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Mathematical Modelling of Infiltration and Ventilation

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Mathematical Modelling of Infiltration and Ventilation

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1. SYNOPSIS

It is particularly important to be aware of the air flow pattern in a building when determining indoor air quality problems or calculating space conditioning loads for energy consumption. Correct sizing of space conditioning equipment is also dependent upon accurate air flow information. A number of infiltration models have been developed to calculate infiltration-related energy losses and the resulting air flow distribution in both, single-zone and multizone buildings. International infiltration research has been conducted since the early twenties -- infiltration modeling, however, is a relatively new task. Most of the modeling effort has taken place during the last 15 years, during part of which time the Air Infiltration and Ventilation Centre has been in operation. This paper gives an overview of the development of infiltration models.

2. INTRODUCTION

The annual heat loss due to infiltration, unlike the equivalent for conduction, is dependent not only on the temperature difference between the inside and the outside of the building, but also upon shielding, terrain, wind speed and direction and on the design of the building. High wind speeds often occur at higher outdoor temperatures and may result in higher infiltration rates than those calculated for in the design.

Awareness of infiltration as a major factor in the overall conditioning load of a building has led to tighter construction of both, building components and the overall building shell. This has decreased the infiltration rate and its related ventilation heat loss but has sometimes created another problem with regard to indoor air quality.

The air-mass flow distribution in a given building is caused by pressure differences evoked by wind, thermal buoyancy, mechanical ventilation systems or a combination of these. Air flow is also influenced by the distribution of openings in the building shell and by the inner pathsways. Actions by the occupants can also lead to significant differences in pressure distribution inside a building. Figure 1 shows various influences on air-mass flow distribution.

Wind pressure distribution depends on the velocity and direction of the wind, the terrain surrounding of the building and its shape. Differences in air density, due to differences between outside and inside air temperatures, cause further vertical pressures which, in turn, influence the air-mass flow. Mechanical ventilation also introduces a pressure field on the building.

There are two fundamental approaches in determining the infiltration rate in buildings. The most straightforward method is to measure infiltration directly, e.g., by using the tracer gas technique. Multizone tracer gas techniques can be used to determine either the air flows between the inside and the outside of the building only, or in addition, the interzonal air flows. It is necessary to understand the latter so as to determine the impact of infiltration on indoor air quality.

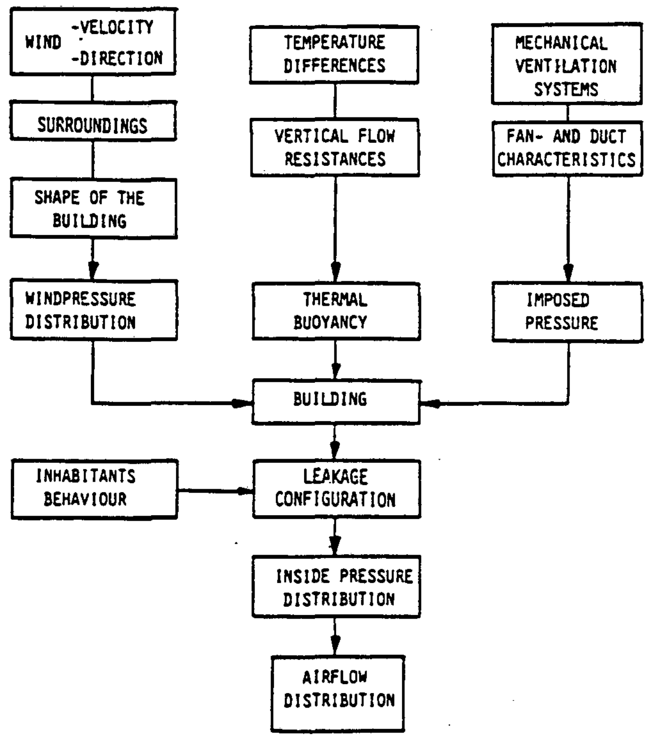

Fig. 1: *Influences on Air Flow Distribution in Buildings*

Tracer gas measurements give a value for infiltration only under prevailing leakage and weather conditions, but a second technique can be used to determine values of infiltration for all leakage and weather combinations. This method uses mathematical models (see Fig. 2).

The Air Infiltration and Ventilation Centre (AIVC) has published a comprehensive handbook, *Air Infiltration Calculation Techniques - an Applications Guide* [1]. This, and a second AIVC publication [2] are valuable tools for obtaining an overview of available techniques in calculating air infiltration.

Infiltration models can be divided into two main categories, single-zone models and multizone models (see Fig. 3). Single-zone models assume that the structure can be described by a single, well-mixed zone. The major application for this model type is the single-story, single-family house with no internal partitions (e.g., all internal doors are open). As a large number of buildings, however, have floor plans that would characterize them more accurately as multizone structures, more detailed models, taking internal partitions into account, have been developed.

Besides the static models described in this paper some models have been developed to determine ventilation rates under dynamic conditions. As these become more important when large openings are present the IEA Annex VIII "Inhabitants' behaviour with regard to ventilation" has investigated these patterns.

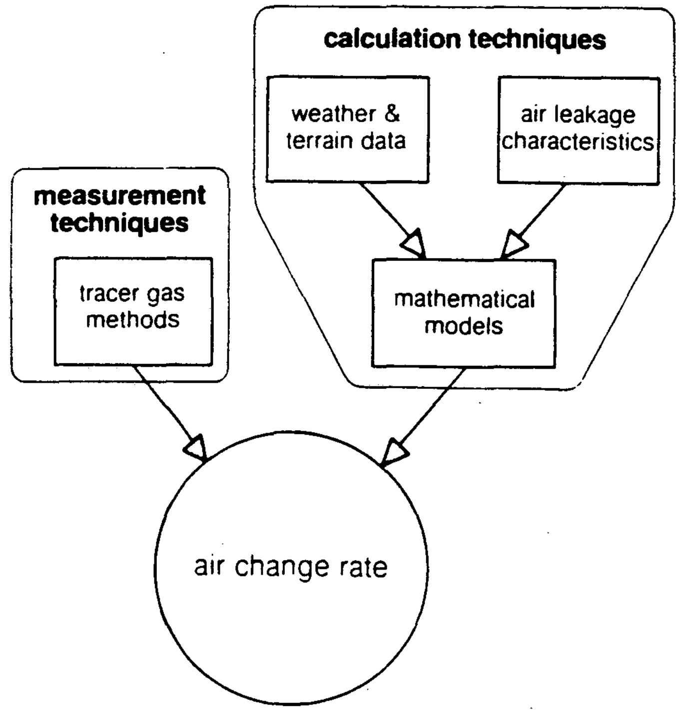

Fig. 2: *Alternative Ways of Determining Infiltration [1]*

A report giving some rules of thumb for estimating air flow rates through open windows has been published by AIVC [3].

3. SINGLE-ZONE MODELS

3.1 General

Single zone models are usually used in determining infiltration rates for single-family buildings. A zone is defined as a fully mixed volume with a constant concentration level of the enclosed gas mixture. Therefore, single-zone buildings do not exist in reality. However, smaller buildings without internal partitions or at least with open internal doors can be simulated with reasonable accuracy by single-zone models (see Fig. 4). Often, however, the limits of the single-zone models are obviously violated by using them for multizonal applications.

Single-zone models can be characterized as either empirical or physical models.

3.2 Empirical Models

Empirical infiltration models are the simplest infiltration models available being based solely on the knowledge obtained from infiltration measurements. Models can be as simple as assuming a constant infiltration rate based on no flow properties of the building; or dividing the leakage obtained by pressurization tests by a

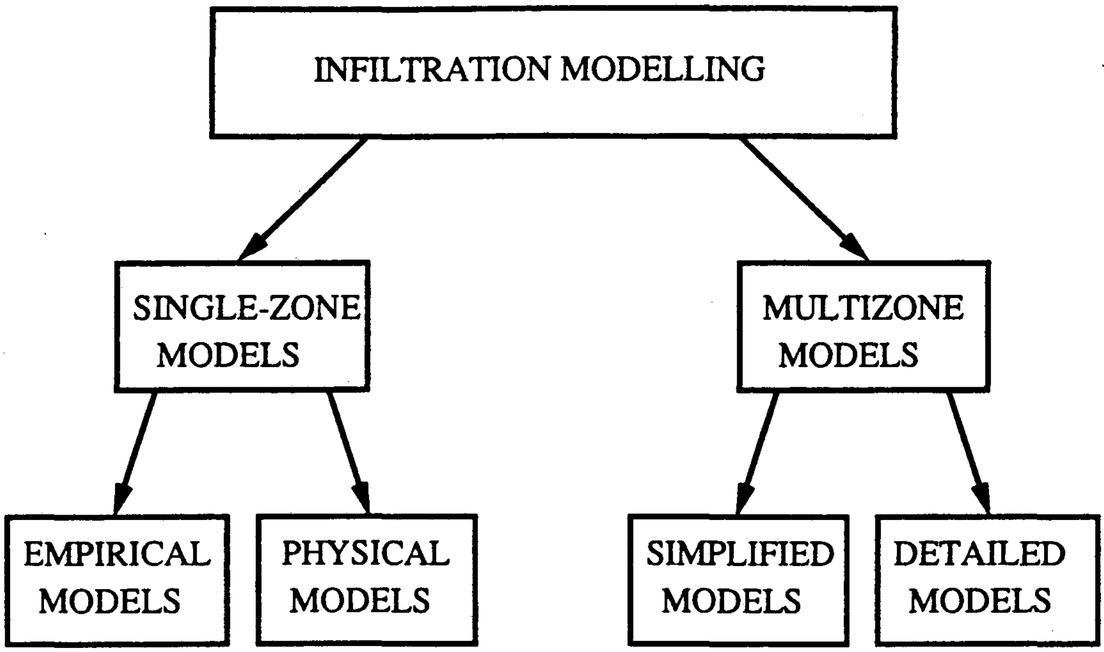

Fig. 3: *Categorizing Infiltration Models*

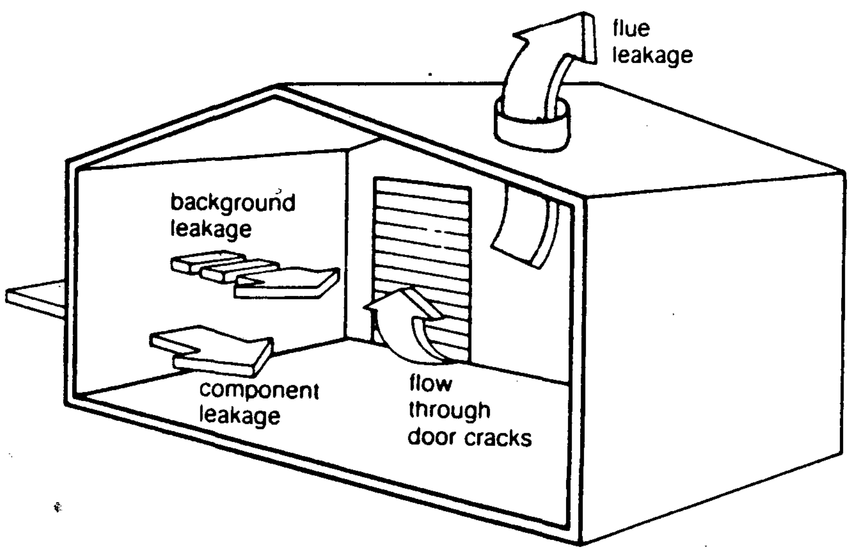

Fig. 4: *Example of a Single-Zone Building [1]*

constant number. Other models must take into account information about wind speed and temperature differences between the inside and the outside of the building.

The **constant rate model** assumes a constant infiltration rate for the whole building irrespective of the factors influencing the amount of air movement between the inside and outside of the building. This kind of model is still included in some of the building simulation programs used to calculate energy requirements for space conditioning but it is an abuse to use it for multizone applications. A more advanced version of the constant rate model determines infiltration as a function of the air flow obtained by pressurization tests. This method gives some indication of the magnitude of average infiltration and so provides some "rule of thumb" for the practitioner.

The **regression method** has been used for some time in order to fit in the enormous amounts of data obtained from tracer gas measurements. The modeling procedure utilizes two weather parameters as the sole weather-related potential for infiltration --the indoor/outdoor dry-bulb temperature difference and wind velocity. Because the regression coefficients reflect structural characteristics as well as shielding effects and occupant behaviour, variances of 20:1 have been found in individual regression coefficients when comparing similar structures [4].

$$Q = A + B\,\Delta T^{\alpha} + C\,v^{\gamma} \qquad (1)$$

with:

Q	infiltration rate
A,B,C	regression coefficients
ΔT	temperature difference
v	wind speed
α, γ	exponents (usually $1.0 \le \alpha \le 2.0$; $0.5 \le \gamma \le 1.0$)

Based on statistical analysis of field data and the assumption that the air permeability of the envelope is uniformly distributed, wind direction is usually not taken into account.

3.3 Physical Models

Once pressurization measurement techniques for building components or whole buildings existed, physical models became possible. The crack model, which uses the flow characteristics of building components, was probably the first physical model for single zone applications. A second group of models uses information from whole building pressurization tests.

The air permeability of the building's envelope depends on the number and size of cracks, windows, doors and gaps between building components. In addition to these visually observable flow paths leakage is caused by the porosity of building material.

The **crack model** is the first real attempt to estimate leakage of the building's envelope. This method assumes that infiltration is proportional to the product of crack coefficient and crack length and can be expressed by the empirically power law function.

$$Q = a\ l\ \Delta p^n = C\ \Delta p^n \tag{2}$$

with:

Q	infiltration rate
a	crack flow coefficient
l	crack length
C	flow coefficient
Δp	design pressure drop
n	flow exponent

Values for the exponent range between n = 0.5 for fully turbulent jets or turbulent flow and n = 1.0 for fully laminar flow. However, due to the head losses which are directly dependent on the square of the velocity, n = 1.0 cannot be reached in reality. The exponent for calculating infiltration by the crack method is usually set at $n = 2/3$. A comparison of air leakage measurements conducted by means of the blower door technique in 196 houses showed, in respect of the whole house, a mean value for the exponent of 0.66 [5]. This is in good agreement with the measured flow characteristics of building components.

The flow coefficient is determined by the measured crack length of each building component and its specific crack flow coefficient. The latter are published in various handbooks and infiltration standards [6,7].

Single-zone network models are based on the mass balance equation taking any number of flow paths between the outside and the internal zone into account. Essential input data are flow path distribution, flow path characteristics, weather data, shielding and terrain roughness conditions, and the characteristics of the mechanical ventilation system. For a structure with k flow paths the mass flow balance is given by:

$$0 = \sum_{j=0}^{k} \left\{ \rho\ C_j\ \left| p_{o_j} - p_i \right|^n \left(\frac{p_{o_j} - p_i}{\left| p_{o_j} - p_i \right|} \right) \right\} \tag{3}$$

with:

ρ	density of air
C_j	flow coefficient for flow path j
p_{o_j}	external pressure for flow path j
p_i	internal pressure
n	flow exponent

The latter term determines the flow direction which would otherwise have been lost in the previous term.

Examples of models based on the network idea are ENCORE [8] from the Norwegian Building Research Institute and INFIL [9] from GRI.

The principal disadvantage of the single-zone network approach is its data requirements. This has led to the development of **simplified single-zone models.** These models usually work on the basis of an assumption, which can be obtained from pressurization tests about the distribution of whole house leakage. Wind-induced infiltration and stack-induced infiltration are calculated separately and superimposed later.

The most widely used simplified single-zone model is probably the LBL-model [10]. Airport weather data is converted into local wind conditions with shielding and local terrain also taken into account. The height of the building and the assumed distribution of leakage over its envelope are sufficient, along with the weather data, to calculate the air flow. The LBL-model assumes infiltration to be proportional to the square root of the applied pressure.

$$Q = A \sqrt{\frac{2}{\rho} \Delta p} \qquad (4)$$

with:

A effective leakage area

Infiltration due to wind and stack action is calculated separately and later combined. The wind-induced infiltration calculates to:

$$Q_{wind} = f_{wind} \, A \, v \qquad (5)$$

and the stack-induced infiltration can be expressed by:

$$Q_{stack} = f_{stack} \, A \sqrt{g \, H \frac{\Delta T}{T}} \qquad (6)$$

with

f_w function describing the wind influence

f_{stack} function describing the stack effect

As a consequence of the flow assumption the flows due to wind and stack driven pressures are combined by summing the results in quadrature.

$$Q_{total} = (Q_{wind}^2 + Q_{stack}^2)^{1/2} \qquad (7)$$

As the LBL-model is an easy to use tool further work has been done to improve its performance (mainly when wind and stack effect have the same magnitude) and to adjust the model to the more realistic flow characteristics found in field measurements [11].

Based on the results of a detailed multizone infiltration model the NRCC model [12] uses the following equation for the superimposition of flows:

$$Q = Q_{large}\left[1 + 0.24\left[\frac{Q_{small}}{Q_{large}}\right]^{3.3}\right] \tag{8}$$

with:

Q_{small}	smaller of Q_{wind} and Q_{stack}
Q_{large}	larger of Q_{wind} and Q_{stack}

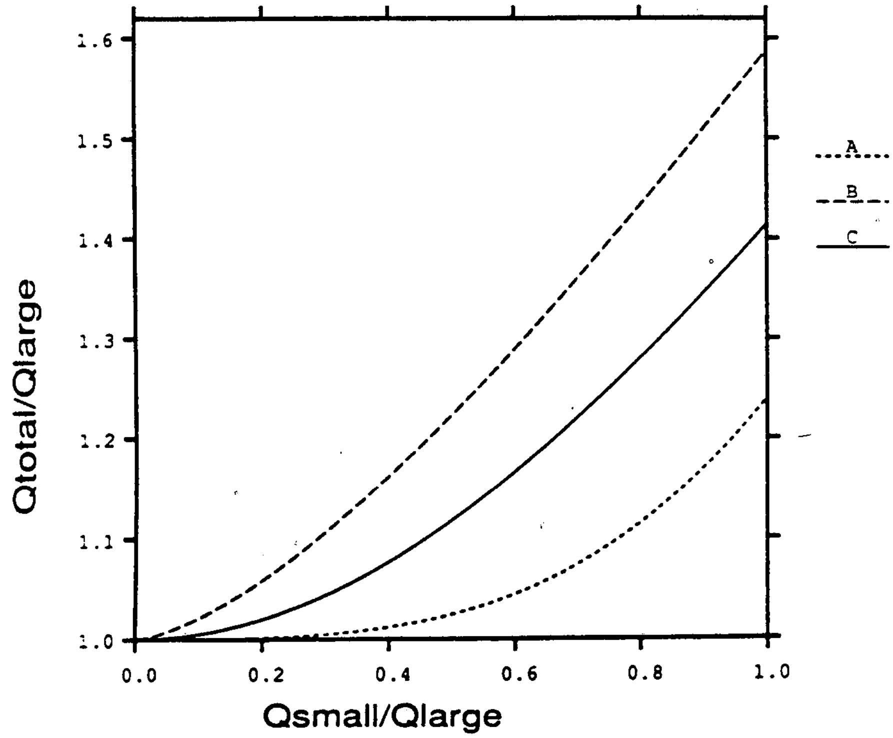

Fig. 5: *Superimposition of Flows [curve a) Eq. 8; curve b) Eq. 7 based on flow exponent n = 2/3; curve c) Eq. 7 based on flow exponent n = 1/2]*

In order to calculate the infiltration rate for one zone the BRE-model [13] relates to the air flow determined at a pressurization test. Air movement under ambient conditions is described by the power law equation.

$$Q = Q_{ref}\left[\frac{\rho v^2}{\Delta p_{ref}}\right]^n F_v\left[Ar, \phi\right] \tag{9}$$

with:

Q_{ref}	air flow at pressurization mode
Δp_{ref}	reference pressure difference ($10\,Pa \leq \Delta p_{ref} \leq 60\,Pa$)
F_v	infiltration rate function, including the effects of weather dependent parameters
v	wind speed at ridge height

This equation can be reduced to wind only and stack effect only action.

As with the LBL-model the BRE model assumes that the air leakage is uniformly distributed across each face and that the exponent n applies to all flow paths.

Several models have been developed to calculate the natural ventilation when ventilation shafts are present. Ertl et al. [14] not only developed and validated an algorithm which allows the performance of ventilation shafts to be evaluated but also published a review of the algorithms used for this purpose.

4. MULTIZONE MODELS

4.1 General

Multizone models are required when there are internal partitions in a building, or in the case of inhomogeneous concentration in the space. Multizone buildings can be either single-room structures (e.g., airplane hangars) single family houses or large building complexes. Fig. 6 shows an example of a very simple multizone building.

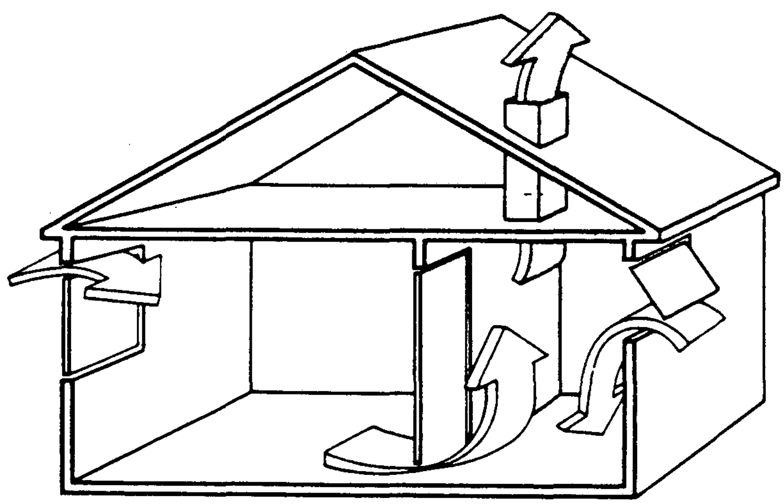

Fig. 6: *Example of a simple Multizone Structure [1]*

A number of infiltration programs have been developed to calculate air flows penetrating the building's envelope and travelling through the different zones of a multizone structure. Besides being able to simulate infiltration in larger buildings these models are able to calculate mass flow interactions between the different zones.

Knowing about the air-mass flow in buildings is important for several reasons:

- exchanging of outside air with the air inside the building is necessary for its ventilation
- energy is consumed to heat or cool incoming air to inside comfort temperature
- air is needed in different zones for combustion in open fireplaces and the exhaust of gasses
- airborne particles and germs are transported by air flow in buildings.
- air flow determines smoke distribution in case of fire.

The necessary information can be obtained either by multizone infiltration network models or by simplified multizone models.

In terms of air-mass flow buildings represent complicated interlacing systems of flow paths. In this grid-system the joints represent the rooms of the building and the connections between the joints simulate flow paths. These include the flow resistances caused by open or closed doors and windows and air leakage through the walls. The boundary conditions for the pressure can be described by grid points outside the building. Wind pressure distribution depends on the velocity and the direction of the wind, the surrounding terrain of the building and the shape of the building. If the physical interrelationship between flow resistance and the air flow is known for all flow paths the air flow distribution for the building can be calculated --as long as there is no temperature difference between outside and inside air. Differences in density of the air due to differences between outside and inside air temperatures, cause further vertical pressures while also influence the air-mass flow.

Mechanical ventilation can be included in this network, the duct system being treated like the other flow paths in the building. The advantage for calculating the air flow distribution effects of mechanical ventilation systems is that the duct pathways, as well as their connections with the building, are known. In the case of mechanical ventilation systems the fan can be described as the source of pressure differences, lifting the pressure level between two joints according to the characteristic curve of the fan.

4.2 Multizone Infiltration Network Models

Multizone infiltration network models deal with the complexity of flows in a building by recognizing the effects of internal flow restrictions. They require extensive information about flow characteristics and pressure distributions and, in many cases, are too complex to justify their use in predicting flow for simple structures such as single-family residences [15].

As for their single-zone counterparts these models are based on the mass balanced equation:

$$0 = \sum_{l=0}^{m} \left\{ \sum_{j=0}^{k} \left[\rho\, C_{j,l} \left| p_{o_{j,l}} - p_i \right|^{n_{j,l}} \left(\frac{p_{o_{j,l}} - p_i}{\left| p_{o_{j,l}} - p_i \right|} \right) \right] \right\} \tag{10}$$

with:

ρ	density of air
$C_{j,l}$	flow coefficient for flow path j of zone l
$p_{o_{j,l}}$	external pressure for flow path j of zone l
p_i	internal pressure
$n_{j,l}$	flow exponent for flow path j of zone l

Unlike the single-zone approach, where there is only one internal pressure to be determined, in the case of the multizone model one pressure for each of the zones must be determined. This adds considerably to the complexity of the numerical solving algorithm, but by the same token, the multizone approach offers wide potential in analyzing infiltration and ventilation air flow distribution.

A literature review undertaken in 1984 [16] revealed 26 papers describing 15 different multizone infiltration models which had been developed in eight separate countries. A review currently under way is producing additional information about the status of network models. One of the first we found was Jackman's model "LEAK" [17] which was published in 1970. In 1974 it was followed by the NRCC model [18], which was the first one available for use by interested parties. Indeed, this numerical tool is probably still the most widely used multizone infiltration model.

Several multizone models were developed in the aftermath of the oil price crises. Between 1975 and 1977 a series of steps were taken at TU Berlin to develop such a model. This resulted in the program STROM [19] which was later extended to handle HVAC-systems and has recently been rewritten to improve the solver and to be combined with a thermal model [20]. Concurrent with STROM, ELA 4 [21] has been developed. The models VENT 1 and VENT 2 [22] as well as BREEZE [23] were developed in the late 70s by researchers from British Gas and the Building Research Establishment. In the early 80s, first versions of Nantka's INFILTRATION & VENTILATION [24], Walton's AIRNET [25] and Herrlin's MOVECOMP [26] appeared. The latter two programs were the first to address the mathematical problem of solving the set of non-linear equations for zones with very different leakage characteristics. Open doorways in otherwise tight constructions are the main cause of significant problems in convergence. This has been solved in both cases by introducing under-relaxation factors to the well known Newton method.

By focussing on the work done in AIVC-member countries, we have neglected extensive program developments undertaken in Japan, France and Brazil. KGVCP from Hayakawa dates back to 1979 [27]. More recent work done in Japan has been published by Ishida and Udagowo [28] as well as Hayashi and Urano [29], Sasaki [30], Okuyama [31] and Matsumoto et al. [32].

France, as a possible future AIVC member, has also developed several multizone models; the recent review unveiled models from CSTB, INSA [33] and EDF. From Brazil, Melo's model FLOW2 [34] has been detected.

The latest development in infiltration modeling is the COMIS model [35]. In a twelve month period ten scientists from nine countries developed a reliable, well-running multizone model on a modular base. Because of its modular structure COMIS is designed to expand its capability to simulate buildings. To accomplish a "user-friendly" program special emphasis was given to the input routines. Support of the international group, working together at Lawrence Berkeley Laboratory, by IEA's Air Infiltration and Ventilation Centre will be likely to help the wide distribution of this model to all interested parties. COMIS can be used as a stand-alone infiltration model with input and output features or as an infiltration module for thermal building simulation programs. It also serves as a module library.

We discovered from the two reviews of the literature above that most of the models described by program authors use the FORTRAN (75%) programming language, followed in order of use, by BASIC, HPL and in one case each by PASCAL and C. As most of the programs represent research tools developed at universities they run on main frame or work station type computers (56%).

Because of the nonlinear dependency of the volume flow rate on the pressure difference, the pressure distribution for a building can only be calculated by using a method of iterations. Multizone network models were developed to deal either with simple structures of only a few zones or with buildings, having arbitrary floor plans, allowing an unlimited number of zones (limited only by the computer to be used). Many models have been developed which simulate a specific structure only, so allowing for the use of simple solving routines. Models which deal with arbitrarily chosen building types use either a great deal of CPU-space or are equipped with very sophisticated mathematical routines to reduce the storage need.

Large computer storage was necessary in the past, when calculating the air flow distribution of more complicated buildings. Nowadays, however, most programs use solver modules which reduce the space requirement, e.g., by band matrices or the skyline method. The Newton method is the most common tool used to solve the set of non-linear equations.

Although most models have been developed in FORTRAN on main frame computers, many use interactive mode to input the necessary data. Only one of the models, however, allows CAD-input. Three-dimensional building description and schedules for climatic data and occupants are more common today than they were

Table 1: Review of Multizone Infiltration Network Models		
Program Language:	FORTRAN	33
	BASIC	6
	PASCAL	1
	C	1
	HPL	3
Computer Type:	Main Frame Computer	23
	Personal Computer	18
Solver:	Newton	22
	others	8
Input Features:	interactive input	10
	CAD-input	1
	weather data from weather files	18
	3-D building description	8
	schedules (e.g. occupants)	14
Output Features:	file of arrays used by the model	23
	graphical output	7
	statistical functions	
Miscellaneous:	combined with thermal model	12
	combined with pollution model	8
Program Available?	yes	7
	no	11
	yes, but	11

five years ago but a comprehensive way of designing the output seems still to be a problem. Most of the models use the file of arrays to present the calculated result --not really a user-friendly method. Few models use the capabilities of personal computers to show the air flow distribution in two-dimensional graphs.

Twelve of the infiltration models are combined with a thermal model and eight feature a further combination with a pollutant transport model. For seven out of twenty-nine models the authors specify their product as "available to third parties". Eleven authors believe that, lacking user-friendliness, their models would be of no use for third parties. The remainder do not wish to make their tools available to others.

The multizone models investigated were, in regard to the equations used, very similar to each other. The flow equation used to describe the air flow characteristics of the buildings is similar to the one describing measured results for air flow through building components (see Eq. 2). Most programs use an empirical power-law expression type of equation, even though the pressure exponent may differ from 0.5 to 1.0, depending on the nature of flow. Only few models consider wind dynamics.

The programs still differ markedly in their ability to simulate mechanical ventilation systems. Twenty of them are able to simulate forced ventilation systems by means of fan and duct characteristics. This is a tremendous change from the last review.

The difficulty of measuring infiltration in buildings under controlled boundary conditions means that none of the models has been validated properly, if at all. The possibility of doing piecemeal validations of certain algorithms has been considered; e.g., the algorithms for air flow through open doorways or air flow through cracks have been tested separately [36]. Measuring a few cells of the whole structure could still provide a severe test for existing models.

These data are important not only for validation purposes but also as a means of further understanding air movement in large multizoned buildings. We need to identify the critical variables in different building types in order to develop more accurate input data and, ultimately, more accurate models. Wind pressure coefficients, for example, represent a factor that needs further study, and the collating of existing data should help our efforts in simplifying data requirements.

4.3 Simplified Multizone Infiltration Models

Most multicellular models in use at present are not available to the public or are written as research tools, rather than for professional engineers or architects. There is an obvious need for a simplified multichamber infiltration model capable of providing the same accuracy as the established single-cell models.

The extended **crack model** is the simplest multizone model. It is used to design conditioning loads and size the conditioning equipment [37]. The method is based on the single-zone crack model and has been refined to multizone applications by also taking into consideration the crack flow through internal partitions. Buildings are characterized according to their cross flow and stack flow capabilities.

The stack pressures of the core zones for multistory structures are pre-calculated for design weather conditions and published in look-up tables. Together with pressures due to the effect of wind and permeability distribution this enables a user to calculate the infiltration for each of the outside zones.

$$\dot{Q}_{shaft} = \left[\varepsilon_{shaft,wind} \sum(a\ l)_{wind} + \varepsilon_{shaft,lee} \sum(a\ l)_{lee}\right] H\ r\ (T_i - T_o) \tag{11}$$

$$\dot{Q}_{story} = \varepsilon_{story,wind} \sum(a\ l)_{wind}\ H\ r\ (T_i - T_o) \tag{12}$$

with:

$\dot{Q}_{shaft}$	infiltration heat loss for a zone in a shaft-type building
$\dot{Q}_{story}$	infiltration heat loss for a zone in a story-type building
$(a\ l)_{wind}$	crack permeability windward side
$(a\ l)_{lee}$	crack permeability leeward side
ε	coefficient, depending on wind speed and vertical location of the zone in the building
H	coefficient, depending on building type
r	coefficient, depending on permeability distribution of the zone

The **Simplified Multizone Infiltration Model** [38] developed at LBL is able to calculate the air flow distribution for arbitrary structures in any given weather conditions. The basic idea is to determine the flow network and to calculate the effective air permeability of a zone from the combination of flow paths arranged in series and/or parallel. The use of these equations assumes that all permeabilities have the same flow characteristics and, therefore, the same exponent, n (see Eq. 2).

Air flows caused by separate mechanisms (such as wind and thermal buoyancy) are not able to be added because the flow rates are not linearly proportional to the pressure differences. To superimpose the flows, it is necessary to add the pressures.

To describe the air flow distribution inside a building we introduced several lumped parameters reflecting the different permeability distributions of the building's envelope and the flow resistances inside the building; the envelope permeability ratio (epr) which describes the cross-ventilation of the building, the vertical permeability ratio (vpr) to determine the stack influence and the resultant permeability ratio (rpr). The latter describes the removal of the incoming air flow for each zone.

$$epr(\phi) = \frac{D_{lee,envelope}}{D_{total,envelope}} \tag{13}$$

$$vpr = \frac{D_{shaft}}{D_{total,envelope} + D_{shaft}} \tag{14}$$

$$rpr(\phi) = \frac{D_{res,zone,lee}}{D_{res,zone,total}} \tag{15}$$

with:

epr	envelope permeability ratio
vpr	vertical permeability ratio
rpr	resultant permeability ratio
$D_{lee,envelope}$	permeability of the leeward side of the building
$D_{total,envelope}$	permeability of the whole envelope
D_{shaft}	permeability from the shaft to the story
$D_{res,zone,lee}$	leeward resultant permeability of the zone
$D_{res,zone,total}$	resultant permeability of the zone

The resultant permeability ratio (*rpr*) is the ratio of the resultant permeability of the downstream side to all resultant permeabilities of this particular zone. To keep the model simple no mass balance equation is used to predict the air flows. Because of the pre-calculation of the simplified network the model gives a comprehensive understanding of the flow characteristics of the structure under investigation. The model is simple to use and requires only simple mathematical tools, e.g., pocket calculator.

5. SUMMARY

Traditionally, models of residential buildings were based on the regression analysis of measured data for infiltration and the driving weather forces. As the regression coefficients for these empirical models reflected structural characteristics as well as shielding effects and occupant behaviour, the regression coefficients between similar residences have varied tremendously. These models may therefore not be appropriate for use as a design tool for building energy analysis.

The next step in residential infiltration modeling was the development of physical single-zone models. The amount of information required for single-zone network models led to the development of simplified models. Their development has been justified by their widespraed use. These models are based on the physical phenomena of air flow through the building envelope by assuming a certain distribution of air permeability. Shielding effects and local vertical wind profiles are taken into account for calculating the infiltration rate. Measured data for a large number of houses are used to fine-tune, still further, especially the effects of shielding.

Following the analysis of an enormous number of measured ventilation rates in the case of houses for which the leakage characteristics have been determined by pressurization tests, a very simple model has been introduced --in which the air change rate measured at a given pressure differential, is divided by a constant number. This model does not take weather influence or leakage distribution into account.

Even before the development of physical single-zone models took place a number of computer models had been developed to calculate the air flow distribution in multizone buildings. The building is described by a set of zones interconnected by flow paths. Each node represents a space with uniform pressure conditions inside or outside the building and the interconnections correspond to impediments to air flow. The network models are usually based on the conservation of mass in each of the zones in the building. The first of these models to be developed was probably the BSRIA-model "LEAKS" which was published in 1970. Since that time, many more models have been developed but most of them have been written as research tools and are not available to third parties. As a consequence they are difficult to use and are, at the best, "user-tolerant" rather than "user-friendly".

The first very simple multizone model for equipment design calculation for low-rise buildings was introduced with the crack model. This model was later refined to cover high-rise buildings. A simplified approach was followed in the development of LBL's infiltration model, which allows the calculation of all interzonal air flows by means of a pocket calculator.

While multizone infiltration models have existed for the last two decades some of the thermal building simulation models are still working with constant rate models. Now that energy conservation and indoor air quality have become important issues this type of model is inadequate.

6. FUTURE OUTLOOK

Except for the fine-tuning of existing models, the development of single-zone models seems to be completed. As multizone models offer much more potential for further investigation, work will probably go on for some time to suit models to specific needs.

The development of multizone infiltration and ventilation models shows a relatively slow evolution. Lack of exchange of information, restricted distribution of models and the lack of a flexibil structure are probably the reasons why models developed in the early seventies are not very different from those developed in the late eighties.

Although several of the models discovered during this review serve a particular purpose they could have been developed using existing models. The COMIS workshop is trying to overcome these problems by creating a multizone infiltration model with a modular structure which will allow modules to be changed easily. The availability of the program together with the international authorship should help to establish COMIS as an infiltration standard on which specific applications can be built.

Along with stand-alone infiltration models, network models will also now finally find their way into thermal building simulation models. With the expected advances in the development of the next generation of building simulation programs infiltration modules will be needed for implementation in the program libraries.

Future tasks include the development of methods to determine the required input parameters, especially the wind pressure distribution. Further work must be done through sensitivity studies to reduce the input requirement and to increase user-friendliness by using the output features of the PC's.

Validation of the models is another essential task. In order to understand physical phenomena related to transport mechanism in buildings and to develop numerical descriptions, measurements must first be performed under steady state conditions. It is necessary, in order to measure mass flow transport mechanism accurately, to be able to control the pressure level and its fluctuation for each of the outside walls. This is only possible if the building is itself located in a building. Such a test facility would not only validate air flow models as a whole but would also help to validate the tracer gas techniques to be used to validate infiltration models in field experiments.

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8. REFERENCES

1. Liddament, M.W.: "Air Infiltration Calculation Techniques - an Applications Guide", Air Infiltration and Ventilation Centre, Bracknell, 1986

2. Liddament, M.W. and C. Allen: "The Validation and Comparison of Mathematical Models of Air Infiltration" Air Infiltration Centre, Technical Note AIC 11, 1983

3. Wouters, P., W.F. de Gids, P.R. Warren, and P.J. Jackman: " Ventilation Rates and Energy Losses due to Window Opening Behaviour", in Proceedings, 8th AIVC Conference "Ventilation technology - Research and Application", Ueberlingen, 1987

4. Ross, H. and D.T. Grimsrud: "Air Infiltration in Buildings: Literature Survey and Proposed Research Agenda", Lawrence Berkeley Laboratory, LBL-7822, 1978

5. Sherman M. H., D. J. Wilson and D. E. Kiel: "Variability in Residential Air Leakage", in Proceedings, ASTM-Symposium on Measured Air Leakage Performance of Buildings, Philadelphia, 1984

6. German Standard DIN 4701: "Regeln fuer die Berechnung des Waermebedarfs von Gebaeuden", Beuth Verlag Berlin, 1959

7. Reinhold, C. and R. Sonderegger: "Component Leakage Areas in Residential Buildings" Lawrence Berkeley Laboratory, LBL-16221, 1983

8. Larsen, B.T.: "Energy Consumption of Residential Buildings. The Computer Program ENCORE", Norwegian Building Research Institute, 1977

9. Cole, J.T., J.A. Kinast, T.S. Zawacki, R.H. Elkins, and R.A. Macris: "Development and Field Verification of a Model of House Air Infiltration for Single Family Residences", Gas Research Institute, Final Report, 1981

10. Sherman, M.H.: "Air Infiltration in Buildings", Lawrence Berkeley Laboratory, LBL-10712, 1980

11. Wilson, D.: personal communication at Lawrence Berkeley Laboratory, May 1989

12. Shaw, C.Y. and G.T. Tamura: "The Calculation of Air Infiltration Rates caused by Wind and Stack Action for Tall Buildings", ASHRAE-Transactions 83, Part II, 1977

13. Warren, P.R. and B.C. Webb: "The relationship of tracer gas and pressurization techniques in dwellings", AIC Conference "Instrumentation and Measuring Techniques", Windsor, UK, 1980

14. Ertl, H., A. Fail and E. Panzhauser: "Natuerliche Schachtentlueftungsanlagen, Messung - Beurteilung - Planung" Wohnhabitat, Archivum Oecologiae Hominis, Wien 1987

15. ASHRAE 1985 Handbook of Fundamentals, Chapter 22, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 1985

16. Feustel, H.E. and V.M. Kendon: "Infiltration Models for Multicellular Structures: A Literature Review", *Energy and Buildings*, Vol. 8, No. 2, 1985

17. Jackman, P.J.: "A Study of Natural Ventilation of Tall Office Buildings", Inst. Heat Vent. Eng., Vol 38, 1970

18. Sander, D.M. "FORTRAN IV Program to calculate Air Infiltration in Buildings", DBR Computer Program No. 37, National Research Council Canada, 1984.

19. Feustel, H.E.: "Entwicklung eines FORTRAN Programms zur Bestimmung der Luftstromverteilung in Gebaeuden", Diplomarbeit, Technische Universitaet Berlin, 1977

20. Jianxiong Guo: "Weiterentwicklung des Programms mit dem Ergebnis einer Beruecksichtigung thermischer Druckdifferenzen auch innerhalb eines Geschosses und einer spuerbaren Verringerung der Rechenzeiten", Interner Institutsbericht, Technische Universitaet Berlin, 1988

21. de Gids, W.F.: "Calculation Method for the Natural Ventilation of Buildings", TNO Research Institute for Environmental Hygiene, Delft, 1977

22. Etheridge, D.W. and D.K. Alexander: "The British Gas Multi-Cell Model for Calculating Ventilation", ASHRAE Transactions, Vol. 86, Part II, 1980

23. Evers, E. and A. Waterhouse: "A Computer Model for Analysing Smoke Movement in Buildings", Building Research Establishment, 1978

24. Nantka, M.: "A Numerical Method for Air Change Rate of Buildings Calculated" in Proceedings, 5th International Conference on HVAC, Praha, 1981

25. Walton, G.N.: "Thermal Analysis Research Program Reference Manual", NBSIR 83-2655, U.S. Department of Commerce, 1983

26. Herrlin, M.K.: "MOVECOMP: A static Multicell Air Flow Model", ASHRAE Transactions, Vol 91, Part 2B, 1985

27. Hayakawa, S and S. Togari: "Flow Rate Variation of Air Conditioning Systems due to Stack Effect and opening a Window", Kajima Institute of Construction Technology, Japan, Report Nr. 30, 1979

28. Ishida, K. and M. Udagowo: "Validation of the Ventilation Net Work Model for the Estimation of Room Temperatures and Heat Load of Residential Buildings with Measured Data", Transactions of the Architectural Institute of Japan, 1988

29. Hayashi, T., Y. Urano, T. Watanabe and Y. Ryu: "Passive System Simulation Program PSSP and its Applications", in Proceedings, "Building Energy Simulation Conference 1985, Seattle, 1985

30. Sasaki, T.: "Der Lueftungszustand von der Luftschicht durch Wind-Unruhe", Transactions of the Architectural Institute of Japan, No. 372, 1987

31. Okuyama, H.: "Network Numerical Analysis Method for Heat Transfer and Air Flow in Buildings", in Proceedings, 17th Symposium by the Committee of Building Heat Transfer, Building Environment Committee of Architectural Institute of Japan, 1987

32. Matsumoto, M. and H. Yoshino: "A Calculation Method for Predicting Air Pollution in Multi-Celled Buildings", The Meeting of the Tohoku Branch of the Architectural Institute of Japan, 1988

33. Cacavelli, D., J.J. Roux; and F. Allard: "A simplified Approach of Air Infiltration in Multizone Buildings", in Proceedings, "9th AIVC Conference, Gent, 1988

34. Melo, C.: "FLOW - An Algorithm for Calculating Air Infiltration into Buildings", in Proceedings, ICBEM'87 International Congress on Building Energy Management, Lausanne, 1987

35. Feustel, H.E., F. Allard, V.B. Dorer, M. Grosso, M. Herrlin, M. Liu, J.C. Phaff, Y. Utsumi, and H. Yoshino: "The COMIS Infiltration Model", in Proceedings, "Building Simulation '89, The International Building Performance Simulation Association", Vancouver, 1989.

36. Shaw B. H. and W. Whyte: "Air Movement through Doorways - the Influence of Temperature and its Control by Forced Air Flow", BSE 42 (1974), No. 12, pp. 210-218

37. German Standard DIN 4701: "Regeln fuer die Berechnung des Waermebedarfs von Gebaeuden", Teil 1: Grundlagen der Berechnung Teil 2: Tabellen, Bilder, Algorithmen Beuth Verlag Berlin, Berlin, 1983

38. Feustel, H.E. and M.H. Sherman: "A Simplified Model for Predicting Air Flow in Multizone Structures", Energy and Buildings, Vol 13, No. 3, 1989

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