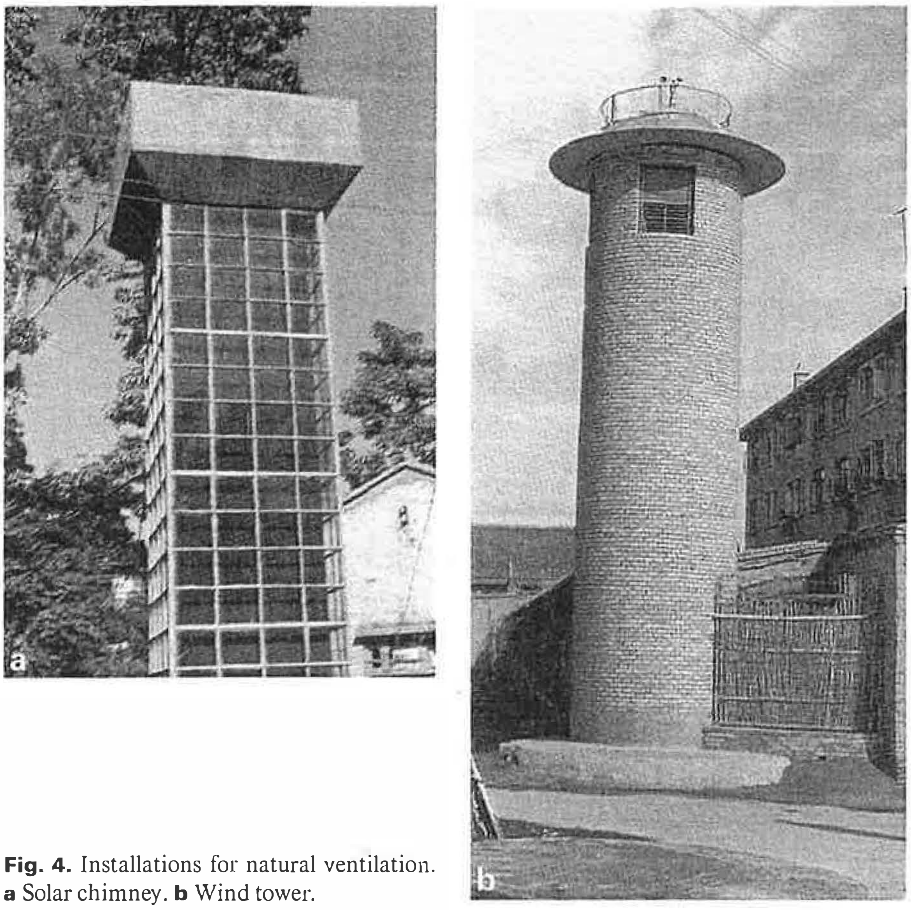


Fig. 4. Installations for natural ventilation. **a** Solar chimney. **b** Wind tower.

New Developments in Natural Ventilation Techniques and Natural Ventilation Inlets and Outlets

It is worth considering some of the newer buildings which use natural ventilation to improve the indoor thermal environment. In these buildings, particular attention is paid to new strategies and techniques, such as the optimisation of natural ventilation inlets and outlets, the design of stack devices and solar chimneys and to the progress of recent theoretical research in these areas (fig. 4) [1, 7–9].

It is well known that the thermal pressure difference is quite small in rooms containing sources of heat or cooling, while the pressure forces from the outside wind are of a stochastic nature. The thermal (stack) and wind pressures combine to provide natural ventilation. The most efficient way to optimise natural ventilation systems is to optimise the air inlets and do this with respect to the forces of stack and wind. Because of the varying nature of these forces, the air distribution in naturally ventilated

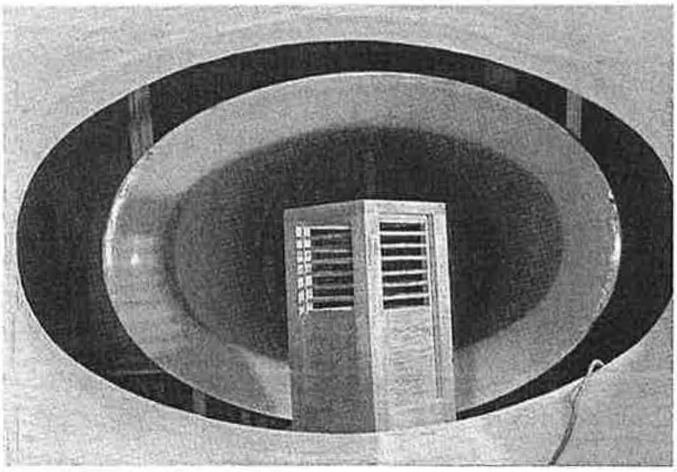
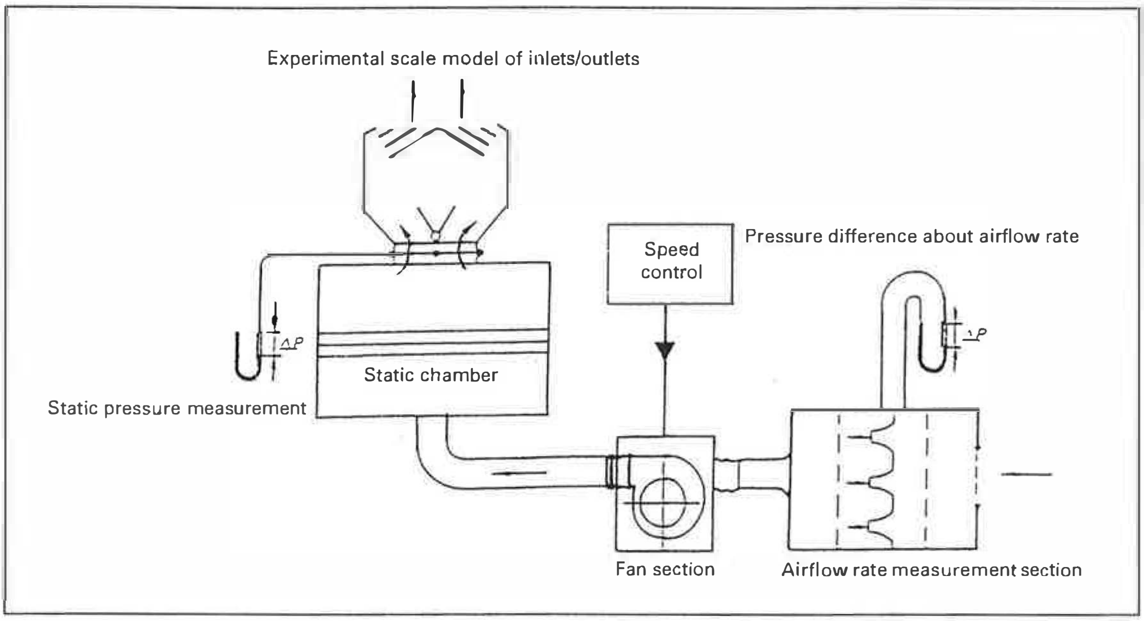


Fig. 5. Test rig equipment for simulating wind pressure on inlets/outlets: wind tunnel and the installation position of inlets/outlets.



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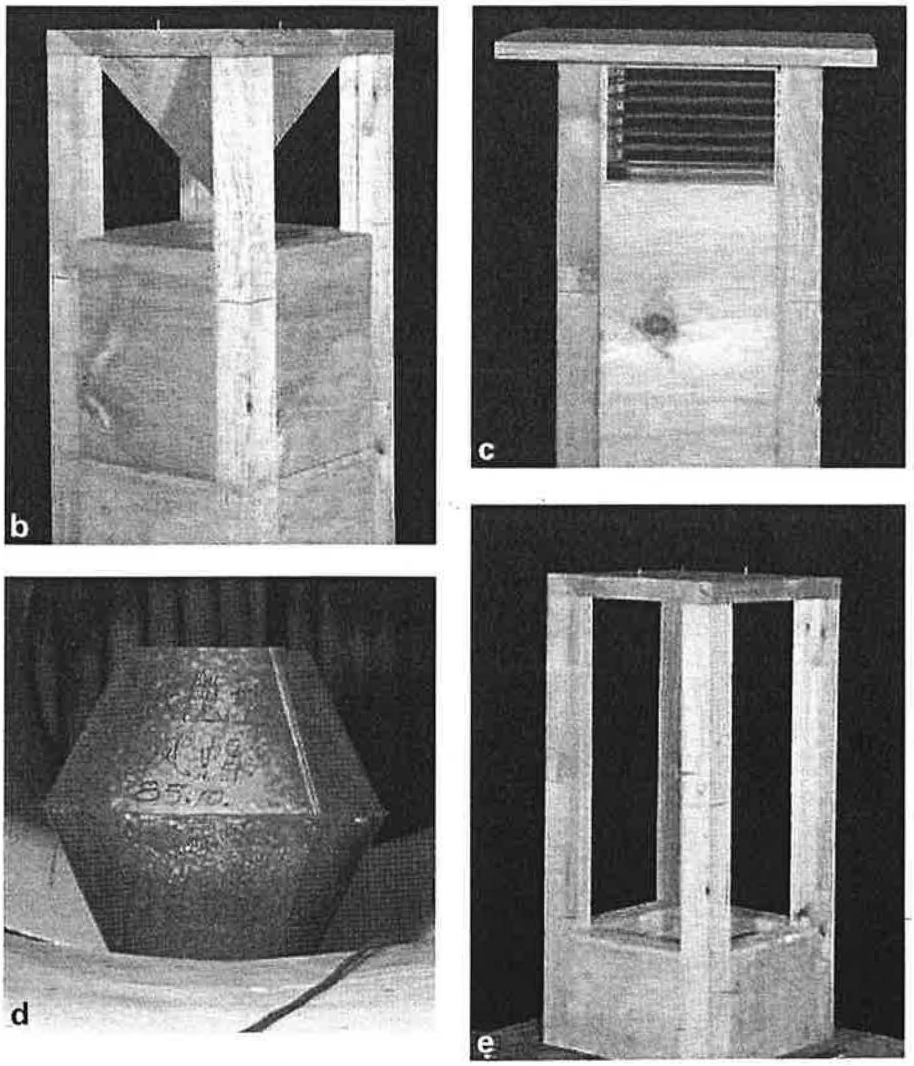

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Fig. 6. Diagram of test rig for simulating heat pressure on inlets/outlets: test modelling and the installation position of inlets/outlets.

Fig. 7. Some typical natural ventilation inlets. **a** Turning inlets. **b** Inverted pyramidal inlets. **c** Louvred inlets. **d** Rugby-ball-shaped inlets/outlets. **e** Open-sided inlet/outlet.

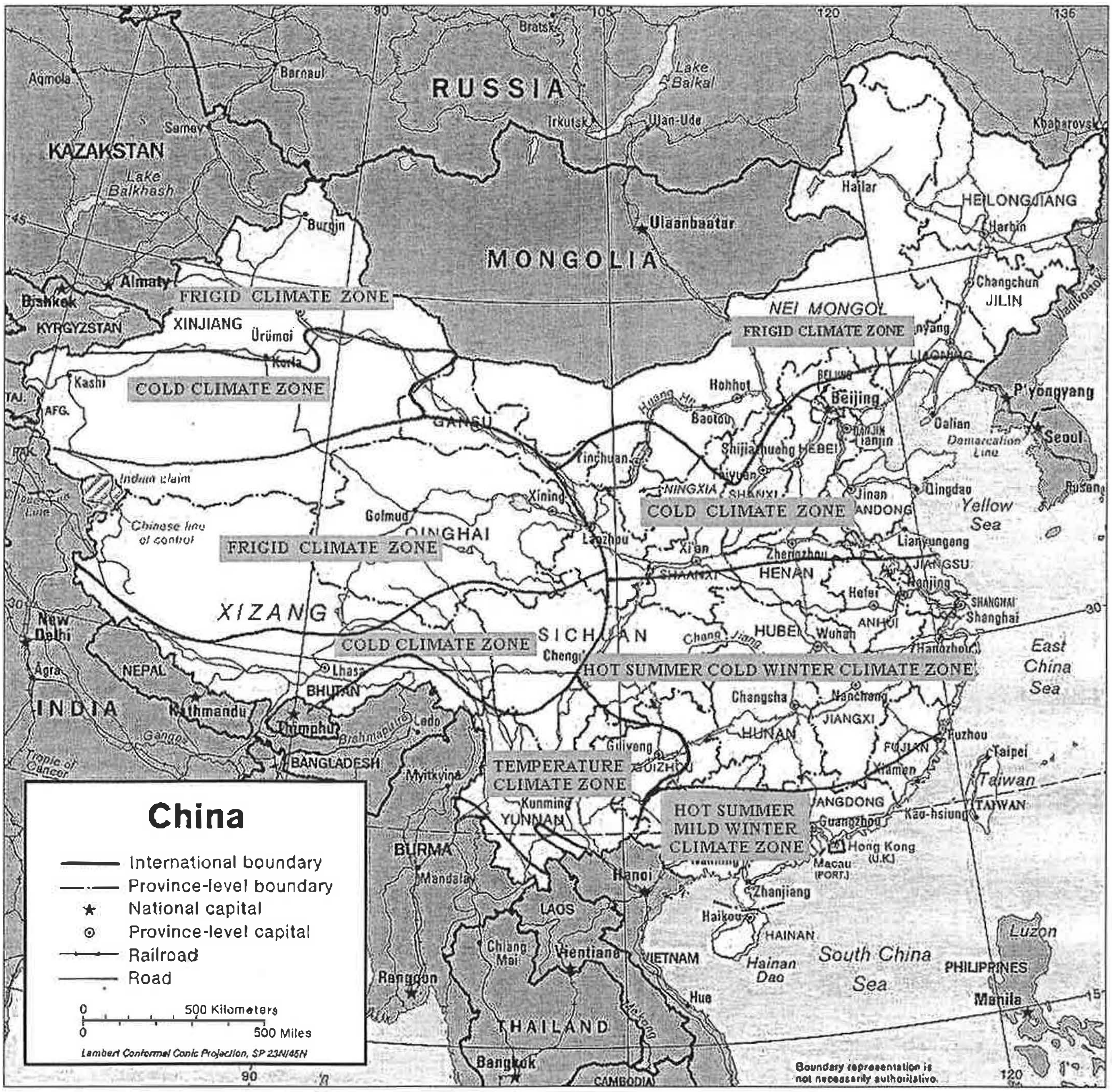

Fig. 8. Map of China showing the climate zones classification for the HVAC design guide.

rooms is difficult to predict. There are often large differences between predicted values for ventilation and airflow distribution and those measured under operating conditions.

Research in China has investigated the performance of high-efficiency air inlets and outlets [10, 11]. The size and shape of inlet and outlet devices has a major effect on their natural ventilation efficiency. Figures 5 and 6 illustrate experimental test rig equipment used for carrying out scale model tests on inlet and outlet devices, while figure 7 shows some typical inlet and outlet devices.

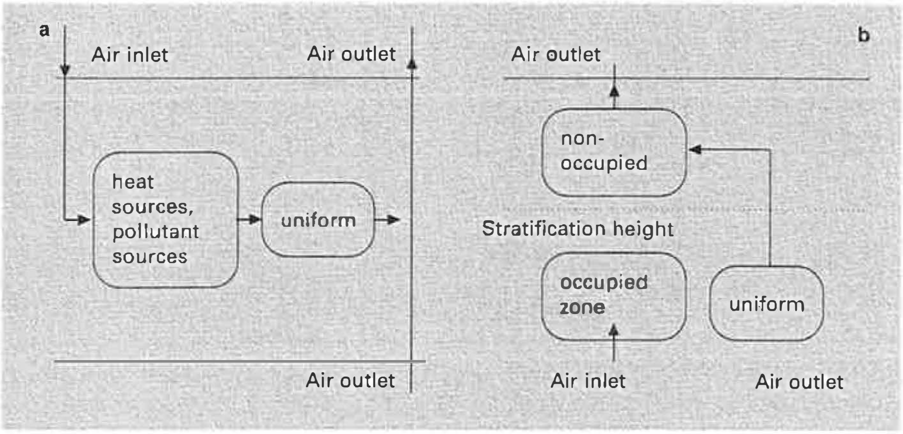

Fig. 9. a Single-zone mixed air distribution. **b** Two-zone stratified air distribution, both used widely in China.

A number of such inlet and outlet devices have been carefully investigated by wind tunnel tests followed by site-specific field measurements. There is a range of different-shaped devices which have been tested and of tests which have been done:

(1) Solar chimney to give natural ventilation
(2) Field tests on inlets and outlets
(3) Tests on an open-sided inlet and outlet (variable opening area)
(4) Tests on rugby-ball-shaped inlets and outlets
(5) Tests on hopper-shaped inlets and outlets with a pyramidal design inside
(6) Tests on louvre shapes for inlets and outlets
(7) Tests on pyramidal shapes for inlets and outlets

Mechanical Ventilation in Response to Climate

Generally speaking, China may be characterised as having a continental climate (fig. 8). Although the country spans a latitude range of nearly 50°, the greater part of the Chinese territory is situated in the temperate zone. Its southern part is in the tropical and subtropical zones, and its northern part approaches the frigid zone. Temperatures differ therefore rather strikingly across the country. The northern part of Heilongjiang Province has long winters but no summers; while the Hainan Island has long summers but no winters. The Huaihe River valley is marked by distinctive seasonal changes, but it is spring all year round in the south of the Yunnan-Guizhou Plateau. In the Northwest hinterland, the temperature changes dramatically. In the high tundra region of Qinghai-Tibet, the temperature is low in all four seasons. For the design of ventilation and other heating and air-conditioning systems, the climate of China is officially classified into 5 climate zones [12]:

(1) Frigid climate zone
(2) Cold climate zone
(3) Temperature climate zone
(4) Hot summer, cold winter climate zone
(5) Hot summer, mild winter climate zone

In warm-humid climate regions, such as the Changjing River basin, air temperatures typically exceed 35°C, reaching 45°C, combined with a relative humidity exceeding 70%, conditions which fall outside most definitions of thermal comfort zones. Mechanical ventilation, even air-conditioning is therefore necessary. However, both mechanical and natural ventilation systems could be combined to maintain a satisfactory internal environment at different times of the day or season of the year, in order to minimise the cost, energy penalty and other potential problems, which are attributed to full air-conditioning systems.

Research on the Distribution of Room Air with Mechanical Ventilation

The key difference between mechanical and natural ventilation airflow processes lies in the fact that the volume flow rate and the flow direction at the ventilation openings are pre-determined in the former system and are less predictable in the latter. Mechanical forces drive mechanical ventilation. It is very common for a one-zone mixed air distribution system or a two-zone stratified air distribution system to be used for office, commercial or industrial buildings (fig. 9). Because of the complexity of geometry or structure of modern buildings or industrial

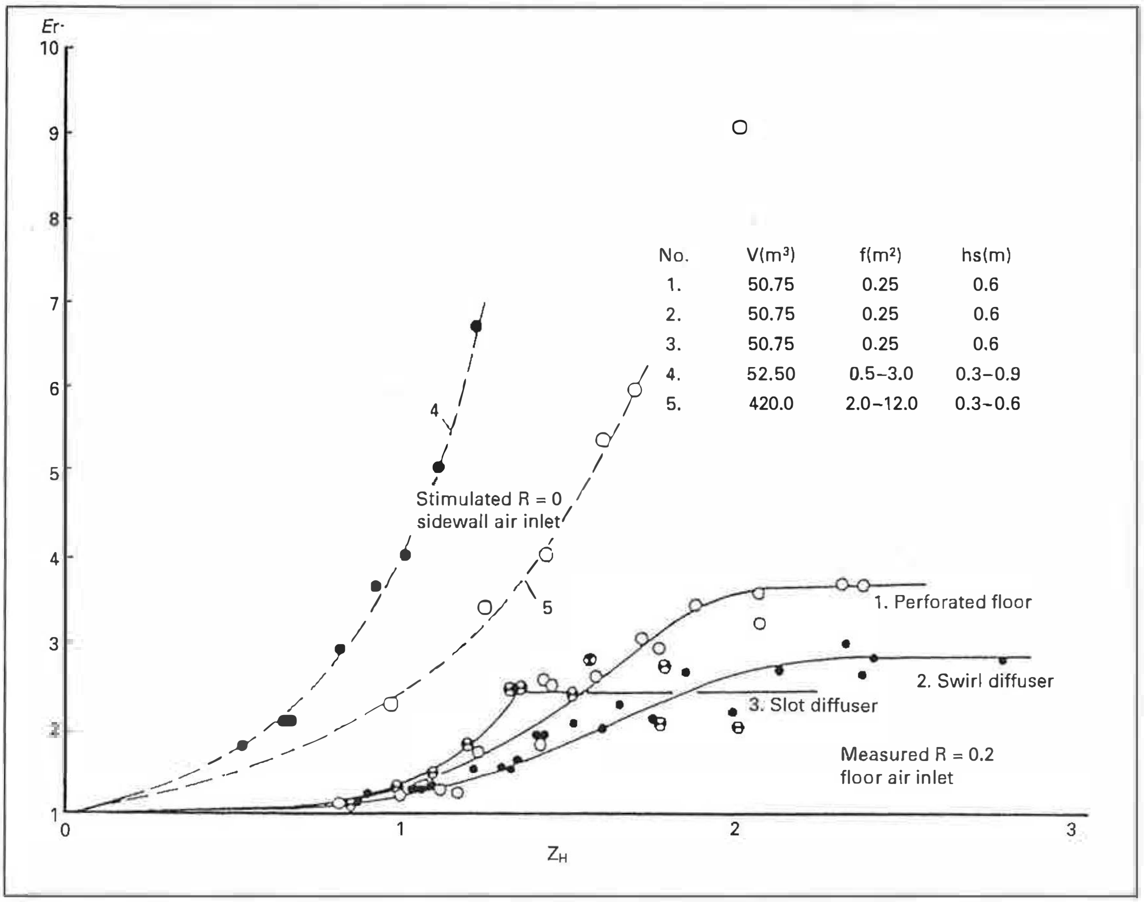

Fig. 10. The temperature efficiency characteristics of air diffusers investigated through scale-modelling tests or CFD technique.

halls, a lot of scale model tests have to be made to verify the ventilation efficiency at the initial project design stage.

To give an example: at the Xi'an University of Architecture and Technology, scale model experiments (using scale models constructed in the range between 1:10 and 1:15) have been carried out to understand the internal air flow and to analyse the temperature efficiency, E_T, in various buildings such as stadium halls, underground hydropower stations, main machine halls, subway waiting halls and some commercial buildings. The temperature efficiency characteristics of various air diffusers, such as swirl diffuser, slot diffuser and perforated floor have been investigated through such scale model tests as well as through the CFD technique (using PHOENICS software). Figure 10 shows the relationship of temperature efficiency, E_T, versus thermal stratification height, Z_H, for these different air diffusers [13]. E_T is defined as follows:

$$E_T = \frac{t_e - t_0}{t_{oz} - t_0}$$

where: t_e = temperature of exhaust air, t_0 = temperature of supply air and t_{oz} = temperature of occupied zone.

In addition, field tests on mechanical ventilation systems for different rooms or tall halls have been carried out to verify the ventilation effectiveness and improve the design procedure.

Mechanical Ventilation for High-Ceiling and Large-Area Halls of Industrial Plants

Two schemas for types of high-ceiling and large-area industrial plants are summarised here. One is for factory buildings with a height of more than 10 m and having a total building volume of over 10,000 m³. The other is for buildings with a height of less than 10 m and having total floor area larger than 5,000 m².

For those industrial plants in which buildings have a height of over 10 m, as required by the production pro-

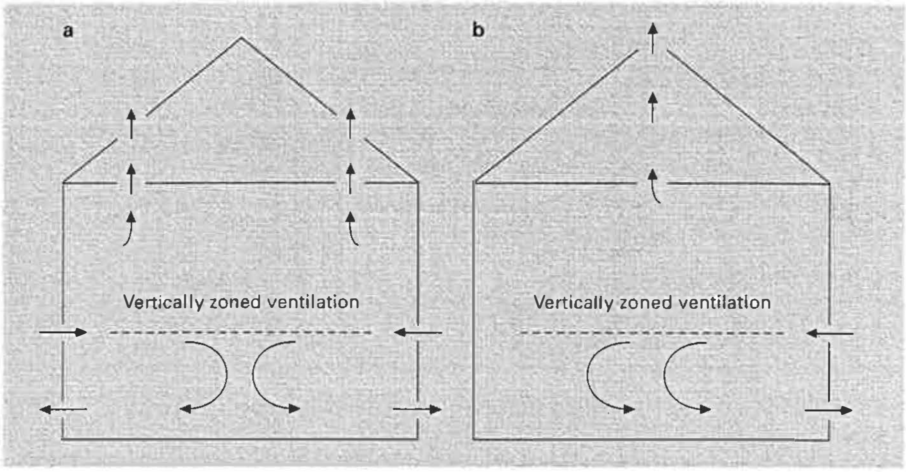

Fig. 11. VZV for high-ceiling and large-area halls on industrial plants. **a** Double-sided air supply. **b** Single-sided air supply.

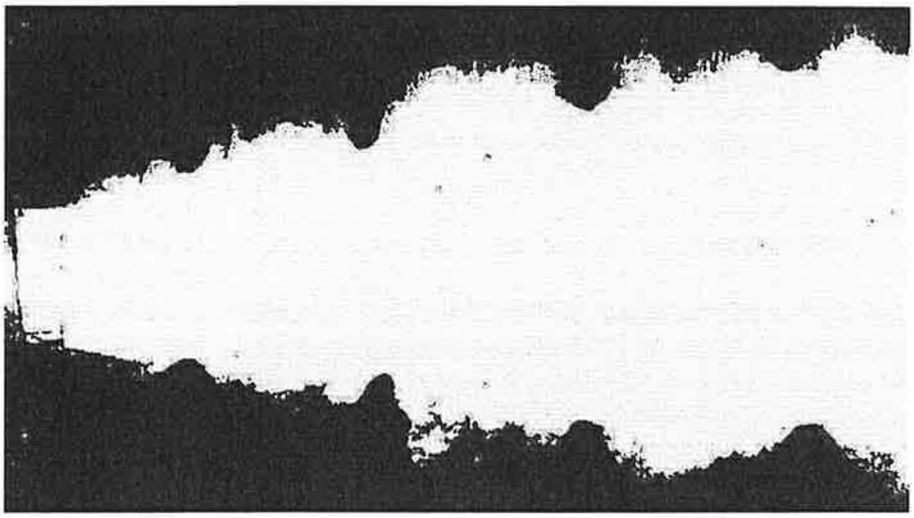

Fig. 12. Undulating air diffuser produces undulating air currents to the occupied zone. Smoke-tracing photograph.

cesses, only partial ventilation within a certain height (including the occupied zones) is necessary (fig. 11). This approach is taken with a view to reducing running costs as well as lower equipment costs [14, 15]. The ventilated space is separated from the non-ventilated space by air jets, termed vertically zoned ventilation (VZV). Usually, outdoor air is supplied from side-walls at middle height. VZV systems have been designed for, and satisfactorily operated in, many high-ceiling and large-area industrial plants in China . For example, in 1976, VZV systems were installed in the Nanjing Turbine Electrical Machinery Plant, the First Machine Tool Plant of Tianjing and the Pingdingshan High-Pressure Switching Factory, all of which are reported to perform well. Furthermore, the Chinese Academy of Construction Science has organised a project involving scale model and field tests on technical aspects of VZV in High Ceiling and Large Area Industrial Plants. The 2nd, 6th and 7th Design Institutes of the Mechanical Industry Ministry also took part in the project. Later on, a number of research reports and design guidelines were published, including air distribution calculation of multi-stream or non-isothermal air jet, and system selection of VZV. VZV systems have been widely applied in China, in such high-ceiling and large-area commercial buildings as the departure lounges of Shenzhen Airport and Zhengzhou New Airport, as well as in nuclear power stations and the main halls of large hydropower stations.

Air Inlet Diffusers for Mechanical Ventilation

Mechanical ventilation can be centralised with ducted distribution or localised using individual wall or roof fans. Air inlet diffusers play an important role in delivering fresh air to the occupied zones. Various air diffusers have been studied and designed. Two examples are given here.

Air-Fluctuating Diffuser

This kind of air diffuser produces undulating air currents, which can change the air velocity in direction or mass over time, supplying fluctuating air streams to the occupied zones (fig. 12). The effect is to make people feel refreshed and cool, countering the dull and gloomy feeling caused by the more traditional steady-flow air diffusers. The effect is similar to that of natural outdoor wind. On a smaller scale, fluctuating fans form a large proportion of the various fans used in individual houses in China.

Swirling-Flow Diffuser

Swirling air diffusers produce swirling air currents, where the air velocity will decrease rapidly along the jet axis. These are suitable for low-rise buildings avoiding the feeling of draught caused by traditional air diffusers.

Conclusion

Constructed, as opposed to adventitious, natural ventilation systems have been in use in China since ancient times. Today, natural ventilation is widely used in various dwellings and industrial buildings. In modern China, attention is now paid to the development of new techniques and strategies for natural ventilation systems which involve optimising ventilation inlets and outlets in relation to the stack effect and solar chimneys.

Inlets and outlets have a considerable effect on natural ventilation efficiency. Some designs of inlets and outlets, such as open-sided, rugby-ball-shaped or hopper-shaped designs with pyramidal geometry inside, various louvres and pyramidal structures have been carefully investigated by wind tunnel tests, taking account of wind pressure or thermal pressure. In addition, field experiments on such inlets and outlets have been carried out in a number of buildings.

Mechanical ventilation systems are also used both in domestic and non-domestic buildings. In some areas, it has been found to be advantageous to use mixed or hybrid ventilation systems because of the particular climate in the region. In fact, hybrid systems have been shown able to maintain a satisfactory internal environment throughout the day and during all seasons of the year regardless of climatic zone.

In large buildings, mechanical ventilation may be used for air distribution to create a fully mixed single zone or a stratified two-zone air distribution. Tests on scale models at the initial design stage of any project have been performed to verify ventilation efficiency throughout the complicated geometric structure of modern buildings or industrial halls. For industrial plants having a height of over 10 m, partial ventilation within a certain height (including occupied zones) is used to reduce running costs and equipment costs. VZV systems have been designed and now operate in many high-ceiling and large-area industrial plants in China.

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