Journal of Wind Engineering
and Industrial Aerodynamics 67&68 (1997) 711–719

A resistance approach to analysis of natural ventilation airflow networks

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Abstract

Many buildings in warm humid climates, particularly in tropical regions, rely for much of the time on natural ventilation from prevailing breezes for indoor thermal comfort. Much effort in recent years has been directed toward the use of computational fluid dynamics in evaluating airflow through buildings based on the solution of Navier–Stokes equations incorporating a turbulence model. This approach requires extensive data preparation and a reasonably powerful computer to yield results within an acceptable computation time for both numerical solution and simulated flow visualisation. Quantitative evaluation of natural ventilation through many low budget buildings in tropical regions is not evaluated due to a lack of suitable simple computer programs. What is needed are programs that can run on modest personal computers and be used quickly to compare the relative natural ventilation performance of alternative building layouts for prevailing breeze directions during the preliminary design stage. Smaller buildings are often designed for cross ventilation by prevailing breezes with flow entering a windward opening and exhausting through a leeward opening. Such flow through a limited number of openings in series can be calculated very quickly on a personal computer using an orifice flow approach based on estimates of pressure differences and discharge coefficients of openings. When buildings have external ventilating openings in a number of rooms and flow branches within the building, it is no longer possible to calculate directly the airflow in the various branches of the airflow network. Flow in such networks can be analysed iteratively on a personal computer by repetitive solution of simultaneous equations for flow rates in branches at nodes and conservation of mass flow through the network. The procedure described in the paper uses the *Hardy Cross* method of balancing flows at network nodes until errors throughout the network are acceptably small. Sources of data on wind pressure distributions over building walls and shielding influence of nearby buildings are provided together with a detailed description of a procedure for solving network airflows sufficient for readers to write their own computer code.

Keywords: Networks; Airflow; Natural; Ventilation; Resistance

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PII S0167-6105(97)00112-8

1. Introduction

Significant advances have been made over the past decade in computational methods for estimating airflow through buildings. Recent efforts have focused mainly on computational fluid dynamics based on solution of the Navier–Stokes equations [1,2]. Three-dimensional modelling using this technique can provide detailed information on indoor airflows but requires costly software and considerable computation. Such a technique is unlikely to be used in the design of the numerous low-cost buildings built in developing countries in humid tropical regions where natural ventilation is often the only means of achieving indoor thermal comfort. The low-speed indoor airflow in lazy eddy regions away from the main air streams is usually of little value for indoor thermal comfort. Simpler computational methods that restrict airflow information to the main air stream through large openings are generally adequate for basic design purposes [3]. These methods make use of pressure differences and discharge coefficients for simple cross ventilation and network flow analysis where multiple inlets and outlets and internal flow branching occurs [4,5]. These computational techniques can be performed on modest personal computers using public-domain software developed at National Institute of Standards and Technology by Walton [6].

2. Shielding influence of adjacent buildings

Most wind pressure distribution data on building shapes is for buildings without nearby obstructions. In reality there often are buildings of a similar size within six building heights of the building of interest. The shielding effects of these adjacent buildings on wind pressure differences between windward and leeward walls of the shielded building have been studied by Lee et al. [7].

These studies suggest that for cuboid buildings of similar size arranged in a regular grid staggered grid patterns there are three distinct flow regimes, skimming, wake interference and isolated roughness regimes.

For cuboid buildings in a regular grid a skimming flow dominates when clear spacing between buildings is less than 1.4 building heights. This results in wind pressure differences between windward and leeward walls of the shielded building being reduced virtually to zero at very close spaces rising to approximately 25% of the corresponding pressure difference on an isolated building.

For cuboid buildings in a regular grid a wake interference flow dominates when clear spacing between buildings is between 1.4 and 2.6 building heights. This results in wind pressure differences between the windward and leeward walls of the shielded building being reduced from 25% to 50% of the corresponding pressure difference on an isolated building.

For cuboid buildings in a regular grid an isolated roughness flow regime dominates when clear spacing between buildings exceeds 2.6 building heights. This results in wind pressure differences between the windward and leeward walls of the shielded building being reduced from 50% of the corresponding pressure difference on an isolated building at a spacing of 2.6 building heights rising to around 100% when clear spacings approach six building heights.

For cuboid buildings arranged in a staggered grid a skimming flow dominates when clear spacing between buildings is less than 1.4 building heights. This results in wind pressure differences between the windward and leeward walls of the shielded building being reduced virtually to zero at very close spaces rising to approximately 12% of the corresponding pressure difference on an isolated building.

For cuboid buildings arranged in a staggered grid a wake interference flow dominates when clear spacing between buildings is between 1.4 and 2.6 building heights. This results in wind pressure differences between the windward and leeward walls of the shielded building being reduced from 12% to 33% of the corresponding pressure difference on an isolated building.

For cuboid buildings arranged in a staggered grid, an isolated roughness flow regime dominates when clear spacing between buildings exceeds 2.6 building heights. This results in wind pressure differences between the windward and leeward walls of the shielded building being reduced from 33% of the corresponding pressure difference on an isolated building at a spacing of 2.6 building heights rising to around 100% when clear spacings approach 7.5 building heights.

The limitless permutations and combinations of possible building shapes and spacings preclude the likelihood of definitive data being available for specific building shapes and shielding situations. Short of conducting a boundary layer wind tunnel study for a specific shielding situation, the data above for arrays of cuboids will give an indication of the type of effects to be expected.

3. Discharge coefficients

A simple means for estimating the volumetric turbulent flow rate or discharge through an opening in a pipe due to a nominated pressure difference (head loss) is to apply the Bernoulli equation to points along a streamline upstream and downstream of the opening. As this method cannot accommodate the complex fluid dynamics of separated flow downstream of the opening an empirical correction factor or discharge coefficient is used to obtain a realistic estimate [8].

The volumetric airflow rate, Q ($\mathrm{m^3/s}$) through an opening with a free area A ($\mathrm{m^2}$) and a discharge coefficient, C_d (dimensionless) and usually taken as 0.65 for sharp edged rectangular openings, as the head loss is H_L (Pa), is

$$Q = C_d A (H_L)^{0.5} \quad (\mathrm{m^3/s}). \tag{1}$$

The mean velocity, V (m/s) through an opening with turbulent flow can be calculated by dividing the volumetric flow rate by the area of the opening A ($\mathrm{m^2}$):

$$V = C_d (H_L)^{0.5} \quad (\mathrm{m/s}). \tag{2}$$

Head loss, the difference between the upstream total pressure and the downstream static pressure, is well defined in the case of orifice flow in pipes. Specific locations are defined for pressure measurement upstream and downstream of the orifice plate. In the case of flow through wall openings in buildings the equivalent head loss would be between the total pressure (dynamic + static) at the windward opening and the static pressure near the wall beside the leeward opening. The pressure energy in the form of dynamic pressure in the air jet issuing from leeward opening does not contribute to the head loss between windward and leeward wall openings and is dissipated downstream from the building.

4. Resistance approach

Many of the airflows of interest to wind engineers are external flows in the Earth's turbulent boundary layers or around solid objects. This paper focuses on airflow through openings in building envelopes or through the interior of buildings. Discharge coefficients which reflect the discharge efficiency of openings are commonly used to estimate airflow through openings by wind engineers [9–11]. In simple situations, such as cross ventilation where there is only one windward opening and one leeward opening, this approach using discharge coefficients is satisfactory.

When more complex airflows with multiple inlet and outlet openings and internal flows occur through a network of alternate branching flow paths, electrical circuit analogies can be used. Analysis of complex airflow networks using computer software based on electrical circuit analogies such as Kirchhoff's first and second laws and Atkinson's equation is commonplace in mine ventilation engineering [4.12–15].

Atkinson's equation relates, H_L, the head (pressure) losses (Pa) in an airway proportionally to the square of the discharge, Q (m^3/s), through the airway with the constant of proportionality being the resistance, R ($N\ s^2/m^8$) of the airway:

$$H_L = RQ^2 \quad \text{(Pa)}. \tag{3}$$

Kirchhoff's first law for air circuits states the quantity of air leaving a junction must equal the quantity of air entering the junction. Kirchhoff's second law states that the sum of pressure drops around any closed path must be equal to zero. Pressure differences or head losses are analogous to voltage, electrical current is analogous to volumetric airflow rate and electrical resistance is analogous to airflow resistance [12]. This approach provides a useful framework when developing computer software packages for calculating airflow through complex networks.

Airflow resistance of wall openings can be expressed in terms of their discharge coefficients C_d, the mass density of air, ρ (usually 1.2 Kg/m^3), and the area of the opening, A (m^2).

$$R = (\rho/2)/(C_d^2 A^2) \quad (N\ s^2/m^8). \tag{4}$$

The volumetric turbulent airflow rate Q through an opening is

$$Q = (H_L/R)^{0.5} \quad (m^3/s). \tag{5}$$

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The mean velocity, V (m/s) through an opening can be calculated by dividing the volumetric flow rate by the area of the opening A (m^2):

$$V = (H_\mathrm{L}/R)^{0.5}/A \quad (\mathrm{m/s}). \tag{6}$$

When indoor airflow passes through a number of sequential openings with resistances $R_1, R_2, \ldots, R_n$, the equivalent resistance R_eq for all the openings in series can be calculated using the equation:

$$R_\mathrm{eq} = R_1 + R_2 + \cdots + R_n \quad (\mathrm{N\,s^2/m^8}). \tag{7}$$

When indoor airflow passes through a number of openings with resistances $R_1, R_2, \ldots, R_n$ in parallel, the equivalent resistance R_eq for all the openings can be calculated using the equation:

$$1/R_\mathrm{eq} = 1/R_1 + 1/R_2 + \cdots + 1/R_n \quad (\mathrm{m^8/N\,s^2}). \tag{8}$$

5. Estimating head loss from wind pressure distributions on external walls

The total pressure at a windward wall opening is difficult to define as flow is not contained as is the case in pipe flow for which discharge coefficients were developed. Static pressure at the leeward wall of buildings presents less of a problem. For practical reasons, estimates of head loss for natural ventilation usually are based on pressure distributions measured on isolated solid building models in boundary layer wind tunnels. There are also data on mean wind pressure coefficients of walls of high and low-rise rectangular buildings derived from numerous wind tunnel studies [16,17]. The term isolated indicates that the model on which the wind pressures on surfaces are measured has no other building models nearby, that is within approximately six building heights. Pressure coefficients on the surfaces of isolated solid models near the location of proposed inlet and outlet wall openings are used to estimate head loss.

$$H_\mathrm{L} = 0.5\,\rho\,V^2(C\mathrm{p_i} - C\mathrm{p_o}) \quad (\mathrm{Pa}) \tag{9}$$

where H_L is the estimate of head loss between inlet and outlet ventilation openings (Pa), ρ the mass density of air (1.2 $\mathrm{Kg/m^3}$), V the mean approach wind speed at reference height associated with pressure coefficients, $C\mathrm{p_i}$ the wind pressure coefficient on wall of a solid model near the location for the inlet opening, $C\mathrm{p_o}$ the wind pressure coefficient on wall of a solid model near the location for the outlet opening.

Head at the inlet opening, H_i and outlet opening, H_o are

$$H_\mathrm{i} = 0.5\,\rho\,V^2\,C\mathrm{p_i} \quad (\mathrm{Pa}), \tag{10}$$

$$H_\mathrm{o} = 0.5\,\rho\,V^2\,C\mathrm{p_o} \quad (\mathrm{Pa}). \tag{11}$$

6. Complex network flows

Flows in networks with parallel branches can be analysed directly using Eqs. (1)–(8). When parallel branches overlap, or are interconnected, a complex network is created in which flows cannot be calculated directly and iterative approximation methods are employed.

A nomenclature has been established to describe complex networks. A complex network consists of *branches* which are segments of airflow between *nodes*. *Nodes* are locations where branch flows merge. Nodes where more than 2 branch flows merge are referred to as *junctions*. Complex networks are described by assigning unique numbers to each node. Branches are identified by the node numbers at each end. Flow direction in a branch is defined by using a strict order of node numbers for the branch [4]. Any node with only two branches are eliminated by converting the connected branches into a single equivalent branch with an equivalent resistance. Any sections of the network with parallel branches in parallel between the common nodes is converted to a single equivalent branch with an equivalent resistance. When this has been completed the network should conform to the following equation:

$$m_n = n_\mathrm{b} - n_\mathrm{n} + 1 \tag{12}$$

where m_n is the number of fundamental meshes in the network, n_b the number of branches in the network, n_n the number of nodes in the network.

A fundamental mesh consists of a unique series of interconnected branches completing a closed circuit which contain at least one of the nodes associated with a known head. One of these fundamental meshes will have the least resistance and incorporate the circuit between the two nodes for which the heads are known. To assist in the identification of this mesh it is useful to sort the branches in order of their resistances.

7. A procedure for solving complex network flows

Calculation of complex network flows is achieved by an iterative approach of successive approximations of network variables. Each iteration must conform with Kirchhoff's laws of conservation of mass and flow and balancing of heads. A variety of techniques can be used to accelerate convergence toward a solution with an acceptably small error.

One method used to perform this iteration is the Hardy Cross method of balancing flows. It is equivalent to Newton's method of tangents as it uses the derivative of an estimated flow to adjust the next iteration. In the case of natural ventilation, the knowns in the network are the estimated wind pressures at inlets and outlets and the resistance of branches. The unknowns in the network are the flow rates in each branch and the head losses throughout the network.

The Hardy Cross method keeps heads balanced in the network and balances flows by successive corrections. Initially unknown flows are assigned an arbitrary value.

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Pressures at inlet and outlet nodes are then calculated from the velocity of the reference design wind speed and pressure coefficients at the inlet and outlet openings.

With the head loss established between inlet and outlet openings, flows are balanced at all junctions through the mesh with the least resistance followed by the other meshes in the network [4]. Flow rates in each branch are calculated using Eq. (5). These flows are summed at each junction assuming:

- flow into the junction is negative and
- flow out of the junction is positive.

Since Kirchhoff's first law requires the sum of flow at a junction to be zero, an equal and opposite flow equal to the sum of the flow at each junction is distributed between the branches at the junction using the following equation:

$$\Delta Q_i = -\frac{\sum_{j=1}^{n} R_j|Q_j|^2}{2\sum_{j=1}^{n} R_j Q_j} \quad (\text{m}^3/\text{s}) \tag{13}$$

where ΔQ_i is the increment of flow required in each branch to balance total flow at n junctions in mesh i (m^3/s), R_n the resistance of branch n ($\text{N s}^2/\text{m}^8$), Q_n the current estimate of flow in branch n (m^3/s).

The term $2R_j\,Q_j$ is the derivative of the term for total head loss along a branch, $R_j\,Q_j^2$. All terms between the symbols | | are absolute values. This requires a strict adherence to the sign of the flow at a junction when summing terms.

When summing the total head in a mesh, which includes the head loss due the wind pressure difference between inlet and outlet openings, the head loss due to this pressure difference must be deducted from the numerator in Eq. (13) to satisfy Kirchhoff's first law.

When flows have been balanced at a junction, flows at each end of each branch are summed. Since these net flows should also be zero, out of balance flow is balanced with an equal and opposite flow distributed equally between each end of the branch. There are exceptions to this procedure in the case of ends of branches which are inlets or outlets which are treated as infinite sources or sinks and the entire branch flow imbalance is absorbed.

When an iteration of balancing of flow in branches is completed, the net flows at each of the junctions is once again out of balance. The balancing of flows at junctions and in branches is repeated in the iterative process until the flow rate being distributed has reached a selected negligible amount. At this point of the computation, head losses for each branch are calculated using Eq. (3) and the analysis is complete [4].

There are a number of other methods used to perform iterations in solving network flows. Each method has different convergence characteristics for various types of networks [15]. Some networks, particularly those with both very high and low resistance branches can cause slow convergence toward a solution if balancing of flows at junctions is performed in a random fashion. To avoid slow convergence balancing of flows is performed by starting with junctions in the fundamental mesh with the lowest circuit resistance followed by junctions in the mesh with the next lower resistance. When matrix methods are used to solve the flows in networks, storage minimisation procedures such as skyline, or sparse matrix banding methods are often applied.

8. Conclusions

During the early design stage of low-cost naturally ventilated buildings in warm humid tropical regions, simple computer software for estimating natural ventilation in network flows can be extremely valuable for comparing the relative natural ventilation potential of alternative designs during the preliminary design stage. At this stage of building design, when many building features are in a state of flux, simple user friendly software is needed to accommodate numerous runs to allow exploration of design options when limited data is available.

The sophisticated three dimensional computational fluid dynamics software based on Navier–Stokes equations with turbulence modelling is often costly, requires users to have a good background in fluid dynamics and usually has tedious data entry procedures which are disincentives to their use.

Other simpler fluid modelling approaches such as orifice flow and network flow analysis do not offer as much detailed information on airflow outside the main air streams. These lazy eddy flows typically have mean velocities around 10% of the mean velocity in the main air stream and are of limited interest when the focus is on airflow for indoor thermal comfort. Average airflow due to wind and thermal forces in the main air stream near large wall or roof openings are adequate for these purposes.

A resistance approach to airflow in networks using electric circuit analogies can provide a useful framework when developing computer software packages for estimating airflow in complex indoor airflow networks. For such applications, computer software needs to be low cost, user friendly with simple data entry, fast in execution and suitable to run on commonly used personal computers. Public domain software such as CONTAM developed by Walton [6] at the National Institute of Standards and Technology in Gaithersburg contains AIRNET modules for solving complex network air flows.

More sophisticated fluids modelling software based on Navier–Stokes equations may be used for natural ventilation applications for estimating indoor thermal comfort in low cost buildings, but it is likely to be at a later design stage when the building design is approaching its final stage and the detailed configuration of the building is better established.

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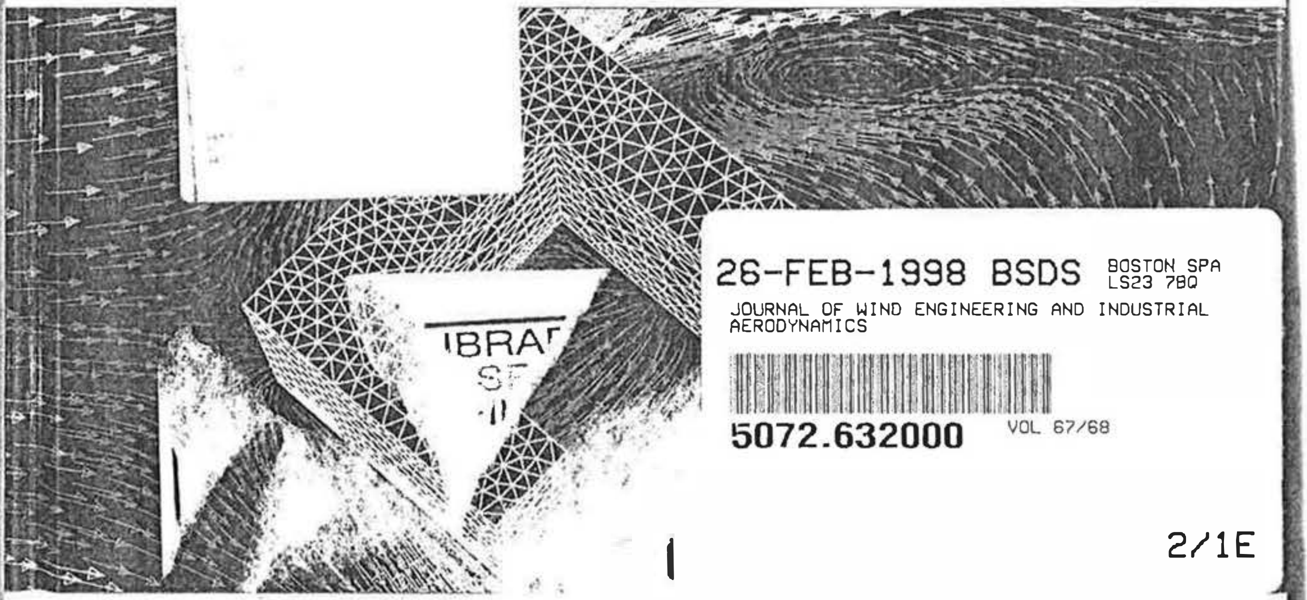
Edited by
R.N. Meroney and B. Bienkiewicz



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Computational Wind Engineering 2

Proceedings of the
2nd International Symposium on
Computational Wind Engineering (CWE 96)
Fort Collins, Colorado, USA
August 4-8, 1996

Edited by

Robert Meroney
and
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Department of Civil Engineering
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1997
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ELSEVIER SCIENCE B.V.
Sara Burgerhartstraat 25
P.O. Box 211, 1000 AE Amsterdam, The Netherlands

Reprinted from Journal of Wind Engineering and Industrial Aerodynamics, 67 & 68 (1997)

ISBN: 0 444 82878 8

This book is printed on acid-free paper.

Printed in The Netherlands.