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Natural ventilation of tall buildings – options and limitations

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David Etheridge

David is a graduate of the University of London, with a BSc in Aeronautical Engineering and a PhD in aerodynamics. His early industrial research was on high-lift wings, followed by a return to University for postdoctoral research on erosion of river beds. This was followed by industrial research with British Gas, where he led a team which was at the forefront of ventilation research for many years. He was also closely involved in the development of novel ultrasonic gas meters.

He has received several awards for his work, including the MacRobert Award from the Royal Academy of Engineering, the Gold Medal of the Institution of Gas Engineers and the CIBSE Silver Medal.

During his time in industry David worked on many aspects of ventilation, with emphasis on the theory and measurement of natural ventilation e.g. the development of mathematical models and experimental techniques for measuring ventilation at full-scale and in the wind tunnel. Since joining the University of Nottingham this work has continued, with emphasis on steady and unsteady flows through building envelopes. Most recently he has been researching the feasibility of natural ventilation of tall buildings. This has included the application of conventional envelope flow models to such buildings with the aim of identifying fundamental problems and possible solutions. These investigations have included the use of novel envelopes, such as porous walls, and the use of phase change materials, to resolve problems associated with natural ventilation during the heating and cooling seasons.

Brian Ford

Professor Ford is an architect and environmental design consultant with 25 years experience in architectural practice and consultancy, both as a partner and with his own practice. He is currently Professor of Bioclimatic Architecture and Head of the School of the Built Environment at the University of Nottingham. He has specialised in the design of naturally ventilated and passively cooled buildings, and his experience in different parts of the world includes acting as consultant for the Sydney Olympic Stadium, Australia; Pittsburgh Convention Center, USA; Torrent Research Laboratories, India; the Malta Stock Exchange, as well as theatres, offices and University buildings. His tall building experience comes from working with WSP Environmental on projects both in London and the far East. This includes acting as consultant to the Architectural Services Department of Hong Kong on the micro-climate implications of proposals for the 'Joint-User' Building, Rock Hill Street, Hong Kong.

Since 1996, Brian has initiated over 3.0 million Euro of funded research projects within both EC and UK Government Research and Development Programmes. He is joint author with Dr David Etheridge (University of Nottingham) and Steve Irving (Oscar Faber) of the CIBSE Applications Manual AM10 'Natural Ventilation in Non-Domestic Buildings', 2005.

Natural ventilation of tall buildings – options and limitations

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Abstract

The design of non-domestic buildings which adopt a purely natural ventilation strategy is now commonplace in many parts of the world, and increasingly this strategy has been shown to be viable in city centres as well as ‘green field’ locations. However, the adoption of natural ventilation in tall buildings is less common. This is not surprising in view of the potential risks to a successful design. This paper explores the basic principles and strategic options for natural ventilation of tall buildings, and refers to prominent examples which have adopted a ‘mixed mode’ approach. The prospect of purely naturally ventilated tall buildings is considered in terms of the envelope design. The paper concludes that in terms of designing the envelope and its openings, the challenges for tall buildings are greater than for low rise, primarily because the potential magnitudes of the driving forces become greater and their relative magnitudes can vary over a wider range. Segmentation offers the least risky approach for envelope design of non-residential tall buildings, provided the aerodynamic effects can be reliably accounted for. Tall buildings may also lend themselves to some forms of innovative envelope.

Keywords: Natural Ventilation, Design, Mixed-mode, Double-skin, Openings

Introduction

The potential energy savings and other benefits of natural ventilation are as valid for tall buildings as they are for low-rise non-domestic buildings, perhaps more so. However there are few, if any, non-residential tall buildings (25 storeys or more) that rely *solely* on natural ventilation. There are several notable buildings that have been designed with a natural ventilation system, but they also have some form of mechanical system so they are strictly mixed-mode (or hybrid) designs. This is an understandable approach, since it reduces the risks associated with a purely natural system. However it means that the full benefits of a natural system (reduced capital and running costs; carbon reductions) will not be achieved.

Figure 1 illustrates the complexity of the mechanical systems that are employed in a hybrid system and the benefits that would be accrued if a reliable and purely natural system were feasible.

The primary objective of a natural ventilation system is to allow the occupants (and/or a control system) to achieve envelope flow rates such that the occupants can remain comfortable under most conditions. A particular problem with tall buildings is that they are often prestigious buildings that are air-conditioned to give close control of the internal environment under all conditions. These high expectations put more emphasis on achieving a natural system that gives as much control as possible, which is a major challenge.

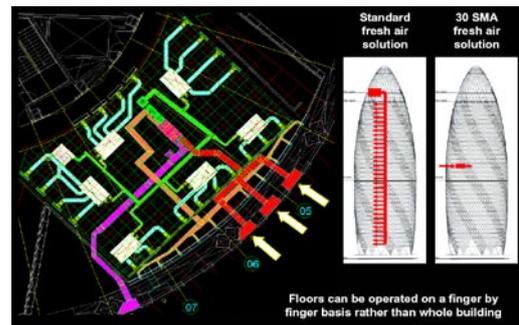


Figure 1 Example of a hybrid ventilation system in the Swiss Re office tower, London (image courtesy Foster & Partners)

Basic mechanisms

The physical mechanisms for natural ventilation of tall buildings are of course the same as those for other buildings i.e. pressure differences are generated across openings in the building envelope, leading to ventilation. The pressure differences are generated by the wind and by gravity acting on density (temperature) differences between the internal and external air.

The wind pressure difference can be expressed in the form

$$\Delta p = 0.5 \rho U^2 \Delta C_p \quad (1)$$

where U denotes the wind speed measured at the height of the building, ρ the air density and ΔC_p is a pressure coefficient which depends on such factors as building shape and wind direction. Wind pressures on tall buildings can be relatively large due to the increased value of U and the exposed nature of the building leading

to high ΔCp . From the viewpoint of natural ventilation design, this means that the system will need to operate over a wider range of wind pressures and this can exacerbate control difficulties.

An overall measure of the buoyancy pressure is

$$\Delta p = \Delta T \rho g h \quad (2)$$

where ΔT denotes the temperature difference, g the gravitational constant and h the height over which the temperature difference acts. Clearly the buoyancy pressures can also be large, if the temperature difference acts over the whole building height, H .

Examples of the pressures that can be generated by these mechanisms can be found in Daniels et al, 1993. This is perhaps one of the earliest and most comprehensive design exercises published for a tall building. It gives a good indication of the importance of building aerodynamics to such designs.

Overall design process

The design of any naturally ventilated building can be a lengthy process involving several stages, which are likely to be iterative. CIBSE AM10 2005, is probably the most comprehensive design guidance available for non-domestic buildings and in principle can be applied to tall buildings.

In very simple terms, the design process can be divided into four stages, as shown in Figure 2. The feasibility of natural ventilation for a tall building will ultimately depend on the acceptability of the design to the client and the building's occupants. Feasibility will also depend on the urban context. For example, the geometry of the surrounding buildings, and their relationship to the prevailing wind and street pattern, can have a significant effect on wind velocities and the pattern of air movement at different levels. Microclimate mapping of cities is being used by planners in Germany (Katzschner, 2000) in assessing the impact of major new developments, and will be used increasingly at the feasibility stage. However, in this paper, our concern is with Stages 2 and 3, which are concerned with the building envelope and are crucial to a successful design. The aim of Stage 2 is to choose a ventilation *strategy* i.e. the flow pattern that is required, which is basically concerned with where fresh air enters the building. There may of course be more than one strategy for different times of the day or year.

Having chosen the pattern, the aim of Stage 3 is to ensure that the magnitudes of the air flow rates through the envelope openings can be achieved over a range of specified conditions. This basically means determining the positions of the envelope openings and the range of their sizes.

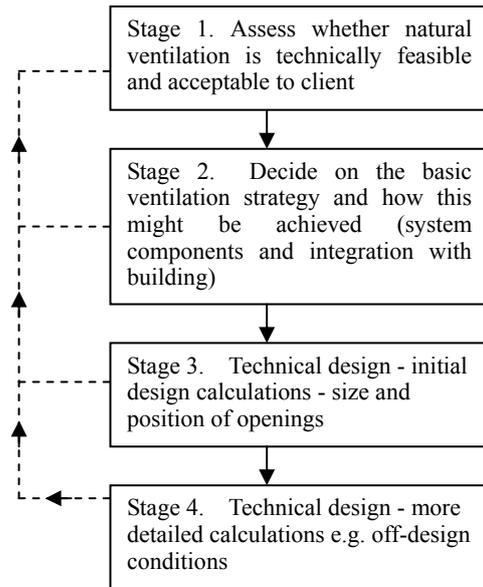


Figure 2. A simplified view of stages in the overall design process (Etheridge, 2007)

Ventilation strategies

The more common strategies are identified in the following. It is relevant to divide them into two basic categories (isolated and connected spaces). In all cases the flow pattern is such that fresh (external) air enters each occupied space. This pattern should be maintained under a wide range of conditions. The magnitudes of the flow rates, as distinct from their directions, are involved in Stage 3.

Isolated spaces. In some buildings the spaces or rooms can be considered as isolated (in terms of air flow) from other parts of the building. For this to be true, the openings to other parts of the building must be small in relation to openings in the external envelope. Figure 3 illustrates such spaces and possible ventilation strategies. Spaces A and B are examples of *single-sided ventilation*, with a large single opening and two small openings at different heights. Spaces C and D are examples of *crossflow ventilation* of an isolated floor, again with large and small openings. In both cases the flow pattern is that due to the action of wind alone. Space E shows the flow pattern due to buoyancy alone.

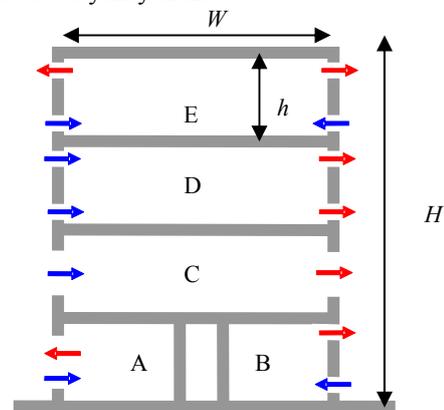


Figure 3. Ventilation patterns for isolated spaces (based on CIBSE, 2005)

From the technical viewpoint there is an advantage to this approach, in that the design for one floor can be studied in isolation from the others and replicated for the other floors (with allowance for different pressures). From the practical viewpoint it may be difficult to achieve complete isolation (bearing in mind the need for lifts and service shafts), but it can be achieved in residential apartment blocks. For example, the impacts of natural ventilation strategies and façades on the indoor thermal environment have been investigated for naturally ventilated residential towers in Singapore (Liping, et al., 2007).

A possible problem with this approach is that it can impose limits on the width to height ratio of the building. It is commonly assumed that crossflow ventilation of a space is only effective for $W/h < 5$, where W and h are respectively the width and height of the space. If W/h is too large, some areas of the space may be poorly ventilated, by virtue of the fact that they receive external air that is no longer fresh. If one takes the limiting value of W/h to be 5, say, the aspect ratio, H/W of a 10-storey building will need to be greater than 2, but for a tall building with 50 storeys it will need to be greater than 10. A possible way round this problem is to divide each floor level into several isolated spaces e.g. in the form of pods.

Another problem with isolated spaces arises from the high wind pressures that can be encountered, whereas the buoyancy pressures remain low, because they are determined by h . This leads to large differences between the open areas required to achieve the flow rates under wind alone and buoyancy alone conditions. An example of this can be seen in the Menara Umno office tower by Ken Yeang, where wing walls were used to encourage cross flow, but where significant variations in internal conditions have been reported (Jahnkassim et al, 2000).

Connected spaces - single-cell building. When the spaces in a building are connected by large internal openings, they effectively form a single-cell, with the flow through any opening dependent on the flow through the other openings. Such spaces are relatively common in naturally ventilated buildings, partly because of the desire to minimize internal resistance to flow and partly to enhance internal mixing. Figure 4 illustrates one such strategy (side "A"), based on the use of an atrium. The atrium is used to generate inward flow of fresh air into all of the occupied floors i.e. crossflow ventilation of all floors. An advantage of this strategy is that wind and buoyancy will act in unison, provided the outlet opening is in a region of relatively low wind pressure and the internal temperature is higher than the external. The same effect can be obtained by means of a stack (chimney), or possibly a stairwell, although fire safety is an issue here.

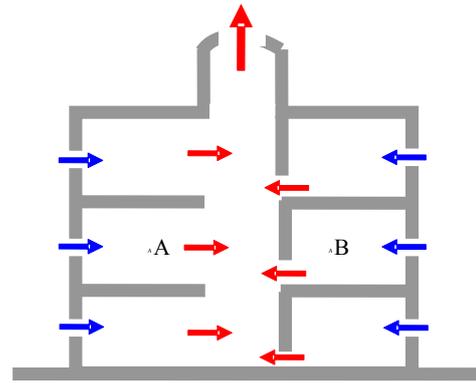


Figure 4. Ventilation patterns using an atrium

The main problem with applying this approach to tall buildings arises from the high pressure differences that can be generated by buoyancy, due to the large value of H in equation 2 i.e. since the building acts as a single space, the overall height H is the determinant of the buoyancy force. Taking $H = 180$ m and $\Delta T = 20$ K the pressure difference across the envelope at ground level could be up to 140 Pa. Such pressures could cause problems in opening doors and windows (the force on a 1.5 m² door would be 210 N). This problem can in theory be overcome by the use of internal resistances (small openings), as shown by the side "B" in Figure 4. This is presumably why the problem is not encountered in mechanically ventilated tall buildings. However, with natural ventilation in a tall building the number of internal openings and their possible permutations would be large and could lead to less predictable behaviour.

There is a way round the problem and that is the use of segmentation i.e. the building is divided into several segments that are isolated from one another by open spaces, as illustrated in Figure 5. The design problem is now to achieve the required flow directions and magnitudes for each segment. This is still likely to be more challenging than the equivalent low-rise building, because of aerodynamic effects around the outlet of each segment, which will depend on wind direction. Some novel approach, such as the axi-symmetric venturi considered by Daniels et al (1993), may be necessary.

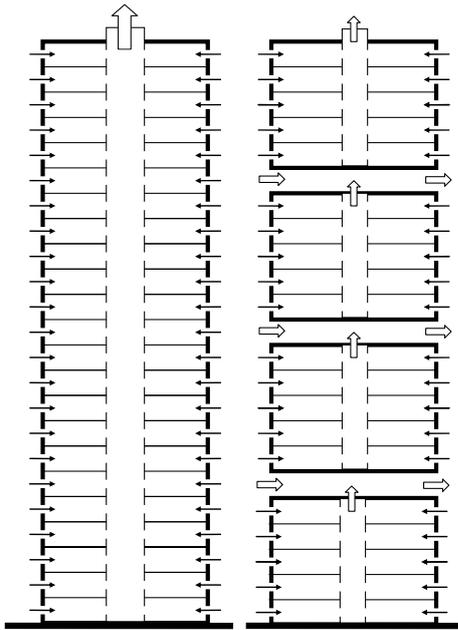


Figure 5. Illustration of segmentation of a tall building

Tall buildings of this nature already exist, including the Commerzbank by Norman Foster, Figure 6, and the Menara Mesiniaga by Ken Yeang.

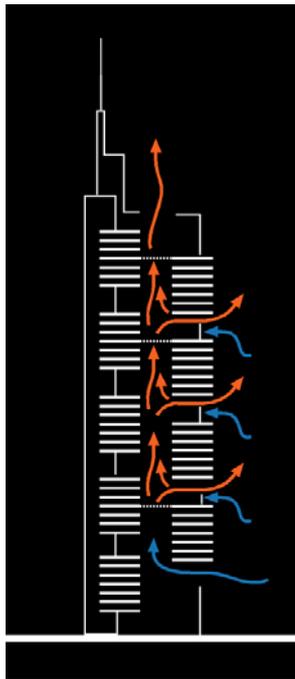


Figure 6. Sectional diagram of Commerzbank (courtesy of Foster & Partners)

The open space can be in the form of a “skycourt”, Figure 7. With this strategy each segment can be designed in isolation, using conventional procedures. Such an approach is therefore potentially less risky.

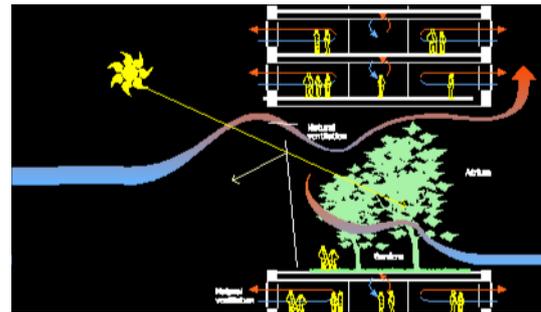


Figure 7. Part section through Commerzbank office/skycourt (courtesy of Foster & Partners)

Envelope openings

Having chosen the ventilation strategy it is necessary to determine the flow rates required under specified conditions (e.g. heating and cooling seasons). This is by no means a trivial exercise, but once completed the required sizes of the openings can be determined for each condition. For isolated spaces and single-cell spaces, the sizes can be found analytically by an explicit solution of an envelope flow model. For buildings with internal resistances multi-cell envelope models are readily available. Double-skin facades fall into the same category.

Envelope flow models can of course be used to look at off-design conditions (Stage 4 in Figure 2). Some preliminary calculations using an envelope flow model have been carried out as part of an undergraduate project that looked at the potential benefits of segmentation (Davey, 2006). As shown by the simple example in Figure 8, segmentation can offer a reduction in the variation of fresh air entry rate with floor height i.e. the variation is 2 to 23 m³/s for the complete building, but only 5 to 11 m³/s when the building is split into three segments. This is a somewhat artificial example, because the openings on each floor were taken to be equal. However it implies a greater level of control as a result of segmentation.

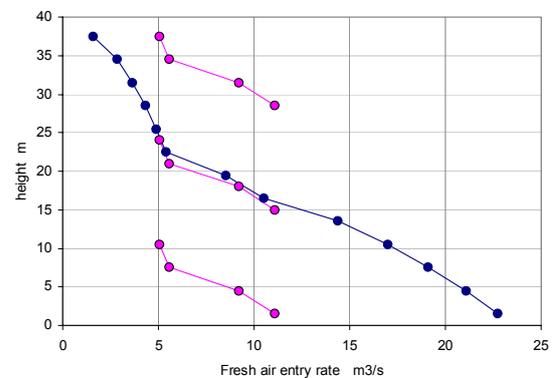


Figure 8. Variation of fresh air entry rate with height – effect of segmentation (Davey, 2006)

Innovative envelopes

It is not just the openings in the envelope that are important to natural ventilation. The fabric of the envelope can provide one or more of the following functions:

- adventitious leakage
- thermal insulation
- thermal storage (for night cooling)
- environmental conditioning (e.g. double-skin façade)

Adventitious leakage is usually considered undesirable during the heating season and the nature of the construction of tall buildings (pre-fabrication of components and assembly to close tolerances) lends itself to minimise this source of leakage. This feature of tall building construction could also lend itself to innovative forms of envelope related to the other three functions.

One particularly interesting idea is the use of porous envelopes through which the ventilation air is induced to enter (basically purpose-designed adventitious leakage). During the heating season, the envelope acts as dynamic insulation (the U-value of the fabric is reduced to near-zero). Calculations have shown that it is theoretically possible for dynamic insulation to work with natural ventilation i.e. without the use of electric fans (Etheridge and Zhang, 1998).

Thermal storage is particularly useful with natural ventilation to provide cooling during the day by means of cooling of the fabric during the night. This is now a recognised technique and various enhancements using phase change materials are under development. Studies at Nottingham and elsewhere have looked at the feasibility of using porous materials. Basically the porosity of the material should increase the extent to which the material is cooled during the night (Tan, 2000).



Figure 9. Deutsche Post Office Tower, Bonn (Murphy Jahn, 2003)

Tall buildings may also lend themselves to certain types of double-skin façade. The main advantages of a double skin (or ventilated façade) is that it can provide a thermal and acoustic buffer between interior and exterior. They have been used extensively in office buildings in Germany to promote natural ventilation of the interior, using the driving force of thermal buoyancy generated within the glazed cavity.

Ventilated facades on tall buildings can provide the driving force for a segmented natural ventilation strategy and help to control varying diurnal and seasonal ventilation requirements. This strategy was adopted in the Deutsche Post office tower in Bonn by Murphy Jahn architects (completed 2003). Air in winter is tempered in the cavity of the outer double skin and then drawn through the perimeter office spaces and exhausted via the nine storey high 'sky gardens' which are stacked vertically between the two halves of the building.



Figure 10. Deutsche Post office tower, Bonn (Murphy Jahn 2003)
External view from west.

Natural ventilation of the Deutsche Post tower occurs primarily in the Spring and Autumn, and during extremes of summer or winter a displacement system, driven by a perimeter convector, cools or heats the supply air along the perimeter. Although the building is therefore 'mixed mode', it does not use a centralised mechanical back-up system, and therefore has advantages in terms of space savings. Not only did this strategy save a whole floor of plant, but also the lack of ductwork has meant lower floor to floor heights. This approach is also very responsive to the occupants, who can open a window at any time if they want fresh air, and the action of opening the window switches off the perimeter convector.

Unfortunately, ventilated facades have a tendency to overheat, and raise the cooling load of the adjacent occupied spaces (Ford, and Schiano-Phan, 2005). Strategies adopted to mitigate this tendency can lead to higher envelope costs. However, we are moving to the point where conventional heating and cooling systems may no longer be required in tall buildings in many locations this will lead to reductions in capital, maintenance and running costs.

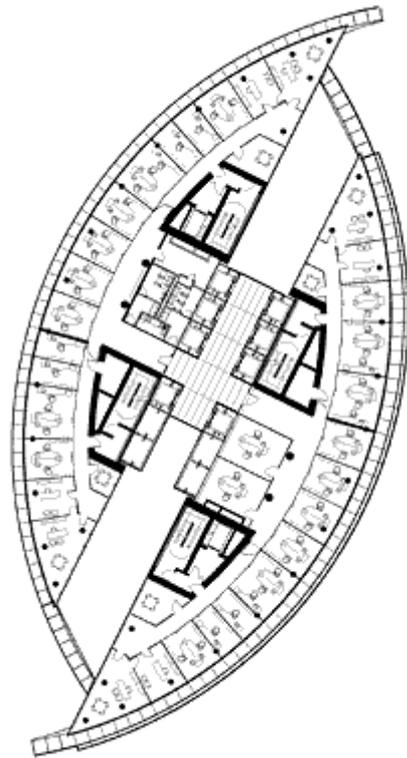


Figure 11. Deutsche Post Tower, Bonn (Murphy Jahn, 2003) Typical Floor Plan showing double skin & 'sky courts'.

Conclusions

A purely naturally ventilated building is a major challenge to the designer even for conventional buildings. In terms of designing the envelope and its openings, the challenges for tall buildings are greater, partly because the potential magnitudes of the two driving forces (pressures due to wind and buoyancy), become greater and their relative magnitudes can vary over a wider range. The high exposure of a tall building to wind means that means that building aerodynamics becomes particularly important. Furthermore, the sheer number of openings means that the permutations of envelope configurations is greatly increased.

Segmentation offers the least risky approach for envelope design of non-residential buildings, provided the aerodynamic effects can be reliably accounted for. The potential for innovative envelopes (e.g. porous walls and ventilated facades) is increased, by virtue of pre-fabrication and high quality construction.

If strategies for natural ventilation can be determined that are robust enough under widely varying conditions, the era of the naturally ventilated tall building may have arrived.

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