#2980

OT-88-13-2

A RESISTANCE APPROACH TO ESTIMATING AIRFLOW THROUGH BUILDINGS WITH LARGE OPENINGS DUE TO WIND

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ABSTRACT

Natural airflow due to wind has been utilized since antiquity to provide both fresh air and indoor summer thermal comfort in warm humid climates.

Lack of suitable existing wind pressure data has resulted in the use of wind tunnel data from studies of solid models. This practice results in the elimination of the velocity pressure component at inlet openings and a corresponding source of error in estimates of flow. Another source of error is the effect of inclined wind incidence on discharge through inlet openings. Studies of these effects are cited.

Current numerical methods for estimating the airflow rates through buildings with large openings are based on orifice flow theory. These methods do not account for internal flow losses due to obstruction of flow by furniture or surface friction. Friction losses can be significant in long corridors as local velocities often exceed 200 ft/min (1 m/s).

Resistance-based flow theory, currently used for estimating mine ventilation, is suggested as a means of including losses due to orifices, obstruction by furniture, bends, and surface friction in a single simple flow equation. Flow conditions discussed include estimates of airflow through sequential orifices between inlet and outlet openings. Methods are provided for determining airway resistances from existing dynamic loss and discharge coefficient data. Calculation of the equivalent resistance of combined parallel airway branches and resistance associated with friction losses along surfaces of airways are discussed.

Many flows through buildings take the form of complex interconnected branching network flows. Application of the resistance approach to the iterative solution of complex network flows is described and areas in need of further research are identified.

INTRODUCTION

Wind has been utilized in buildings since antiquity to provide fresh indoor air and to cool occupants, particularly in warm humid climates. Practical advice on the best orientation of houses with respect to prevailing summer breezes was given by the Roman architect and engineer, Vitruvius (Morgan 1960) and in "Feng-shui" doctrine in Chinese dynasties after the Chou dynasty (Cotterell 1975).

Development of the science of fluid mechanics by Bernoulli and others made numerical estimates of ventilation possible. Shaw (1907) gave a series of lectures at Cambridge University titled "Air Currents and the Laws of Ventilation." Shaw's theory used airflow equations based on electrical circuit analogies combined with empirical fluid flow resistances for orifices.

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Most recent studies of airflow through buildings due to wind relate to estimation of infiltration through small cracks in the external envelope and its impact on heating or cooling loads (Jackman 1970; Vickery 1981; Walton 1984). Relatively few recent studies have dealt with airflow through large openings in buildings due to wind (Vickery 1981; Aynsley 1982; Chandra 1986; Vickery 1987). Often such estimates are made to evaluate airflow for thermal comfort of building occupants (Aynsley 1977, 1982; Arens 1984).

Current practice among engineers (Vickery 1981) for estimating airflow through large openings in buildings due to wind is to use a discharge coefficient approach adopted from orifice flow theory. This method does not take into account indoor flow losses due to obstructions such as furniture or surface friction along an airway. Friction losses are normally insignificant in the case of infiltration flows, but they can become significant when inlet and outlet openings are large and local air velocities often exceed 200 ft/min (1.0 m/s).

Mine ventilation engineers (Hartman 1982), on the other hand, tend to follow the flow resistance approach, which uses a single simple equation (Equation 1), which provides a convenient means of incorporating resistance due to orifices, obstructions, bends, and skin friction along an airway. This paper outlines the application of the resistance approach to estimation of airflow through large openings in buildings due to wind. Because of its ability to cope with all types of flow losses in a single equation, the method is well suited for developing flexible and comprehensive computer programs to estimate wind-driven airflow through large openings in buildings.

AIRWAY RESISTANCE

Pressure losses, Δp, in an airway are proportional to the square of the discharge, Q, through the airway. This relationship is clearly shown in the following equation (Hartman 1982):

$$\Delta p = RQ^2 \qquad (1)$$

where Δp, lb/ft^2 (Pa), is the pressure loss along the airway; R, $lb/ft^2/(cfm)^2$ or $lb.min^2/ft^6$ $(N.s^2/m^8)$, is the constant of proportionality that represents the resistance to airflow or pressure loss per unit of flow squared in the airway; and Q, cfm (L/s x 1000), is the discharge through the airway.

DYNAMIC FLOW RESISTANCE

Two types of flow resistance are encountered in wind-driven airflows through large openings in buildings, dynamic and frictional. Resistance from a dynamic loss is associated with flow through an orifice, an abrupt expansion in cross section of the airflow channel, a bend in the airflow channel, or dissipation of jet energy from an outlet. Flow rates through airways, being the unknown quantity sought by calculation, are estimated by substituting wind pressure differences and resistances from data published in reference texts (Aynsley 1977; ASHRAE 1985) in the flow equation, Equation 1.

Dynamic loss coefficients, C_L, for pressure losses, Δp, across an orifice, bend, or expansion are referenced to the mean velocity pressure immediately upstream from the condition generating the dynamic pressure loss.

$$C_L = \frac{\Delta p}{(\rho/2)V^2} \qquad (2)$$

where ρ in $slugs/ft^3$ (kg/m^3) is the mass density of air and V, ft/min (m/s), is the velocity immediately upstream of the orifice, bend, or expansion responsible for the pressure loss, Δp lb/ft^2 (Pa).

Resistance associated with dynamic loss coefficients can be calculated from dynamic loss coefficients using the equation:

$$R = \frac{(\rho/2)C_L}{A^2} \qquad (3)$$

where R, $lb.min^2/ft^6$ $(N.s^2/m^8)$, is the resistance associated with the dynamic loss coefficient, C_L (dimensionless), and an orifice or airway's cross-sectional area, A ft^2, (m^2).

Another commonly used coefficient in flow calculations is the discharge coefficient, C_d, which is a measure of the discharge efficiency of an orifice. Resistance of an orifice can be calculated from an orifice's discharge coefficient using the equation:

$$R = \frac{(\rho/2)}{C_d^2 . A^2} \qquad (4)$$

where R, $lb.min^2/ft^6$ ($N.s^2/m^8$), is the resistance associated with the discharge coefficient, C_d (dimensionless) and the orifice area, A, ft^2 (m^2); and the mass density of air, ρ, is generally assumed to be 0.0024 $slugs/ft^3$ (1.2 kg/m^3).

For wind inclined to openings, the area, A, of such openings should be reduced by a factor equal to the cosine of the angle of incidence. For angles of wind incidence greater than 60 degrees, entry conditions at inlet openings become more complex, and their effective area is even less than that suggested by the cosine correction.

FRICTIONAL FLOW RESISTANCE

Frictional flow resistance is associated with skin friction as the viscous air moves past the stationary surfaces of the airway. Frictional losses increase with surface roughness and are proportional to air velocity. This resistance is not proportional to the square of the discharge but a power ranging somwhere between 1.75 and 2, depending on the Reynolds number of the flow. As Reynolds numbers encountered in airflows through large openings in buildings due to wind are normally above 4000, using a square relationship does not result in significant error. An advantage of accepting the square relationship is that dynamic losses can be converted to an equivalent length, Le (ft), of airway using the equation:

$$Le = \frac{3235.R_h.X}{10^{10}. K} \qquad (5)$$

or in SI units:

$$Le = \frac{(\rho/2)Rh.X}{K} \qquad (6)$$

where Le is the equivalent length in feet (metres);, R_h is the hydraulic radius of the airway (cross sectional area/perimeter) in feet (metres); X is the dynamic loss factor (dimensionless) for the orifice (referred to as "shock loss factor" by mine ventilation engineers); and K is the friction factor, $lb.min^2/ft^4$ (kg/m^3), associated with the surface roughness of the airway. An equivalent length for an orifice can be added directly to the length, L, ft (m), of the airway over which skin friction resistances are calculated. To determine the total resistance, R, to the flow:

$$R = \frac{K.P(L+Le)}{5.2\ A^3} \qquad (7)$$

or in SI units:

$$R = \frac{K.P(L+Le)}{A^3} \qquad (8)$$

where R, $lb.min^2/ft^6$ ($N.s^2/m^8$) is the combined resistance of an orifice and a length of airway, P, is the perimeter, ft (m), of the airway , and A, ft^2 (m^2) is the cross-sectional area of the airway. Appropriate values for the friction factor, K, are listed in mine ventilation reference texts (Hartman 1982). A K value of 25 x 10^{-10} $lb.min^2/ft^4$ (3.7 x 10^{-3} kg/m^3) is appropriate for airways clear of furniture, and a K value of 34 x 10^{-10} $lb.min^2/ft^4$ (6.5 x 10^{-3} kg/m^3) is suggested for airways with furniture. These values are intended for rooms geometrically similar to mine spaces. Testing is needed to determine friction factors for a wider range of building spaces and blockage conditions.

WIND PRESSURE DIFFERENCES

The Bernoulli equation for flow through a building with an inlet subscripted as "i" and outlet opening subscripted as "o" is:

$$p_i + (\rho/2)V_i^2 + \rho_i g z_i = p_o + (\rho/2)V_o^2 + \rho_o g z_o + \Delta p \qquad (9)$$

where p_i and p_o, lb/ft^2 (Pa), are the static pressures at the inlet and outlet openings, respectively; $(\rho/2)V_i2$ and $(\rho/2)V_o2$, lb/ft2 (Pa), are the velocity pressures at the inlet and outlet openings, respectively; $\rho_i g z_i$ and $\rho_o g z_o$, lb/ft^2 (Pa), are the potential pressures at the inlet and outlet openings; and Δp, lb/ft^2 (Pa), is the pressure loss in flow through the building.

Stack effects, arising from differences in potential pressure, are usually negligible in conditions of high airflow rates, particularly where inlet and outlet openings are a similar height, z, ft (m), above datum. As there is little opportunity for heating of the air during its rapid passage through the building, changes in air density are minimal. Given these conditions, Equation 9 can be reduced to pressure losses and wind pressures:

$$p_i + (\rho/2)V_i^2 = p_o + (\rho/2)V_o^2 + \Delta p \qquad (10)$$

Dynamic losses incurred by the jet after exiting the outlet orifice, $(\rho/2)V_o^2$, are dissipated in turbulence downstream and cannot contribute to airflow through the building; Δp is the loss inside the building. This leaves the pressure difference available from wind to produce flow through the building (equal to internal losses) as the difference between the total pressure (static plus velocity pressures) at the inlet and the static pressure at the outlet:

$$p_i + (\rho/2)V_i^2 - p_o = \Delta p \qquad (11)$$

Data on total pressure at inlet openings are rarely available. Instead, for purposes of estimating airflow through large openings due to wind, it is common practice to use the static pressure at the location of the inlet opening derived from pressure coefficients measured on the surfaces of solid building models in wind tunnel studies.

Current practice for estimating the static pressure difference between inlet and outlet openings, Δp, is to use the equation:

$$\Delta p = (\rho/2)(Cp_1 - Cp_2)(0.682Vz)^2 \qquad (12)$$

or in SI units:

$$\Delta p = (\rho/2)(Cp_i - Cp_o).Vz^2 \qquad (13)$$

where Δp, lb/ft^2 (Pa), is the static pressure difference between the inlet and outlet of an airway; ρ is the mass density of air, 0.0024 slugs/ft^3 (1.2 kg/m^3); Cp_i is the pressure coefficient near the inlet opening; Cp_o is the pressure coefficient near the outlet opening; and Vz, mph (m/s), is the reference wind speed at a height, z ft (m), above ground associated with the reference dynamic pressure for the pressure coefficients.

AIRFLOW THROUGH ORIFICES IN SERIES

The simplest condition of wind-driven airflow through a building is where flow passes through an inlet orifice, a sequential series of internal spaces and orifices, and exhausts through an outlet orifice. The equation for estimating the flow rate, Q, given these conditions, is:

$$Q = \left(\frac{(\rho/2)(Cp_i - Cp_o)(0.682Vz^2)}{\frac{(\rho/2)}{Cd_i^2.A_i^2} + \ldots \frac{(\rho/2)}{Cd_o^2.A_o^2}} \right)^{1/2} \qquad (14)$$

or in SI units:

$$Q = \left(\frac{(\rho/2)(Cp_i - Cp_o)(Vz^2)}{\frac{(\rho/2)}{Cd_i^2.A_i^2} + \ldots \frac{(\rho/2)}{Cd_o^2.A_o^2}} \right)^{1/2} \qquad (15)$$

where Q, cfm (L/s x 1000), is the volumetric discharge rate; $(\rho/2)(Cp_1-Cp_n)(0.682Vz)^2$ is the static pressure difference, lb/ft^2 (Pa), between the inlet and outlet orifices in the building; Vz, mph (m/s), is the reference windspeed at a height z, ft (m), above ground associated with the pressure coefficients; Cd_n (dimensionless) is the discharge coefficient for opening number 'n'; A_n, ft^2 (m^2), is the effective clear area of opening number 'n'; and ρ is the mass density of air generally assumed to be 0.0024 slugs/ft^3 (1.2 kg/m^3) (Daugherty 1977).

AIRFLOW THROUGH ORIFICES IN SERIES WITH PARALLEL BRANCHING

Where parallel branching occurs, branches can be combined for purposes of calculation to form a single branch of equivalent resistance. This reduces the amount of input data when a computer program is used to estimate airflow rates. Equivalent resistance, Req, for 'n' parallel branches is calculated using the equation:

$$Req = \left(\frac{1}{\dfrac{1}{\dfrac{(\rho/2)}{Cd_1^2.A_1^2}} + \ldots \dfrac{1}{\dfrac{(\rho/2)}{Cd_n^2.A_n^2}}} \right) \tag{16}$$

where Req, $lb.min^2/ft^6$ ($N.s^2/m^8$), is the equivalent resistance of a number of orifices with resistances, $(\rho/2)/Cd^2.A^2$, in parallel airways sharing a pair of common junctions.

Flow calculation proceeds using the equation for orifices in series. Flow in each of the parallel branches, Qn, can be calculated later from the estimated flow in their equivalent branch, Qe, using the equation:

$$Qn = Qe \left(\frac{Req}{\dfrac{(\rho/2)}{Cd_n^2.A_n^2}} \right)^{1/2} \tag{17}$$

Internal subdivision of building space often leads to interconnection between parallel natural-ventilation airways through the building. When this occurs, the combination of parallel airways into a single equivalent airway for purposes of calculation of flow rates is not possible. These network flows are estimated using iterative trial-and-error methods until the margin of error is acceptably small. One iterative method of "balancing flows" still in use today was described by Hardy Cross (1936). Another method is described by Walton (1984).

DESCRIPTION OF COMPLEX NETWORKS

It is important to establish a reference terminology when describing airflow networks, so that equations can be written that conform to a consistent set of terms. Each airway consists of "branches" beginning at an "initial node" at an inlet opening and ending in the direction of loss of pressure at a "final node" at an outlet opening. "Junctions" are "nodes" where three or more branches join. Each branch is assigned a "direction" for purposes of calculation corresponding to the assumed direction of falling pressure, which may or may not coincide with the direction of airflow determined in the solution of network flow. Flows that appear as negative in the solution are in the opposite direction to the "direction" assigned for purposes of calculation.

ESTIMATION OF FLOWS IN COMPLEX NETWORKS

In natural ventilation estimation, data available usually include wind pressures on the building together with data on the flow resistance of each branch in the network with the unknowns being the flow rates in each branch.

The method of "balancing flows" keeps pressures balanced in the network and balances flows by successive corrections. To commence the solution, pressure coefficients, Cp, at nodes inside the buildings are estimated as being some value between the maximum Cp_i at an inlet opening, decreasing along the airway branch toward the minimum Cp_o at the outlet opening.

With the pressure coefficients established at each end of each branch, flow rates for each branch, Q_n, cfm (L/s x 1000), are calculated using the estimated resistance based on discharge coefficients, Cd, and free areas, A, ft^2 (m^2), for orifices in series in each branch in the equation:

$$Q_n = \left(\frac{(Cp_i - Cp_o)(0.682Vz)^2}{\dfrac{1}{Cd_i^2.A_i^2} + \ldots \dfrac{1}{Cd_o^2.A_o^2}} \right)^{1/2} \tag{18}$$

or in SI units:

$$Q_n = \left[\frac{(Cp_i - Cp_o)(Vz)^2}{\dfrac{1}{Cd_i^2.A_i^2} + \dots \dfrac{1}{Cd_o^2.A_o^2}} \right]^{1/2} \tag{19}$$

Where Q_n, cfm (L/s x 1000), is the discharge through branch "n"; Vz, mph (m/s), is the reference windspeed, z, ft (m), above ground level associated with the pressure coefficients; Cp_i is the pressure coefficients outside the inlet opening; Cp_o is the pressure coefficient outside the outlet opening; and Cd terms are discharge coefficients for each of the orifices along the airway branch, A, ft^2 (m^2). Terms are free areas of orifices along the airway.

Where resistance in an airway branch includes both dynamic and friction components, use the equation:

$$Q_n = \left[\frac{(Cp_i - Cp_o)(0.682Vz)^2}{R_n} \right]^{1/2} \tag{20}$$

or in SI units:

$$Q_n = \left[\frac{(Cp_i - Cp_o)(Vz)^2}{R_n} \right]^{1/2} \tag{21}$$

where R_n, $lb.min^2/ft^6$ ($N.s^2/m^8$), is the total dynamic and frictional resistance in airway branch "n"; Cp_i and Cp_o are the pressure coefficients for the inlet and outlet of the airway branch, respectively; and $(0.682Vz)^2$ is the reference velocity pressure of the wind when the velocity is in miles per hour.

These flows are summed at each junction, assuming flow into a junction to be negative and flow out of a junction to be positive. Since the net flow at each junction should be zero, an equal and opposite balancing flow is distributed between branches at the junction, and an increment in flow for the junction is determined using the equation:

$$dQ = - \frac{| R_1.Q_1^2 + \dots R_j.Q_j^2 |}{(1/2R_1.Q_1 + \dots 1/2R_j.Q_j)} \tag{22}$$

Where dQ, cfm (L/s x 1000), is the increment of flow added to each branch at the junction; R_1 is the resistance to flow in a branch "1"; Q_1 is the current estimated flow in branch "1", and "j" is the number of branches at the junction.

It should be noted that the 2R.Q terms are the derivatives of the terms $R.Q^2$ for pressure loss along a branch, and terms between | | symbols are absolute values. Strict adherence to the sign of terms must be followed when summing $R.Q^2$ terms. When flows have been balanced at each junction, flows at each end of each branch are summed. Since these net flows should also be zero, any imbalance is balanced with an equal and opposite flow, half carried over to each end of the branch. When all branch flows have been balanced, with the exception of branches to inlets or outlets, the internal junctions of the networks are once again unbalanced. An iterative process continues, balancing junctions followed by balancing branches until the flow rate being distributed is acceptably small (say, 20 cfm [10 L/s]). When this point is reached, pressure losses along each branch are calculated using the equation:

$$\Delta p_n = R_n.Q_n^2 \tag{23}$$

where Δp_n, lb/ft^2 (Pa), is the pressure difference between the inlet and outlet of the airway branch "n"; R_n, $lb.min^2/ft^6$ ($N.s^2/m^8$), is the total resistance of the airway branch "n"; and Q_n^2, cfm^2 or $(L/s\ x\ 1000)^2$, is the square of the volumetric discharge through airway branch "n."

DISCUSSION

A common application of aiflow estimates through large openings in buildings is estimating indoor thermal comfort (Ashley 1984). In these cases, local airflow velocities need to be determined. The method described in this paper can only predict local mean velocities where airflow passes through orifices or fully occupies a narrow corridor. In most other locations, airflow will be in the form of a jet that only occupies a limited part of a room, with lazy, recirculating eddies of air in the remainder of the space. Flow visualization with wind tunnel models often helps indicate these flow conditions. Finite element flow analysis methods (Kurabuchi 1987) can be used to obtain numerical data in these complex flow regions; however, super computers are needed to obtain reasonable run times for such analyses.

The current common use of pressure difference data from wind tunnel studies of solid models underestimates the pressure difference by an amount equal to the velocity pressure at inlets and is the principal reason why current practices tend to underestimate airflow rates through large openings in buildings due to wind. Errors in estimates of airflow rates incurred are typically less than 10% as the flow rate varies as the square root of the driving pressure difference. Studies (Aynsley 1980) have shown that for a typical rectangular house, the velocity pressure at inlet openings for normal incidence increases from zero with no opening to a maximum of 7% of the static pressure difference when openings are approximately 20% of the wall area. With further increases in opening size, the pressure loss between the inlet and outlet falls until openings reach 55% of the wall area. For wall openings greater than 55%, the pressure loss between inlet and outlet assumes a constant value of approximately 80% of the static pressure difference as measured from a solid model. Similar studies have been conducted (Vickery 1987). Corresponding effects are more severe on buildings raised above ground level on columns.

Because of the variable nature of windspeed and direction, airflow rates through buildings due to wind need to be calculated for each combination of wind speed interval and direction indicated in the wind frequency data available from NOAA long-term wind records. A more abbreviated source of such data is provided by ASHRAE (Degelman 1986). Use of such data allows airflow rates to be qualified by an estimated percentage of time of occurrence, that is, 3000 cfm (1416 L/s) for 15% of time, through a particular airway in a building, at a particular geographic location (Aynsley 1977).

Until recently, little attention has been given to numerical estimation of natural ventilation. As a result, only limited data are available on losses incurred as air flows through buildings. Some of the airflow resistance data used are taken from other flow situations, such as mine ventilation (Hartman 1982), where skin friction is the dominant resistance. Simple flow conditions of a few orifices in series can be estimated equally well using orifice flow theory, resistance theory, windspeed coefficient approach, or by physical modeling.

The resistance approach to flow calculation in complex networks, unlike most other methods, provides a single simple equation capable of accommodating all types of flow losses. The method provides a common interface for all existing sources of flow data, which makes the resistance approach attractive as a framework for flexible computer programs to solve complex flow networks. As the principal applications for the method have been focused on mine ventilation, more experimental work on buildings is needed to expand the data available for estimating wind-driven airflow through buildings.

There are a number of iterative techniques, such as those of Hardy Cross (1939), Newton (Walton 1984), and others, that can be used with the resistance approach for solving flow in networks. Speed of convergence using these techniques is dependent both on the initial estimates of pressure coefficients at internal junctions and the quantity used in iteration. It is advisable to experiment with a variety of methods in order to find a method that works efficiently with typical proposed data.

CONCLUSIONS

One factor often overlooked in estimating natural ventilation is the velocity pressure component of wind pressure at inlet openings. Neglect of this pressure can result in underestimation of airflow rates. Most readily available wind pressure data for external surfaces of buildings are static pressures on surfaces, generally determined from wind tunnel studies of solid models. Using pressure diferences based on such data excludes the velocity pressure component at the entry orifice. The actual pressure difference, determined from the Bernoulli equation, is the difference between the total pressure at the inlet opening and the static pressure at the outlet opening. Limited indications of the difference between static and total to static pressure differences across one building form with a range of porosities are given by Aynsley (1980, p.250) and Vickery (1987). Further study of this problem is needed to devise a way of adjusting currently used pressure data to account for size and location of openings in buildings.

Another factor often overlooked is the effect of inclined wind incidence at inlets, which has the effect of reducing the effective area of inlet openings. Wind maintains its external direction as it passes through large inlet openings. In the case of oblique incidence, this reduces the effective area of such openings by a factor approximating the cosine of the angle of wind incidence up to 60 degrees. Allowance for this effect can be made by adjusting the area of inlet orifices associated with the discharge coefficient. Further study of this effect is needed.

The resistance approach to estimating wind driven flow through buildings offers a means incorporating all types of pressure losses with a single, simple equation. The method permits the use of a wide range of existing duct and orifice flow data. In addition ventilation resistances associated with partial blockage of mine shafts give insight into effects of airway blockage by furniture in buildings. While the conversion of losses resistances may appear awkward, it should be understood that these conversions normally will carried out within a computer program. The method appears to deserve further consideration estimating wind-driven airflow through large openings in buildings.

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