UNRESOLVED ISSUES IN NATURAL VENTILATION FOR THERMAL COMFORT

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ABSTRACT

An historical background of fluid mechanics used in computation of natural ventilation is provided. Unresolved issues in computation of natural ventilation for thermal comfort are discussed. These issues include the influence of building porosity on wind pressure difference coefficients; wind shelter effects; indoor air flow resistance; air flow for thermal comfort and heat stress relief; air flow computation techniques; and natural ventilation in home energy rating schemes. It is concluded that despite rapid advances in sophisticated computer analysis techniques, development of simpler natural ventilation computation methods is needed for use in the preliminary stage of building design.

1 INTRODUCTION

Mankind has taken advantage of natural ventilation for thermal comfort in built environments for as long as built environments have existed. Ancient records from Egyptian times refer to orientation of buildings to prevailing winds as do Greek, Roman, and Chinese records (Aynsley et al, 1977). This utilisation of natural ventilation was based on empirical knowledge gained from observation. It was not until the development of instruments to measure atmospheric pressure and wind speed that there was an opportunity for a theoretical approach.

The science of fluid mechanics began in the seventeenth century with contributions from Galileo and Newton on uniform acceleration of falling bodies, Newtons Law of viscosity and Pascal introduced Pascal's Law on pressure in fluids at rest. In the eighteenth century Bernoulli with his treatise *Hydrodynamica* and Euler with his equation for acceleration of particles in non-viscous fluids laid the foundations for fluid mechanics published by Rouse & Ince in 1963.

In the nineteenth century Venturi developed techniques for reducing turbulent losses in pipe systems with conical transitions and Navier extended the Euler equation to include attraction of adjacent molecules. This was followed by Stokes deriving the equations of motion in terms of the coefficient of viscosity resulting in the Navier-Stokes equations, published in 1845. Later Saint-Venant developed equations of motion of a fluid particle in terms of shear and normal forces, and Poiseuille developed the equation for laminar flow through capillary tubes. Understanding of vortex motion was extended by Helmholtz and Lord Kelvin. Osborne Reynolds made his contribution by reconciling fluid dynamics theory with observations of fluid behaviour in development of turbulent flow in pipes (published in 1883) through his dimensionless parameter of Reynolds Number; the ratio of inertia force over viscous force in a fluid flow. It was also Reynolds who developed the Navier-Stokes equations by introducing the concept of turbulent shear.

In the twentieth century Prandtl developed the concept of boundary layers at solid surfaces (published by Prandtl & Tiejtjens in 1957) and, together with von Karman, extended understanding of vortex shedding in wake flows (published by von Karman & Rubach in 1912).

These advances laid the foundations for Napier Shaw's series of lectures on *Air Currents and the Laws of Ventilation* presented at Cambridge University in 1903 and published in 1907. His lectures included equations for air flow based on direct current electrical circuit analogy equating total pressure differences to voltage differences and air flow rates to electrical current. A theoretical approach to airflow through networks was addressed in a paper by Hardy Cross (published in 1936). These methods are still used today in mine ventilation (Hartman, 1982).

As professional engineering institutes formed to support the rapidly growing heating and ventilating industry organisations such as the American Society of Heating and Ventilating Engineers began sponsoring empirical research to support the industry. In Great Britain during the 1950's, J. Dick at the Building Research Station reported in 1950 on field studies which showed good agreement between theoretical estimates of air infiltration and field measurements. In the case of higher air flow rates through large openings simple equations based on wind speed coefficients were published by heating and ventilating institutes and societies for use by their members (ASHRAE, 1967).

It was not until the 1970's with the development of Wind Engineering that more detailed computation became feasible, accounting for the variability of wind speed and direction over time (Aynsley et al, 1977). Given the variability of wind, it became important to express natural ventilation potential in terms of the probability of a critical design value being equalled or exceeded. For computational purposes, pressure difference/discharge coefficient approach was commonly used. This was satisfactory for estimating volumetric air flow rates in the case of simple cross ventilation through two openings in series. In more complex cases with many openings and opportunities for branching indoor air flow, direct calculation was not possible so an iterative approach was necessary (Walton, 1989). More detailed evaluation became feasible when computational fluid dynamics (CFD) software using Navier-Stokes equations and $K\varepsilon$ turbulence models and more computationally intensive large eddy simulation (LES) methods became available. Initially established on super computers (Murakami & Mochida, 1988), CFD software became commercially available for workstations in the 1980's and later personal computers in the 1990's (Stathopoulos, 1997).

The current remaining deficiencies in design data for computing natural ventilation are largely due to the low levels of research funding. Until the recent emergence of energy conservation and efficiency brought on by global warming and other environmental crises, engineering consultants and their professional institutes showed little interest in natural ventilation. The European Community has led the way by investing large amounts of money in software development and field validation studies of natural ventilation infiltration in their PASCOOL Joule II project (Allard et al, 1996).

2 UNRESOLVED ISSUES

This paper will identify some unresolved issues in natural ventilation for thermal comfort and suggest directions for further research.

2.1 Wind Forces and Building Porosity

Indoor air flow for thermal comfort in oppressive warm humid climates often requires local velocities of up to 2 m/s past the skin of occupants. This suggests that in warm climates, where temperature differences between indoors and outdoors in naturally ventilated buildings is small, that stack effect will be negligible and natural ventilation will rely principally on wind forces to achieve these velocities.

Wind forces appear in natural ventilation calculations in the form of wind pressure coefficients acting over areas of solid models where ventilation openings are intended in building surfaces. The use of wind pressure coefficients off solid models is largely a matter of convenience as this data measured for wind loading purposes is readily available (Swami & Chandra, 1988).

A cursory study of mean cross ventilation flow through a building using the Bernoulli equation will reveal that the wind energy contributing to the flow is the difference between the total pressure across the windward opening and the static pressure across the leeward opening.

It is also worth noting that the theory of flow through orifices is grounded in flow in pipes. Flow through pipes has no option but to flow through an orifice plate no matter how small the orifice. In the case of cross ventilation through a building, the approaching airflow obviously has the option of either flowing through the building or around the building. It is reasonable to assume that the path approaching flow chooses will be intimately associated with the pressure field developed around the building.

It should not be surprising to note that the difference between the total pressure at the windward opening and static pressure adjacent to the leeward opening as measured in a boundary layer wind tunnel varies with the relative size and location of openings. This can be seen for simple high set and low set rectangular buildings common in tropical regions of Australia in the 1960's (Figures 1 & 2). A general theoretical approach to wind forces on porous structures is discussed by Richards and Robinson (1997).

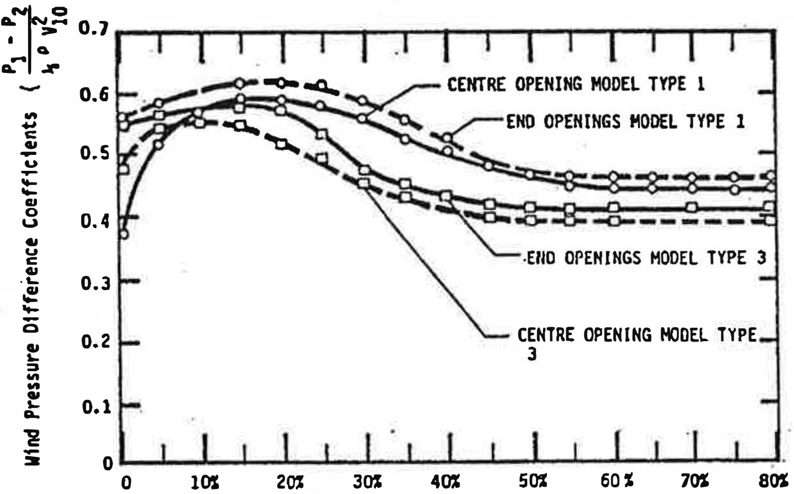

Figure 1. Pressure Difference Coefficients versus Porosity of the Buildings with Three Equal Openings for Wind Normal to a Long Wall

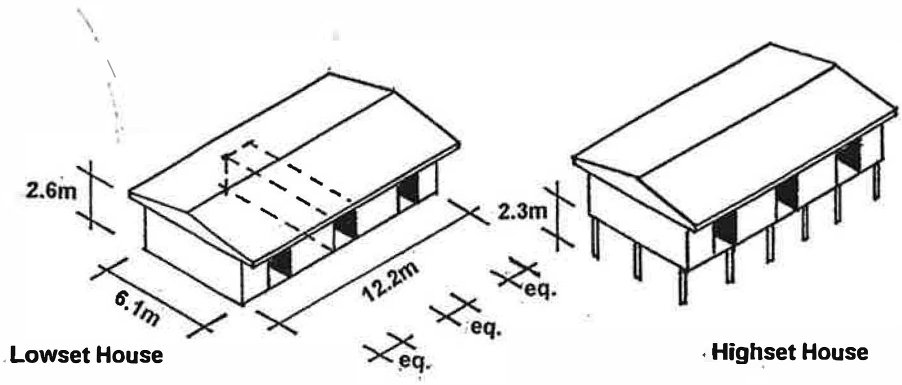

Figure 2. High Set (Type 3) and Low Set (Type 1) Building Model Types Used to Measure Wind Pressure Difference Coefficient Data in Figure 1.

Windward total pressure and leeward static pressure coefficients were referenced to the dynamic pressure of the approaching wind 10 m above ground in a power law suburban boundary layer with a gradient height of 400 m and an exponent of 0.28 (Aynsley, 1978). As such data is unlikely ever to be readily available for a useful range of building shapes and wind incidences, it would be helpful to explore wind pressure fields around buildings using CFD (Tsutsumi et al, 1993) or preferably LES computational methods. Such a study may lead to a theoretical method for adjusting existing wind pressure coefficients from solid model studies to reflect the influence of building porosity on effective pressure differences. Such a study would also need to include studies of the influence of roof shape, particularly roof pitch, on pressure at windward and leeward wall openings.

2.2 Wind Shelter Effects on Closely Spaced Houses

Most wind pressure distribution data on houses is for isolated buildings. Limited data is available for similar buildings arranged in parallel rows (Holmes & Best, 1979) and in in-line and staggered arrays Figure 3 (Lee et al, 1980) but these do not reflect contemporary Australian subdivisions with cul-de-sac layouts for traffic control. Another feature of current residential subdivisions is the presence of significant number of small lots with areas as small as 250 m^2 (Lee, 1998). It is common practice for the houses on these small lots to be built on one side boundary to allow for effective use of the small remaining site area.

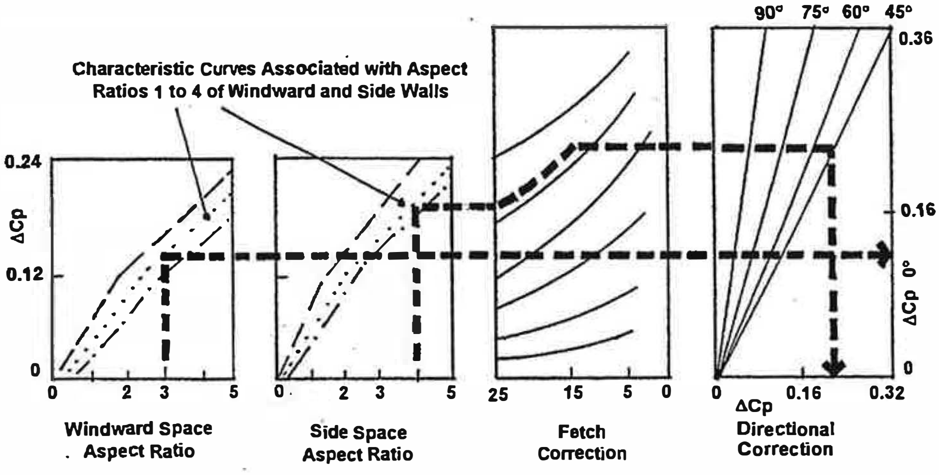

Figure 3. A Schematic Graphical Prediction Technique for Wind Pressure Difference Coefficients for Natural Ventilation, after Lee et al, 1980.

In warm humid climates and tropical regions in particular, where many houses rely on natural ventilation to achieve indoor summer thermal comfort for occupants, further studies are needed to determine appropriate house forms and subdivision geometries compatible with adequate natural ventilation potential. Two storey terrace houses appear to offer higher population densities sought for cost and energy efficient subdivisions while retaining natural ventilation potential. Studies of natural ventilation potential in suburban subdivisions in boundary layer wind tunnel studies supplemented by CFD or LES computational studies are needed to validate the technique developed by Lee et al (1980) for arrays of rectangular prisms.

2.3 Resistance of Natural Ventilation Flow Paths

Computation of natural ventilation air flow is most commonly done using discharge coefficients which quantify the airflow efficiency of an opening or alternately the air flow resistance of openings. Many of the discharge coefficient values used are derived from data traditionally used for fluid flow in pipes and resistance values traditionally used in computation of mine ventilation. In the case of discharge coefficients for window or door openings, a value of 0.6 for a sharp-edged rectangular opening is often used.

It should be noted that entry conditions such as incidence of openings to the approaching wind, presence of insect screens, adjacent wing walls and eaves overhangs, inclined window sashes and position of open doors can significantly influence discharge due to momentum effects at windward openings. Also downstream of an opening, surfaces parallel to the flow and close to the edge of the opening can influence the jet issuing from an opening but are rarely accounted for although they can have significant influences on discharge (Aynsley et al, 1977). Indoors the influence of furniture, seated people such as in classrooms, part-height partitions and walls and hallways which force abrupt changes in the direction of airflow need to be taken into account in terms of resistance to airflow.

Much more work needs to be done regarding these influences to provide reliable design data for computation of natural ventilation. Some wind tunnel (Aynsley, 1980) and CFD studies have been done on personal computers but these need to be validated by full scale field measurements.

2.4 Natural Ventilation for Thermal Comfort and Heat Stress Relief

In warm-humid climatic regions, air temperatures over 30°C combined with relative humidities exceeding 60% fall outside most definitions of thermal comfort zones. The high humidities diminish the opportunity for evaporative cooling by sweating and air flow is the primary means for restoring indoor thermal comfort. There are a number of models for the cooling effect of airflow but a simple approximation suggests a cooling effect of 3.7K for each metre per second of airflow. An upper limit on indoor airflow for thermal comfort of 2 m/s is usually imposed to prevent disturbance of papers etc.

Recent thermal comfort zones centred on thermal neutrality based on adaptive human thermal response model (Szokolay, 1998) suggest a single zone for each month. Earlier adaptive thermal comfort zones in humid tropical regions (Evans, 1979), suggested two thermal comfort zones, one for daytime and one for nighttime. For monthly average relative humidity from 50-70% and annual average dry bulb air temperature over 20°C, Evans suggests the daytime dry bulb air temperature comfort zone as 23-29 °C, and nighttime dry bulb air temperature comfort zone as 17-23 °C.

Given the typical differences in clothing and metabolic rates between awake and sleeping states, it is reasonable to assume that there could be different comfort zones for night and day. Macfarlane (1958,1981) explains that nighttime thermal conditions for sleeping are more important than for daytime conditions and Macpherson (1956) stresses the value of ceiling fans for improving thermal comfort in tropical regions at night when breezes tend to diminish.

As there are frequent excursions beyond dry bulb air temperature comfort zone limits in naturally ventilated buildings in warm humid tropical regions, there is a need to develop means to account for benefits of air flow in reducing indoor heat stress. It may be possible to apply a simple air flow correction for convective heat loss to the dry bulb air temperature component of the Wet Bulb Globe Temperature (WBGT) index (NHMRC (1980)).

2.5 Airflow Computation

Natural ventilation of buildings usually takes place through a series of orifices. It should be noted that where similar orifices are closely spaced and aligned with the flow, the combined resistance to air flow has been observed to be reduced (Dietart, 1922). The explanation for this appears to be linked to the creation of a suction effect in the space between the two sharp-edged orifices as the jet issuing from the first orifice passes through the second orifice still in a contracted state.

Other influences on resistance to airflows can be traced to interaction of jets from windward openings coalescing with surface parallel to the flow. In this case the friction losses associated with flow along the wall are less than the turbulent mixing losses along the boundary of the free jet, and the flow clings to the wall. Entry conditions such as casement and awning sashes, outward swung doors, recessing of doors and windows, wing walls and deep eaves overhangs at windward openings also influence contraction of the jet through an opening. Unaligned orifices in cross ventilation force the flow to change direction, which results in reduced air flow rates. It would be helpful if design data for these influences could be catalogued and published in order to improve the accuracy of the simpler air flow computation methods.

More sophisticated computation methods such as zonal network and CFD methods are not without their difficulties. In the case of natural ventilation by wind through large openings, air flow resistances are very low. When zonal network methods are used to compute flow through a network with both high and low resistance branches, instability is common making it difficult to achieve convergence (Aynsley, 1997). Strategies to overcome this problem include commencing balancing calculations in branches in descending order of resistance. When matrix methods are used, storage minimisation methods such as skyline or sparse matrix banding methods can be applied (Walton, 1989).

Where CFD is used for natural ventilation air flow computation, difficulties can arise because of the large proportion of the mesh devoted to achieve realistic external separated flows. This leaves a limited mesh for modelling indoor flows, particularly in boundary layers. While LES methods can provide improved modelling of external separated flow regions the improvements come at a cost of up to three times the computation time (Murakami and Mochida,1988). These difficulties will eventually be overcome as parallel processing and speed of computers increases.

2.6 Home Energy Rating Schemes

National government concerns regarding the impact of global warming resulting from greenhouse gas emissions, have prompted the introduction of home energy rating schemes based on star ratings from 0 to 5 stars (best) (Ballinger, 1998). Computer programs developed in Australia for this purpose were based on the North American Z-step program for closed envelope houses. While a free running mode is available it has no capacity to estimate the amount or frequency of natural ventilation or its cooling effect on occupants. When such a program is loaded with data for a tropical house designed specifically for natural cross ventilation with good exposure to the prevailing onshore breeze the rating is 0 stars.

There will be short periods of time when breezes are absent during which indoor thermal comfort can be accommodated with ceiling fans. Energy consumed by such fans to supplement natural air flow is a few percent of the energy consumed by air conditioning a similar house in the same location. A thermal comfort based home energy rating scheme software package is currently being considered to address this issue.

3 CONCLUSIONS

Computation of natural ventilation for thermal comfort has come a long way over this century. Powerful tools in the form of zonal network flow analysis, CFD software and LES methods are frequently used on large naturally ventilated buildings. What is lacking is development of simpler computation methods for preliminary design stage when it is still feasible to change the building shape or orientation and for use on smaller lower cost buildings such as houses. This need is particularly important in warm humid climate regions where many houses make use of natural ventilation for indoor summer comfort. The development of user-friendly computer software to compute the probabilities of sufficient natural ventilation for thermal comfort could make a large contribution toward energy efficiency of houses in these regions.

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