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VENTILATION

Simulation tools for analysing natural ventilation of large enclosures with large openings

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This paper briefly describes two modelling approaches for natural ventilation of large enclosures with large openings. The first model is called SIX, a Single-cell Infiltration and eXfiltration calculation approach, based on Bernoulli's equation. The model assumes a fully mixed flow pattern in the enclosure. The model uses a single-element approach for considering bi-directional flows through a large opening.

The second model is based on Ventair, a three-dimensional Computational Fluid Dynamics (CFD) program developed at CSIRO. In Ventair, simple pressure boundary conditions, which include the wind-induced pressure at boundaries, are specified at each opening. While both models can simulate effectively the overall air change rate in the enclosure, the CFD approach can also predict the internal flow pattern, temperature and concentration distributions.

An example application is presented for Sydney's Flemington Market, in which both models have been applied. From an engineer's point of view, there is fairly good agreement between the results predicted by the two models. While it is not our intention to present a perfect solution to this complex ventilation problem, the models developed can provide some design guidance for practical engineers. An experimental technique is needed to provide validation for the tools developed.

Introduction

A new trend in ventilation

There is an encouraging new trend toward the use of natural ventilation over mechanical ventilation both in Australia and in Europe. With moderate weather in many parts of Australia, large enclosures with large natural ventilation openings have been used for a wide range of purposes, eg. free markets, wholesale markets, industrial equipment and processes, central railway stations and so on.

In these enclosures, natural ventilation has been a very effective way of removing contaminants and excess heat. The new draft Australian Standard AS1668.2 on ventilation of buildings has included natural ventilation for the first time. However, the draft does not mention any methods for analysing natural ventilation systems. Simple design methods are available for simple natural ventilation systems, eg. CIBSE (1988), BS5925 (1991) and Md. Mizanir (1993).

In the last ten years, there have been a number of international projects on natural ventilation, such as PASCOOL and the IEA Annex 5, 20, 23 and 26. A new Annex project on Design of Energy-Efficient Natural Ventilation in New and Retrofitted Buildings has been recently proposed. It is often recognised that natural ventilation is energy efficient and environmentally friendly provided it can be controlled, which requires a good prediction tool.

Ventilation engineers and scientists have developed a number of practical and mathematical models for determining ventilation airflow rates. It is now possible to describe quantitatively the basic flow mechanisms and characteristics, although they have not been fully understood and there is still a need to improve accuracy.

Airflow problems

It is commonly accepted that natural ventilation is "*the airflow resulting from the designed provision of specified apertures such as openable windows, ventilators, shafts, etc. and can usually be controlled to some extent by the occupant*" (CIBSE, 1988). On the other hand, the terms infiltration and exfiltration are used to refer to "*the fortuitous leakage of air through a building due to imperfections in the structure*" (CIBSE, 1988).

In this paper, these definitions will be followed. The supply airflow and exhaust airflow in natural ventilation will be simply called air inflow and air outflow respectively. Due to the mass conservation principle, the total air inflow should equal the total air outflow.

With natural ventilation, there are two distinct but related ventilation airflow problems (see Figure 1), namely the airflow rate problem — how much air enters and leaves a building (or a room) through ventilation openings; and the air distribution problem — how fresh air distributes and contaminants disperse in enclosed spaces.

Many ventilation codes specify the minimum specific ventilation flow rates (or air changes per hour) for indoor air quality. A natural

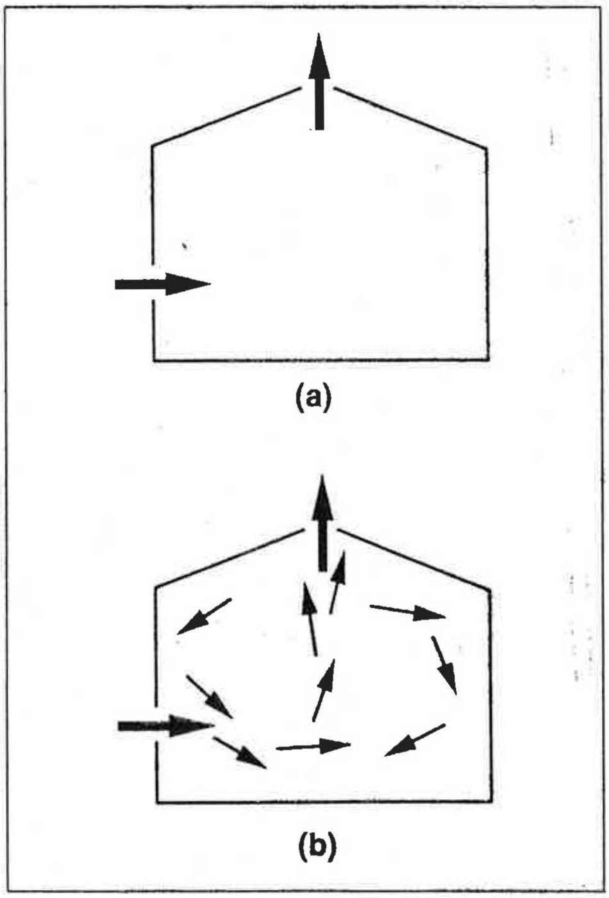

Figure 1. Illustration of airflow problems in natural ventilation of buildings: (a) airflow rate problem; (b) air distribution problem.

ventilation designer always needs to check whether the ventilation inflow provides sufficient fresh air or if additional means of supply will be needed. However, the specific ventilation flow rate alone cannot determine the ventilation performance (Li and Holmberg, 1996).

If the internal airflow pattern is not uniform, which is more likely to occur with natural ventilation than with mechanical ventilation, the air distribution should be analysed in order to predict whether the system meets the design criteria.

Large openings

Large openings are those with relatively large vertical length scales compared to the building height. These openings can be fully openable, such as windows, doorways and ventilators, or porous, such as an entire wall with uniform background leakages. Natural ventilation openings can be grouped into three basic types, according to their location:

- vertical openings — openings located in vertical walls;
- horizontal openings — openings located in horizontal ceilings or floors;
- inclined openings — openings located in inclined roofs. Some window openings may also be classified as inclined openings.

Etheridge and Sandberg (1996) provided a detailed review of the existing knowledge about the geometry, location and distribution of ventilation openings.

The airflow rate through an opening depends upon its area and flow resistance, and the pressure difference across it. The pressure differential can be introduced by either the wind, or an indoor and outdoor air density difference due to a temperature difference, or a combination of the two. This paper concentrates on large enclosures with large ventilation openings. With a large opening, the pressure difference across it varies along its height. Bi-directional flow may also occur under common conditions.

Purpose of the paper

Two simulation tools for both airflow rate and air distribution predictions are presented for large enclosures with large ventilation openings. These are the SIX program, for predicting ventilation airflow rate and the Ventair program, for predicting both the ventilation airflow rate and air distribution in buildings. When needed, the building thermal analysis program CHEETAH is used to provide indoor air temperature for SIX simulations, which again provides ventilation airflow rates for CHEETAH and thermal boundary conditions for Ventair predictions.

An example application is presented for the Sydney's Flemington Market, in which both models have been applied. The airflow rates predicted by both SIX and Ventair will be compared.

SIX: airflow rate predictions

General simulation procedure

For airflow rate problems, a general mathematical procedure is to first quantify ventilation openings, then calculate total pressure differences across each opening, express the flow rates as a function of pressure differences, and apply the air mass balance in each zone of a building to determine internal pressures in each zone, which are finally used to calculate the ventilation flow rate through each opening. The procedure is iterative. To simplify pressure difference calculations, most existing models assume that the flow through an opening is unidirectional (see Liddament and Allen, 1983).

Bi-directional flows and single element approach

To the authors' knowledge, no other infiltration programs fully consider bi-directional flows for both external and internal openings. The need for such a model will be illustrated.

For a large opening centrally located in a vertical wall, when there is no net airflow, the neutral height is at the middle height of the opening. The neutral height occurs where the indoor and outdoor pressure difference is zero. The indoor air temperature is assumed to be uniform, so as the outdoor air temperature. The indoor air is warmer than the outdoor air. There is a linear distribution of the pressure difference (see Figure 2). The possible velocity profile across the opening is also sketched in Figure 2. It is clear that the flow across this opening cannot be assumed to be unidirectional.

For the same opening, assume that there is an air supply in the room which will introduce a net outflow across the large opening. The additional supply air will in fact increase the room air pressure. This room pressure will effectively reduce the height of the neutral pressure level. The pressure difference distribution and the velocity profile are shown in Figure 3. The effect of changing the neutral levels can also be achieved by a wind pressure. A typical situation is shown in Figure 4. The wind velocities and the pressure coefficients along the building height are assumed to be uniform.

The above discussion indicates that consideration of bi-directional flows is necessary for an enclosure with large ventilation openings in its envelope. Some airflow rate models divide a large opening into smaller openings to simulate different magnitude and direction of airflows at different heights. While there is always a problem of how many divisions are optimum, this method also increases the number of flow openings and the computational time. This method is referred to as the *multiple element approach* here.

An alternative method is the *single element approach*. In this method, the pressure difference profile due to both temperature difference and wind pressure across an opening is first established, and neutral heights, where the pressure difference is zero, are then

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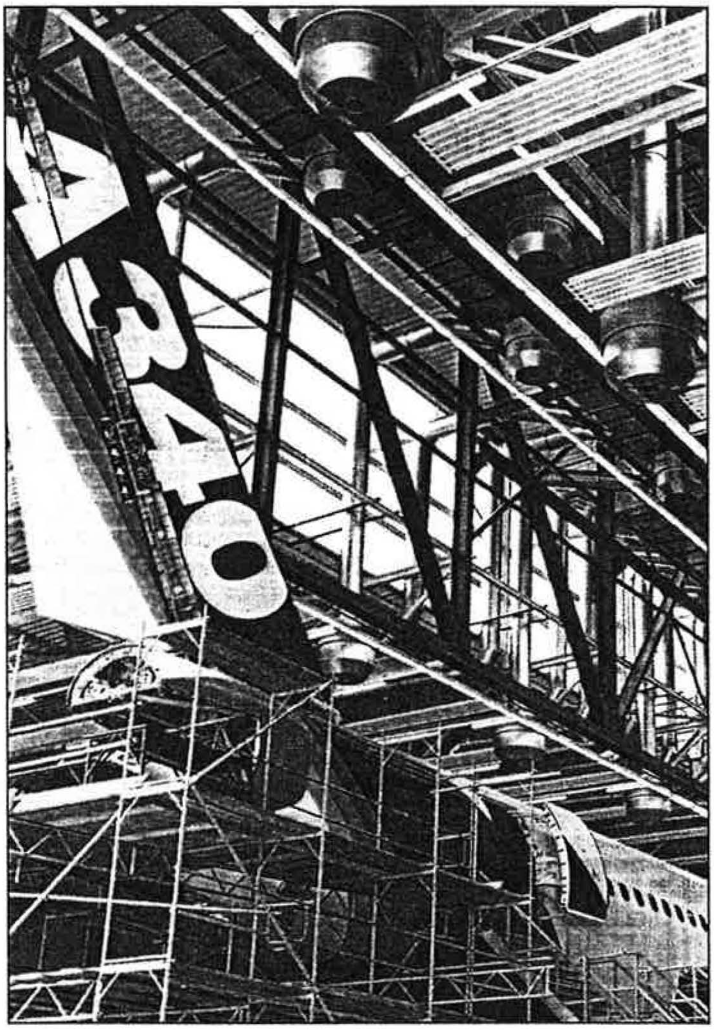

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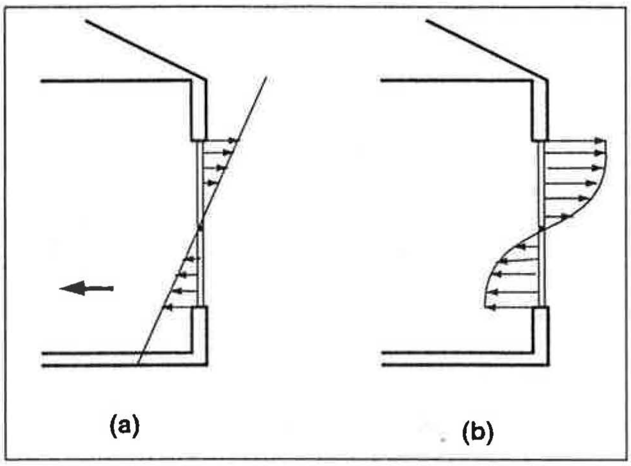

Figure 2. Pressure distribution (a) and velocity profiles (b) in a large opening. There is no net flow across the opening.

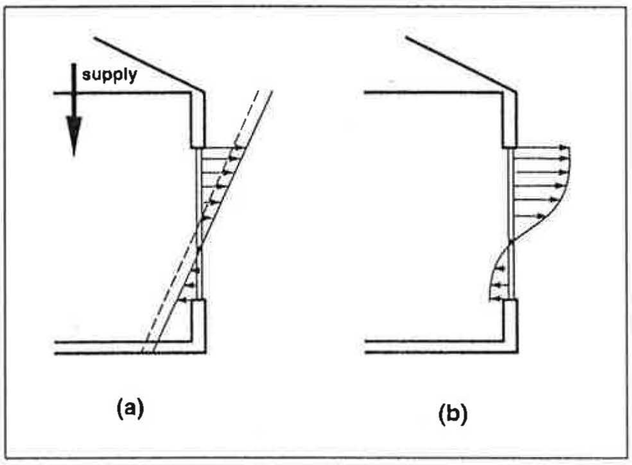

Figure 3. Pressure distribution (a) and velocity profiles (b) in a large opening. A net outflow is introduced across the opening due to supply air in the room.

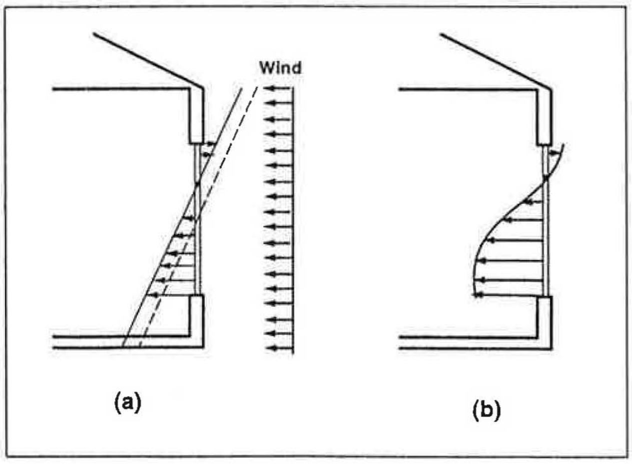

Figure 4. Pressure distribution (a) and velocity profiles (b) in a large opening. A net inflow is introduced across the opening due to wind.

calculated.

The bi-directional airflow rates are determined assuming the orifice equation is valid at each differential height, which is then integrated along the height (see Li and Peterson, 1990).

This single element approach uses the same orifice equation for flow rate calculations as in the multiple element approach. It has at least the following advantages:

• For simple situations, a large opening can be modelled as, at most, two flow subelements — one as an infiltration element and the other as an exfiltration element. The method is in theory more accurate than the multiple element approach. Computational time is also reduced.

• For a certain area in building envelopes or building partitions where many small background openings exist, eg. in a window area with gaps along its frame or an entire wall with cracks, ventilation openings can be modelled collectively as a single large area with small but uniform permeability. Of course, the flow mechanisms are different from those large openings. Bi-directional flows may also exist through these "large" areas. Modelling of these small openings becomes relatively easy in this single element approach as there is no need to define such small openings individually, which is often difficult.

This single element approach is the basic modelling methodology in SIX. The basic formula was first presented by Li and Peterson (1990) for a Multi-cell Infiltration and eXfiltration (MIX) model. MIX has been used for a number of useful applications, including indoor air quality analysis, ventilation analysis, development of simplified methods for combining natural and exhaust ventilation, and calculation of boundary conditions for CFD (see Li, 1993). Since then, the mathematical formulations of MIX have been further developed to include the treatment of vertical air temperature gradients and non-uniformity of wind velocity profiles which can introduce a possible multi-directional flow, and these formulations will be presented elsewhere.

There are many other difficult aspects of infiltration modelling, such as unsteady flow characteristics of ventilation openings, effects of wind pressure fluctuations, determination of pressure coefficients and treatment of special flow paths such as chimneys. Most of these aspects were considered or discussed in detail by Etheridge and Sandberg (1996) and in the original MIX program.

The bi-directional flows through openings considered here are those mainly driven by pressure differences. Thus, the bi-directional flows can only occur across vertical openings. There is another type of bi-directional flow which occurs through horizontal openings due to temperature differences. The occurrence of this bi-directional flow also interacts with pressure-difference-driven flows. This flow will not be considered here although it can be accommodated in the present theoretical framework.

Theoretical Background

For the single-zone building in Figure 5, the building zone is labelled as zone 1 and the outside as zone 0. The middle zone height H_1 is taken as the datum level (pressure reference level). The pressure at any height can be expressed as

$$p_t(z) = p_0 - \int_{H_1}^{z} \rho g dz + \frac{1}{2}\rho C_p(z) v^2(z) \quad (1)$$

where C_p is the pressure coefficient, v is wind speed, ρ is the density of the air and g is the gravitational acceleration. On the right-hand side, the first term is the reference hydrostatic pressure at middle zone height H_1, and the last term is the pressure due to air motion. C_p is the pressure coefficient and $-1 \leq C_p \leq 1$. Both C_p and v can be a function of height z.

As airspeeds within buildings are relatively low, it is often reasonable to neglect the pressure change due to indoor airflow. However, in enclosures with very large openings, such an assumption may not be valid.

At height z close to the vertical wall or opening, the indoor and outdoor pressure can be obtained as follows:

$$p_{t1}(z) = p_{10} - g\int_{H_1}^{z} \rho_1 dz$$

$$p_{t0}(z) = p_{00} - g\int_{H_1}^{z} \rho_0 dz + \frac{1}{2}\rho_0 C_p(z) v^2(z) \quad (2)$$

The total pressure difference across the opening at height z is obtained as:

$$\Delta p_{tot}(z) = p_{t0}(z) - p_{tI}(z)$$
$$= \frac{1}{2}\rho_0 C_p(z) v^2(z) - g\int_{H_I}^{z}(\rho_0 - \rho_I)\,dz - (p_{0I} - p_{00}) \quad (3)$$

In SIX, a positive pressure difference always means an inflow to the zone considered. The term $p_{0I} - p_{00}$ can be defined as the room internal pressure, p_I, at the datum level H_I relative to the ambient pressure at the same level.

For large openings, an orifice flow rate equation may be applied with an appropriate discharge coefficient, C_d, viz.

$$q = C_d A\sqrt{\frac{2\,|\Delta p_{tot}|}{\rho}}\,\mathrm{Sgn}(\Delta p_{tot}) \quad (4)$$

In the multiple element approach, the opening is divided into small parallel sub-openings and flow rates are calculated individually for each small sub-opening.

In the single element approach, no division is needed. The theory is simple. For a differential height dz, the flow equation of Equation (4) is valid as

$$dq = C_d b\sqrt{\frac{2\,|\Delta p_{tot}|}{\rho}}\,\mathrm{Sgn}(\Delta p_{tot})\,dz \quad (5)$$

where b is the opening width.

With $\Delta p_{tot}(z) = 0$, the neutral levels z^* can be determined. In general, numerical solution methods need to be applied to obtain z^*. Based on the obtained neutral levels, the opening $z_l - z_h$ of width b is divided into N + 1 sub-openings, where N is the number of non-equal neutral levels within the opening height and it is assumed that $z_l < z_1^* < z_2^* \ldots < z_N^* < z_h$. In each sub-opening, the flow rates can be obtained simply by integrating Equation (5). For general situations, numerical integration will be needed to evaluate the integral.

In SIX, analytical solutions of neutral levels and simple expressions of flow rates as a function of internal pressure p_I are developed to simplify the calculation procedure, which will not be detailed here.

It should be mentioned that in SIX, the indoor air temperature is a necessary input. Our approach to obtain the indoor air temperature is to integrate SIX with a building thermal analysis program, such as CHEETAH. In fact, ventilation flow rates are the necessary input for building thermal analysis. Thus, the whole process is iterative (see Figure 6).

Ventair: airflow pattern predictions

Ventair program

Ventair is a CSIRO CFD software package, specially developed for building ventilation applications. It uses the conventional finite volume methods for discretising the three-dimensional

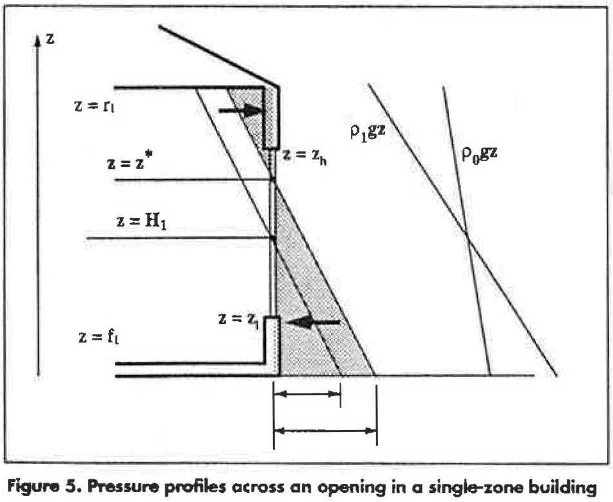

Figure 5. Pressure profiles across an opening in a single-zone building

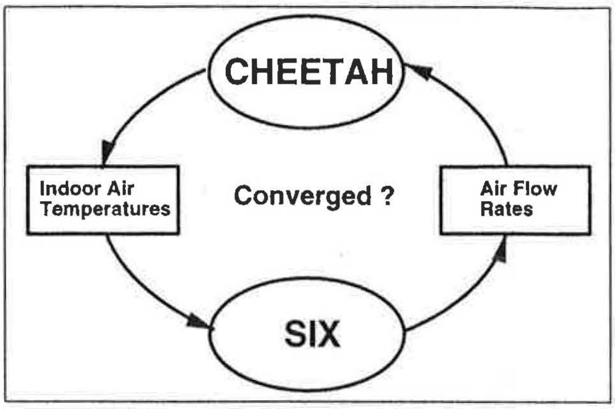

Figure 6. Illustration of the CHEETAH and SIX coupling

flow equations. It always draws on the most recent developments in CFD algorithms, and flow and heat transfer modelling in CSIRO and worldwide. The core of Ventair, like many other CFD programs, applies generally to other incompressible flow problems and, indeed, Ventair has been adapted for other engineering flow problems such as those in mineral engineering. From a building application point of view, its label *Ventilation AirFlo Dedicated* comes from the following features:

- Ventair fully addresses the ventilation air distribution concept. It calculates the three-dimensional distribution of age of air, residence time of contaminants, residence time of air, and thus the ventilation effectiveness and air exchange efficiency. It also calculates the contribution ratio of each ventilation opening in a multiple opening system.
- Various flow sub-models have been developed to model different flow components in ventilation airflow systems, such as large natural ventilation openings, small porous supply registers, regions with small-scale obstructions which are difficult to resolve geometrically, surface radiative heat transfer, etc.
- The code has been validated for many typical flow situations and flow elements which are often found in building airflow situations.

The program Ventair has been described elsewhere and applied to many building ventilation problems (see for example Symons et al. 1996). The discussion here will concentrate on the treatment of large openings.

Treatment of outdoor airflow

Li and Holmberg (1994) suggested three possible approaches to study the interaction between indoor and outdoor thermal environments.

- First, the computational domain can be enlarged to include the outdoor region around a building. The wind around a building and indoor airflow are simulated simultaneously. However, the enlarged dimension also increases the computational cost.
- Secondly, the enlarged domain can be divided into a set of simple sub-domains, eg. outdoor domain and indoor domain, within each of which a grid is generated. The problem can then be solved by computing alternatively the smaller problems in each sub-domain and matching these local solutions by interpolation at joined or overlapped regions.
- The third approach is to limit the computational domain to an indoor domain. The interaction between indoor and outdoor thermal environments is specified at the boundary. An advantage of this simple approach is that the existing experience developed by the HVAC community in modelling multi-room building infiltration, specifying the leakage distribution, and calculating thermal behaviour of buildings, can be used.

A concept of general flow and thermal boundary conditions has been developed and was discussed by Li and Holmberg (1994). It was suggested that the airflow rates predicted by SIX-like programs across the envelope, between rooms, and

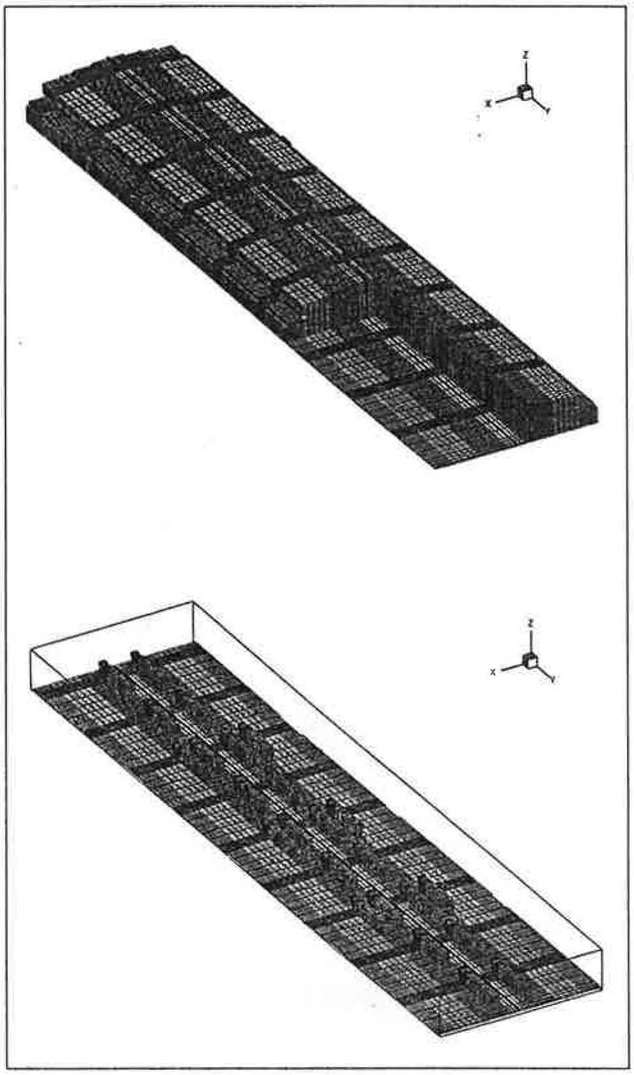

Figure 7. Computational grids: top - grids for the envelope; bottom - trucks and their locations. Finer grid resolutions are provided in the truck heat regions and roof opening regions.

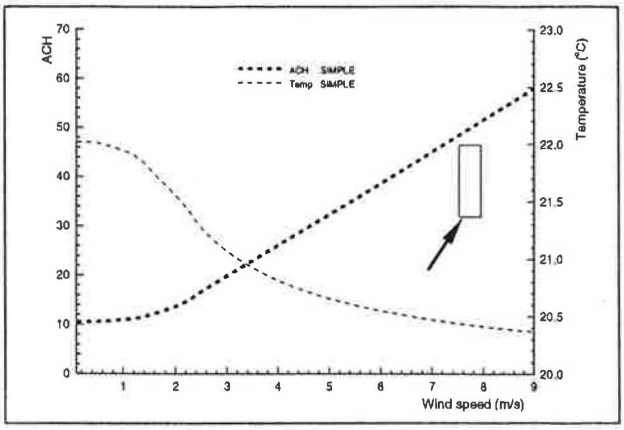

Figure 8. Air change rate and temperature predicted by SIX for summer conditions with NE wind and outdoor air temperature of 20°C

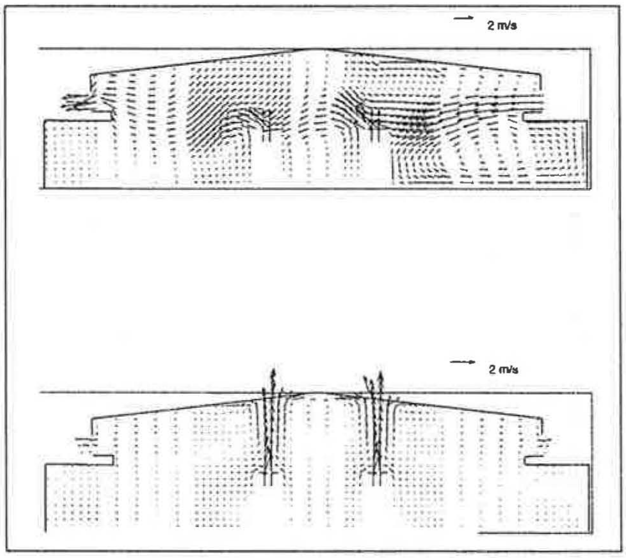

Figure 9. Velocity field at a vertical plane cut through the two centre trucks (100m length): top - NE wind (3 m/s) with outdoor air temperature of 20°C; bottom - NE wind (0.1 m/s) with outdoor air temperature of 20°C. No roof ventilator is installed.

through the mechanical ventilation system can be used as the boundary conditions in CFD simulations.

Simple pressure boundary conditions

In addition to the three approaches discussed above, an alternative way of specifying flow boundary conditions at natural ventilation openings has been evaluated, ie. by specifying the pressure, which can include the wind pressure. No knowledge of airflow rate or velocity distribution across an opening is needed for this boundary condition. However, the velocity direction has to be specified.

At an opening, the pressure is specified as

$$p_0(z) = \frac{1}{2}\rho_0 C_p(z) v^2(z) \qquad (6)$$

The pressure at the first grid point near the opening is p_{int}, which is calculated in the solution procedure.

When $p_0 > p_{int}$, there is an inflow, and the normal inflow component is determined by

$$v_{in} = \sqrt{\frac{2(p_0 - p_{int})}{\rho}} \qquad (7)$$

When $p_0 < p_{int}$, there is an outflow, and the normal outflow velocity component is determined by

$$v_{out} = \sqrt{\frac{2(p_{int} - p_0)}{\rho} + v_{int}^2} \qquad (8)$$

The two tangential inflow or outflow velocity components are determined by the flow direction. A first reasonable approximation for the inflow direction is the wind direction and that for the outflow direction is the indoor airflow direction near the opening, i.e. a zero gradient boundary condition is used.

Examples

The problem

The example enclosure to be presented here is in Sydney's Flemington Market. The enclosure is the space enclosed by the two warehouses, the canopy (roof) and the two end openings. The enclosure is about 200m x 46m x 10m = 92,000m³. There are two side openings at the roof level with each opening about 2m high. In the enclosure, there are always 18 loading/unloading trucks on two centre lanes with six additional trucks on two circulation lanes from midnight to 4:00 am, which is the period for this study. The trucks are the main sources of heat. The need for a ridge vent needs to be studied. There is no other additional mechanical ventilation system for the space. Removal of truck exhaust gases will rely on natural ventilation and moving-truck-induced flows in the enclosure. There are basically two mechanisms for inducing natural ventilation, namely temperature difference and wind pressure.

• Temperature difference between the air in the enclosure and the

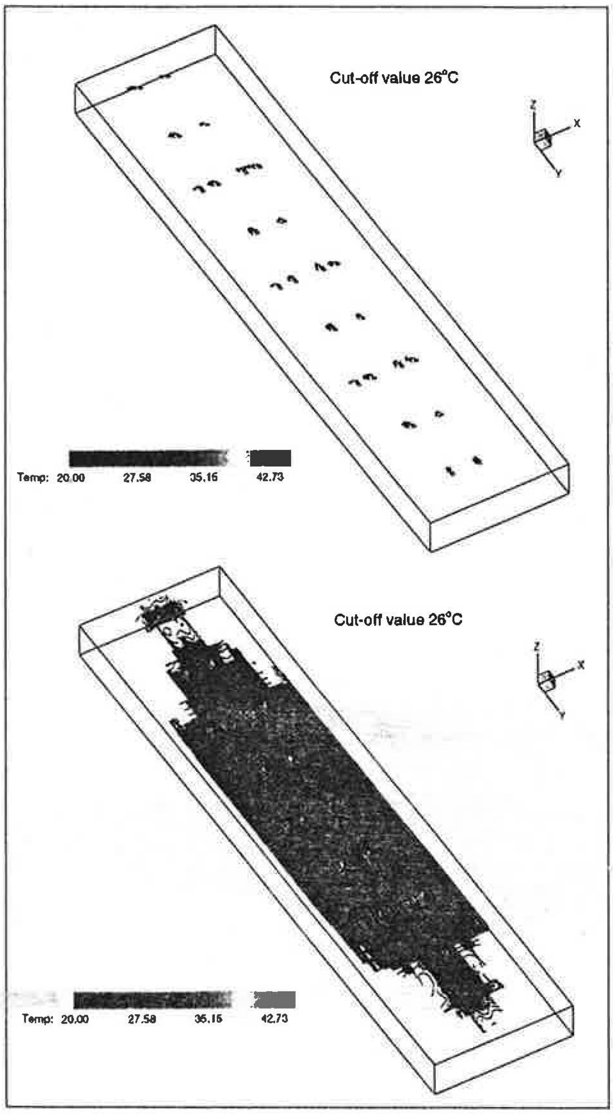

Figure 10. High temperature regions: temperature fields (°C) with any values less than 26°C are blanked. Top - NE wind (3 m/s) with outdoor air temperature of 20°C; bottom - NE wind (0.1 m/s) with outdoor air temperature of 20°C. No roof ventilator is installed.

outdoor air: It is expected that both loading and unloading trucks in the enclosure will produce heat and this will increase the air temperature, which provides a chimney effect to induce air exchange between the enclosure and the outdoor.

• Wind pressure: As the canopy is about 2m above the warehouse and both ends of the enclosure are open, the wind-induced flow will be considerable for winds of any direction. The worst case will be when there is no wind in any direction.

• Moving-truck-induced flow: Trucks entering or leaving can induce some air exchange through the end openings, which is estimated to be about 0.13 air changes per hour. Additionally, while slowly driving in the enclosure, trucks can also contribute to internal airflow mixing, which is difficult to model and was not considered in this study.

For night conditions, it is assumed that there is no heat transfer across the ground, roof and surrounding wall surfaces. For day-time conditions, CHEETAH integrated with SIX was used to predict the indoor air temperature. The pressure coefficients used in this work were obtained from AS1170.

For Ventair simulations, a typical grid is shown is Figure 7. The positive y-direction is north and the positive x-direction is west.

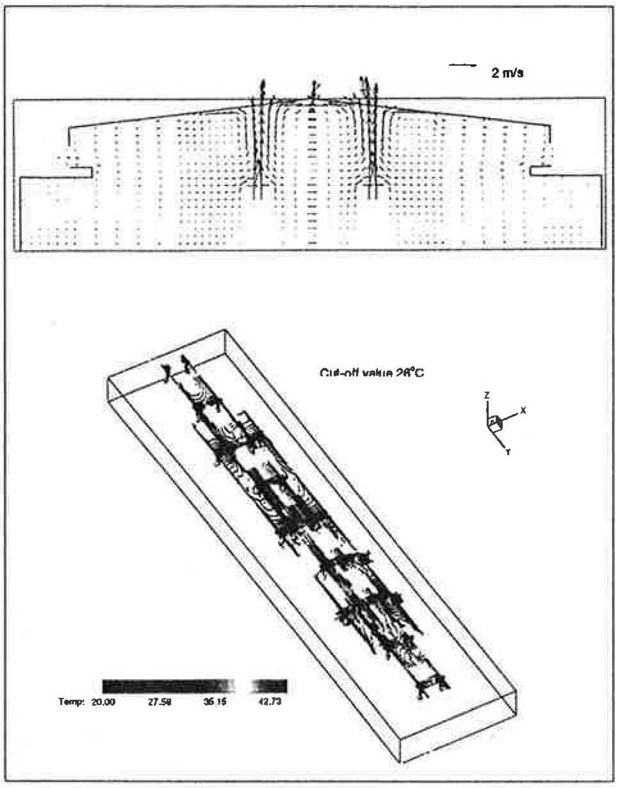

Figure 11. Top - velocity field at a vertical plane cut through the two centre trucks (100m length); bottom - high temperature regions (°C): temperature fields with any values less than 26°C are blanked. E wind (0.1 m/s) with outdoor air temperatures of 20°C. Streamline roof ventilators are installed.

The total number of grid points used is either 56 x 122 x 22 = 150,304 or 62 x 122 x 22 = 166,408.

Each Ventair run takes about 26 hours on a R10000 Indigo2 computer. The truck gas exhaust is modelled as a porous opening, because the area used for the CFD calculation is larger than the real value. To ensure that the simulation is representative of the design, the momentum and volumetric flow rate of the supply air are maintained at their real values by adjusting the free area of the porous opening.

Air change rate

Air change rates (air changes per hour) predicted by SIX and Ventair for six different cases are compared in Table 1. Considering the differences between the two methods, the agreement is fairly good. The largest difference occurs when there is a west wind, which generates a mixed flow pattern in the enclosure as shown by the Ventair predictions. The flow characteristics at the two end openings are very complex, which indicates that the assumption of neglecting the indoor airflow-induced pressure may not be fully valid in SIX.

The effect of wind speeds is shown in Figure 8. The air change rate increases almost linearly as the wind speed increases beyond 2 m/s. At lower wind speeds, ventilation is dominated by the stack effect. If we assume that all the heat generated by the trucks will be carried away by ventilation air, the average air temperature can be calculated by SIX. The result is also shown in Figure 8. It shows a maximum air temperature when the wind speed is less than 0.1 m/s and, as expected, the air temperature decreases as the wind speed increases.

Airflow pattern

The trucks are considered to be stationary in this project, because to include moving trucks in a CFD simulation is still a very time-

Case	SIX prediction	Ventair prediction
West wind (3 m/s), outdoor air (5°C)	20.9	28.8
NE wind (3 m/s), outdoor air (20°C)	19.9	21.6
NE wind (1 m/s), outdoor air (20°C)	11.0	8.6
NE wind (0.1 m/s), outdoor air (20°C)	10.6	7.9
West wind (3 m/s), outdoor air (20°C)	20.9	28.9
South wind (3 m/s), outdoor air (20°C)	20.5	25.9

Table 1: Comparison of predicted air change rates under different conditions.

consuming and expensive approach. An unsteady solution and a moving CFD gridding approach would have to be undertaken.

Two typical flow patterns at two different wind speeds predicted by Ventair are shown in Figure 9 for a vertical plane. The corresponding plots of high-temperature regions are shown in Figure 10. At a high wind speed (3 m/s), the flow pattern is of a cross-ventilation type. Air enters from windward openings, induces large circulations in the enclosure, and finally exits from the leeward openings. This flow pattern is very effective in removing contaminants and excess heat. At a low wind speed (0.1 m/s), the flow is stratified. Plumes from the exhaust gas and the body of heated trucks flow upward, hit the ceiling, turn around and form a stable stratified flow pattern. The air temperature is high in the upper region.

When a ridge vent is installed, the velocity field and the high temperature regions are shown in Figure 11. Clearly, the ridge vent is very effective in removing excess heat and achieves additional ventilation for the enclosure.

Conclusions

Two simulation tools for natural ventilation with large openings are briefly discussed in this paper. The first program, SIX integrated with CHEETAH, is able to predict air change rates for natural ventilation with large openings. The second program, Ventair, is capable of predicting both air change rate and airflow pattern. The air change rates predicted by SIX and Ventair for an example large enclosure agree well. Although this agreement provides some confidence in these predictions, it does not necessarily indicate that the simulation tools presented here are ideal. Reliable experimental techniques are needed, not only as possible design tools, but also to provide experimental validation to analytical models such as those developed here. Such an experimental tool is not available at present, especially for large enclosures with large ventilation openings. Work currently undertaken includes consideration of vertical temperature gradients, vertical wind velocity profile and integration of a multi-cell version of SIX into CHEETAH.

Acknowledgment

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