INTERNATIONAL ENERGY AGENCY
energy conservation in buildings and
community systems programme

Technical Note AIC 9

Mathematical models of air infiltration - a brief review and bibliography

October 1982

AIC

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This report is part of the work of the IEA Energy Conservation in Buildings & Community Systems Programme

Annex V Air Infiltration Centre

Document AIC-TN-9-82
ISBN 0 946075 02 6

Participants in this task:

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Mathematical models of air infiltration
- a brief review and bibliography

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PREFACE

International Energy Agency

In order to strengthen cooperation in the vital area of energy policy, an Agreement on an International Energy Program was formulated among a number of industrialised countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organisation for Economic Cooperation and Development (OECD) to administer that agreement. Twenty-one countries are currently members of the IEA, with the Commission of the European Communities participating under a special arrangement.

As one element of the International Energy Program, the Participants undertake cooperative activities in energy research, development, and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs were identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small Secretariat staff, coordinates the energy research, development, and demonstration programme.

Energy Conservation in Buildings and Community Systems

The International Energy Agency sponsors research and development in a number of areas related to energy. In one of these areas, energy conservation in buildings, the IEA is sponsoring various exercises to predict more accurately the energy use of buildings, including comparison of existing computer programs, building monitoring, comparison of calculation methods, etc. The difference and similarities among these comparisons have told us much about the state of the art in building analysis and have led to further IEA sponsored research.

Annex V Air Infiltration Centre

The IEA Executive Committee (Buildings and Community Systems) has highlighted areas where the level of knowledge is unsatisfactory and there was unanimous agreement that infiltration was the area about which least was known. An infiltration group was formed drawing experts from most progressive countries, their long term aim to encourage joint international research and to increase the world pool of knowledge on infiltration and ventilation. Much valuable but sporadic and uncoordinated research was already taking place and after some initial ground-work the experts group recommended to their executive the formation of an Air Infiltration Centre. This recommendation was accepted and proposals for its establishment were invited internationally.

The aims of the Centre are the standardisation of techniques, the validation of models, the catalogue and transfer of information, and the encouragement of research. It is intended to be a review body for current world research, to ensure full dissemination of this research and based on a knowledge of work already done to give direction and a firm basis for future research in the Participating Countries.

The Participants in this task are Canada, Denmark, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States.

REVIEW

Under normal atmospheric conditions, the flow of air through adventitious openings in the envelope of a building can generally be approximated by the equation

$$Q = k(\Delta P)^n \quad (m^3 s^{-1}) \tag{1}$$

where k = flow co-efficient ($m^3 s^{-1}$ at 1Pa)
n = flow exponent
ΔP = pressure difference across opening (Pa)

The coefficient, k, is related to the size of the opening and the exponent, n, characterises the flow regime. The flow exponent ranges in value between 0.5 for fully turbulent flow to 1.0 for laminar flow. For reasons of dimensional homogenity, a quadratic form of equation (1) in which the laminar and turbulent components of flow are separated is sometimes preferred. This approach has been further developed by Etheridge[1].

The flow parameters may be determined directly from leakage tests made on individual components, or from published values such as those given in Chapter 22 of the *'ASHRAE Fundamentals'*[2]. Alternatively, it is possible to make use of the leakage characteristics determined by pressure testing the entire building. In this instance, the total leakage is distributed according to the leakage area or crack length represented by each leakage path. This method has been used by Sherman et al[4] and Warren et al[5] to correlate the results of building pressurization tests with air infiltration. Whichever method is used, it is important to account for every source of air leakage.

The pressure difference driving the air infiltration process is maintained by the action of wind and stack effect. Relative to the static pressure of the free wind, the pressure resulting from wind impinging on the surface of a building is given by

$$P_w = \frac{\rho}{2} C_p v^2 \quad (Pa) \tag{2}$$

where ρ = air density ($kg\ m^{-3}$)
C_p = pressure co-efficient
v = wind speed at building height (ms^{-1})

If on-site measurements of wind speed are unavailable, correction formulae enabling the use of off-site wind data may be used[3,4].

The pressure coefficient, C_p, is a function of the pattern of flow around the building. It is independent of wind speed but varies with wind direction and position. In mathematical modelling studies, the pressure coefficient is normally expressed as an average value for each face of the building and preferably for each 45° sector in wind direction.

Most information on pressure coefficients comes from the results of wind loading tests made in wind tunnels on scale models of isolated buildings. Examples of such coefficients for simple building shapes are given in *BS5925*[3]. A problem with this type of measurement is that it only refers to buildings in isolation and may therefore not be relevant if the wind pressure on a building is influenced by local obstructions. An alternative solution is to perform wind tunnel tests on scale models of the building in situ.

The stack effect arises as a result of differences in temperature, and hence air density, between the interior and exterior of a building. This produces an imbalance in the pressures exerted by the internal and external air masses, thus creating a vertical pressure gradient. When the internal air temperature is higher than that of the outside, air enters through openings in the lower part of the building and escapes through openings at higher levels. The level at which the transition between inflow and outflow occurs is the neutral plane. In practice, the level of the neutral plane is rarely known and the stack pressure is normally expressed relative to the level of the lowest opening. The flow direction is reversed when the internal air temperature is lower than that of the air outside.

The pressure difference resulting from stack action, between two vertically displaced openings, is given by

$$P_s = \rho_o g \, 273 \, h \left[\frac{1}{T_{ext}} - \frac{1}{T_{int}} \right] (\text{Pa}) \qquad (3)$$

where ρ_o = air density at 273K and ambient pressure (kg m^{-3})
h = vertical distance between openings (m)
T_{ext} = external air temperature (K)
T_{int} = internal air temperature (K)

Air infiltration calculated from wind and stack effect acting alone cannot be directly summed to obtain a combined air infiltration rate. This is because the pressures generated by these two components do not act on the building in an identical manner.

A number of mathematical models of air infiltration based on the theory outlined in equations (1) to (3) have been developed. In general, these take the form of a flow network in which nodes representing regions of differing pressure are interconnected by leakage paths. This network is described by a set of simultaneous equations formed by applying equation (1) to each of the paths. These equations are then solved for air flow through each path by determining an internal pressure distribution, such that a balance is maintained, to a predetermined tolerance, between volume inflow and outflow.

Depending on the level of detail required, the leakage paths may represent individual components such as cracks around doors and windows or a combination of components such as entire sections of a building. It is also possible to include the effects of purpose provided openings and chimneys by incorporating appropriate orifice or duct flow equations. The effect of mechanical ventilations systems may be similarly analysed by specifying the air flow characteristics of the system.

Air infiltration models range in complexity from 'single-cell' approaches in which the interior of the building is assumed to be at a single internal pressure[4-10], to 'multi-cell' methods in which the interior is partitioned into individual rooms or sections[11-17]. The type of model selected will depend very much on the purpose for which it is intended. 'Single-cell' models may be used to predict whole house air change rates and are therefore useful in energy calculations. However, they give no indication of air movement within a building and cannot be used if internal partitioning significantly restricts air movement. 'Multi-cell' models overcome these limitations and, because they can be used to predict internal air movement, are an invaluable aid to indoor air quality studies. The applications of these models are briefly summarised in Table 1. The main disadvantages of 'multi-cell' models are that they require substantial data to describe the internal flow network and often demand a significant amount of computational effort. With care, however, these disadvantages may be minimised by tailoring the size of the flow network to suit the problem to be solved.

With 'single-cell' models, it is normally possible to solve the flow equations directly. Descriptions by Sherman and Grimsrud[4], Warren and Webb[5], Larsen[6], Nylund[7], and Handa and Gusten[8] contain sufficient detail to apply the models to simple examples directly. In addition, Larsen[6] has published a user's manual and Nylund[7] illustrates a simple graphical method of solution.

The much increased scale of complexity of 'multi-cell' models prevents the use of direct

TABLE 1 — Summary of Model Applications

Type of Model	Applications	Advantages	Disadvantages
1. Single-cell[4-10]	— used to determine whole building air change rate — energy calculations — correlation of pressurization test data with air infiltration	— straightforward method of solution, can be performed using small computers or programmable calculators — normally possible to incorporate purpose-provided openings, chimneys and HEVAC systems	— does not predict air movement — not applicable to buildings in which internal partitioning restricts air movement
2. Multi-cell[11-17]	— used to determine whole building and individual room change rates — predicting air movement between individual rooms or sections of building — indoor air quality studies — smoke and fire movement — energy calculations	— simulates air movement within building — normally possible to incorporate purpose-provided openings, chimney and HEVAC systems	— substantial data is often required to describe flow network — considerable computational effort is required for large networks

methods of solution. Instead, numerical methods involving iterative techniques are used. Most descriptions only contain an outline of the techniques used but Bilsborrow[13] and Sander[14] have published detailed computer manuals.

A problem with many air infiltration models is that, because of insufficient air infiltration data, the scale of model validation has been limited. Therefore the general reliability of models for specific applications may be uncertain. One of the tasks of the Air Infiltration Centre has been to prepare reliable datasets from experimental data covering as wide a range of building design and climatic conditions as possible. This is being used to determine the full range of applicability of models and to identify the key parameters which must be defined for reliable estimates of air infiltration. Current results are encouraging and show that good estimates are possible provided that leakage and pressure data are accurately specified. The final outcome of this work will be published in 1983.

References from AIRBASE on air infiltration models

(1) Etheridge D.W.
#NO 21 Crack flow equations and scale effect
Bldg. Environ. 1977, 12, (3), 181-189, 14 figs, 8 refs. #DATE 01:03:1977 in English BSRIA j = in 'Ventilation of Domestic Buildings' #AIC 492.
ABSTRACT
Reconsiders semi-empirical equations derived from earlier laboratory investigation of flow through cracks. Proposes revised method of application. States equations offer improved technique for estimating open areas of room components. Presents supportive experimental results. Demonstrates implications of the equations regarding scale effect for full-scale and model-scale situations. Presents some results of ventilation rate measurements at model scale to illustrate effects of scale and wind turbulence, flow characteristics of scale model windows and of simple circular holes.
KEYWORDS
cracks, models. theoretical modelling,

(2) ASHRAE
#NO 867 Ventilation and infiltration.
ASHRAE Handbook of Fundamentals 1981 Chapter 22 18 figs. 5 tabs. 53 refs. #DATE 01:01:1981 in English #AIC 506
ABSTRACT
Briefly reviews ventilation requirements, types of ventilation , driving mechanisms for natural ventilation and infiltration, natural ventilation, infiltration and air leakage, air leakage sources, empirical models and infiltration measurement.
KEYWORDS
natural ventilation, air infiltration, air leakage, empirical models, measurement techniques,

(3) BS 5925:1980
Design of buildings:ventilation principles and designing for natural ventilation.

(4) Sherman M.H. Grimsrud D.T.
#NO 608 Measurement of infiltration using fan pressurization and weather data.
A.I.C. Conference "Instrumentation and Measuring Techniques." Windsor 6-8 October 1980 #DATE 07:10:1980 in English AIC
ABSTRACT
Presents a technique using fan pressurization results and weather data to calculate infiltration. The geometry, leakage distribution, and terrain and shielding classes are combined into two reduced parameters which allow direct comparison of wind-induced and temperature-induced infiltration. Using these two parameters and the total leakage area of the structure (found from fan pressurization) the infiltration can be calculated for any weather condition. Presents experimental results from 15 different sites for comparison with theoretical predictions.
KEYWORDS
infiltration, pressurization correlation, leakage, weather, theoretical modelling,

(5) Warren P.R. Webb B.C.
#NO 660 The relationship between tracer gas and pressurisation

techniques in dwellings.
A.I.C. Conference "Instrumentation and Measurement Techniques" Windsor 6-8 October 1980 15p. 6 figs. 18 refs. #DATE 07:10:1980 in English AIC
ABSTRACT
Proposes a method of linking pressurization measurements in buildings with infiltration rates. The method is based on a simple theoretical model. Gives details of whole house pressurization tests and tracer gas measurements of ventilation rate (using N2O) in fifteen houses. Gives details of the theoretical model and compares field measurements with model predictions. Finds good agreement and concludes model may be used to estimate air change rates using leakage data. Finds surface pressure coefficients for typical house shapes and notes a dearth of data of this type.
KEYWORDS
theoretical modelling, pressurization correlation, nitrous oxide, house, tracer gas,

(6) Larsen B.T.
#NO 548 Energy consumption of residential buildings
Norway: Building Research Institute. 2 parts. 198pp. unpriced. figs, tabs, 11 ref #DATE 01:01:1977 in English #AICR NO1
ABSTRACT
Users' manual and documentation connected with computer program ENCORE. Program is based on weighting factor method. Provides general description of input data, building location and shape, heating system and building use. Describes in more detail standard output, error messages and warnings. Provides examples concerning warm-air heated house and house with electric space heating system. Supplied detailed documentation of subroutines.
KEYWORDS
computer, energy consumption, residential buildings, electric heating, theoretical modelling,

(7) Nylund P-O.
#NO 515 Infiltration and ventilation
Tjyvdrag och ventilation
National Institute for Building Research, Sweden. T4:1979 64p 30 figs 8 refs. ISBN. 91-540-2963-5 in Swedish. #DATE 01:01:1979 #AIC 50 = D22:1980 ISBN 91-540-3275-X in English #AICR SE6
ABSTRACT
Describes a model for calculating the energy losses caused by ventilation and uncontrolled leakage of air in buildings. Discusses leakage characteristics of building envelope and duct system, the effects of wind and stack effects. Gives general picture of the calculation model.
KEYWORDS
theoretical modelling, energy losses, air infiltration,

(8) Handa K. Gusten J.
#NO 962 Pressure distribution around low rise buildings.
In 'Designing with the Wind' CSTB Seminar Nantes 1981 13pp 9 figs. #DATE 01:01:1981 in English #AIC 577
ABSTRACT
States that one of the major difficulties in estimating air infiltration

rates in buildings is lack of full scale data on pressure distribution on various structural shapes located in different types of surface roughness category. Tries to fill this gap by studying two building structures of different shapes and situated in different environments, registering the mean pressure distribution and calculating the rate of air leakage due to openings. The first house is of old type construction and in a 'semi-urban' environment. The second house is a newly built prefabricated timber house with two floors, and is in an 'open' environment. Compares measured mean pressure coefficients with the values given in the Swedish code of practice, and finds they vary considerably depending on the shape and location of the house.
KEYWORDS
pressure coefficient, low rise building, air infiltration,

(9) Cole J.T. et. al.
#NO 572 Application of a generalised model of air infiltration to existing homes.
ASHRAE Trans. 1980 vol.86 part 2, 1980 p.765-777 6 figs. 18 refs. #DATE 01:06:1980 in English #AIC 248
ABSTRACT
Presents examples of the use of a generalized model of air infiltration, developed earlier, to estimate the air infiltration characteristics of two test homes using data for the structures, weather and furnace installation. One of these is a single-storey home with basement of wood- frame construction, equipped with an oil-fired central heating furnace. The other is a 2-storey frame house equipped with a gas-fired central space heating furnace. Also presents detailed methods used with the model to obtain the "total" effective crackage in each test home, the effect of wind shielding by adjacent structures and the characteristic permeability of the structure. Finds reasonable agreement between predicted and measured infiltration.
KEYWORDS
theoretical model, air infiltration, house, weather, furnace,

(10) Jardinier P.
#NO 651 Ventilation and permeability of dwellings.
Ventilation et transparence a l'air des habitations.
Cahiers techniques du batiment. no.2 Feb/Mar. 1980 = A.I.C. translation no.5 #DATE 01:03:1980 in English, French #AIC 306 = E.C.R.C. OA Translation no.2385
ABSTRACT
Describes method for calculating the adventitious ventilation of a building using information from a pressurization test. The method requires a knowledge of the surface pressures on a building, calculated from wind speed and direction, the inside-outside temperature difference, and the distribution and characteristics of openings in the building shell. Applies formulae to three buildings and finds a great dependence of infiltration on wind direction. Discusses the effect of wind and stack effect, separately and combined. Discusses the effect of the tightness of the building shell on the efficiency of mechanical ventilation.
KEYWORDS
theoretical modelling, air flow, opening, air infiltration, stack effect, wind pressure,

(11) Gabrielsson J., Porra P.
#NO 255 Calculation of infiltration and transmission heat loss in residential buildings by computer.
Jnl. Inst. Heat. Vent. Engrs. 35 p 357-368 12 figs, 2 tabs, 3 refs.
#DATE 01:03:1968 in English #AIC 573.
ABSTRACT
States that current methods of estimating heat demand of buildings are very inaccurate, and so large safety margins are used which usually result in overestimating the necessary heating plant capacity. Describes computer program developed to improve the accuracy of heat demand calculations. Gives formulae used in the program for calculating heat demand, pressure conditions and air flow within the building. Gives example of the use of the program to calculate the effect of wind on an eight-storey residential building.
KEYWORDS
computer, theoretical modelling, heat loss, air infiltration, air flow, high rise building, pressure distribution

(12) Jackman P.J. Den Ouden H.Ph.L.
#NO 520 The natural ventilation of tall office buildings.
Proceedings IHVE/BRS Symposium "Thermal environment in modern buildings" London 29th February 1968. paper 4.1. 6 figs 18refs. #DATE 29:02:1968 in English BSRIA bk.
ABSTRACT
Reports study of the natural ventilation in elementary tall office buildings has been made using the analogy between the flow of air through a building and the passage of an electric current through a circuit of resistances. The prime motive forces, those of wind pressure and stack effect are detailed, and experimental values for these and other parameters related to the building are outlined. Results indicate that, for design purposes, natural ventilation can be assessed for modern slab buildings by prime consideration of the pressure generated by wind impingement and the air infiltration through windows so caused.
KEYWORDS
natural ventilation, air infiltration, high rise building, theoretical modelling, office building,

(13) a) Bilsborrow R.E.
#NO 240 A comparison of computed infiltration rates with results obtained from a set of full-scale measurements.
University of Sheffield, Department of Building Science, report BS2 29p. 5 figs. 7 refs, #DATE 01:11:1972 in English #AIC 89.
ABSTRACT
Presents results obtained from a digital analogue method of calculating infiltration rates in building. The results are compared with a set of full-scale observations carried out by G.T.Tamura and A.G. Wilson. (abstract no.192). Finds that calculated and full-scale results give good agreement in terms of the rate of change of air infiltration rate with wind speed and that both show that total infiltration rate is more sensitive to wind speed than wind direction. Suggests reasons for discrepancies between calculated and full-scale results and emphasises that errors in the method mean that only general conclusions can be drawn.
KEYWORDS
air infiltration, computer, theoretical modelling, wind speed, wind direction

References from AIRBASE on air infiltration models

NOTES
Abstract 239 Bilsborrow, R.E. "Digital analogue for natural ventilation calculations" Dept. of. Building Science BS6 gives description and print-out of program.

(13) b) Bilsborrow R.E.
#NO 381 Natural ventilation of buildings
PhD. Thesis University of Sheffield, Department of Building Science. 335p 78 figs 76 refs. #DATE 01:10:1973 in English.
ABSTRACT
Reports model scale experiments to investigate the validity of digital analogue methods of predicting natural ventilation. Finds calculated ventilation rates up to 30% higher than observed model ventilation rates. Shows differences between observed and computed results caused by operating efficiency of ventilation openings being less than calibrated efficiencies. Corrected ventilation rates, allowing for changes in efficiency due to pressure fluctuations and lateral air flows over model surfaces showed close agreement with observed results Discusses current methodologies for predicting infiltration and natural ventilation rates and suggests alternative methods of predicting infiltration heat losses and likely ventilation rates.
KEYWORDS
air infiltration, computer, theoretical modelling, wind tunnel, empirical models, heat loss,

(14) a) Sander D.M.
#NO 346 Fortran IV program to calculate air infiltration in buildings.
National Research Council Canada, Division of Building Research, computer progra no.37. 53p. 5 figs. 4 refs. #DATE 01:05:1974 in English. BSRIA sp.
ABSTRACT
Describes computer program used to calculate air flows and pressure differential in a building as a result of a combination of wind effect, stack action and the operation of air handling systems. Describes mathematical model of building and the assumptions and limitations of program. Gives listing of complete program.
KEYWORDS
air infiltration, computer, theoretical modelling, wind pressure, air flow,

(14) b) Sander D.M. Tamura G.T.
#NO 347 A Fortran IV program to simulate air movement in multi-storey buildings.
National Research Council of Canada, Division of Building Research, computer program no 35. 55p. 4 figs 1 ref. #DATE 01:03:1973 in English BSRIA sp.
ABSTRACT
Describes computer program used to calculate the air flows and pressure differentials in a multi-storey building as a result of a combination of wind effect, stack effect and the operation of air handling systems. Describes mathematical model of building and assumptions and limitations of program. Gives complete listing of program.
KEYWORDS
air infiltration, computer, theoretical modelling, high rise building, stack effect, wind pressure,

(15) De Gids W.F.
#NO 14 Calculation method for the natural ventilation of buildings.
Verwarm. Vent. July 1978, 35, (7), 551-564, 13 figs, 2 tabs, 7 refs. = Pub. 632 TNO Research Institute for Environmental Hygiene, Delft #DATE 01:07:1978 in English #AIC 29
ABSTRACT
Reviews mechanism of natural ventilation. Provides mathematical expressions for wind pressure distribution, stack effect, and air flows. Treats air leakage component's characteristics, both individually and connected in series or parallel. Employs model simplification to 1 and 2 Junctions. Illustrates a -Junction model calculation. Finds calculated and measured values agreed well for a large factory hall.
KEYWORDS
modelling, component leakage, theoretical modelling, factory, air flow, air movement,

(16) Irving S.J.
#NO 483 The computer simulation of smoke movement during building fires.
Fire. Prev. Sci. Tech. no.22 p3-8 9 figs. 1 tab. 3 refs. #DATE 01:12:1979 in English #AIC 303
ABSTRACT
Gives brief description of the new computer package developed by the Oscar Faber partnership for predicting the movement of smoke during a building fire. The model treats the building as a network and calculates air flow between rooms driven by stack effect and wind pressure. Four levels of complexity in the simulation are possible. Describes the results of these different types of analysis for a multi-storey building.
KEYWORDS
computer, air flow, smoke, fire,

(17) Etheridge D.W. Alexander D.K.
#NO 514 The British Gas multi-cell model for calculating ventilation.
ASHRAE Trans. vol.86 part 2 1980 p. 808-821 #DATE 23:06:1980 in English #AIC 183 = in 'Ventilation of Domestic Buildings' #AIC 492 ABSTRACT
Describes in detail a multi-cell model for predicting ventilating airflows. Gives equations for flow through cracks, wind and stack effect. States that comparisons between prediction and measurements indicate that the method is capable of giving relatively high accuracy for a wide range of ventilation conditions. Discusses advantages and disadvantages of multi-cell and single-cell methods. Argues that multi-cell approach is potentially more accurate and more useful.
KEYWORDS
theoretical modelling, air flow, ventilation, cracks,

THE AIR INFILTRATION CENTRE was inaugurated through the International Energy Agency and is funded by ten of the member countries:

Canada, Denmark, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and United States of America.

The Air Infiltration Centre provides technical support to those engaged in the study and prediction of air leakage and the consequential losses of energy in buildings. The aim is to promote the understanding of the complex air infiltration processes and to advance the effective application of energy saving measures in both the design of new buildings and the improvement of existing building stock.

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